Energy in Buildings and Communities Programme

International Energy Agency EBC Annex 80

Resilient Cooling of Buildings

State of the Art Review

Energy in Buildings and Communities Technology Collaboration Programme

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International Energy Agency

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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 (*)
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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 Code

Executive Summary

This report summarizes an assessment of current State-of-the Art resilient cooling strategies and technologies. It is a result of a collaborative work conducted by participants members of IEA EBC Annex 80. This report consists of four chapters.

In the first chapter are included relevant technologies and strategies that contribute to reducing heat loads to people and indoor environments. These technologies/strategies include Advanced window/glazing and shading technologies, Cool envelope materials, Evaporative Envelope Surfaces, Ventilated Envelope Surfaces and Heat Storage and Release.

In the second chapter are assessed cooling strategies and technologies that are responsible for removing sensible heat in indoor environments: Ventilative cooling, Evaporative Cooling, Compression refrigeration, Desiccant cooling system, Ground source cooling, Night sky radiative cooling and High-temperature cooling systems.

In the third chapter various typologies of cooling strategies and technologies are assessed inside the framework of enhancing personal comfort apart from space cooling. This group of strategies/technologies comprise of: Vertical-axis ceiling fans and horizontal-axis wall fans (such fixed fans differ from pure PCS 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, some including phase change material storage, Radiantly cooled panels (these are currently less for PCS than for room heat load extraction), Conductive wearables, Fan-ventilated clothing ensembles, Variable clothing insulation: flexible dress codes and variable porosity fabrics.

In the fourth chapter technologies and strategies pertinent to removing latent heat from indoor environments are assessed. This group includes Desiccant dehumidification, Refrigeration dehumidification, Ventilation dehumidification, and Thermos-electric dehumidification.

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1 Introduction

1.1 General Context

The world is facing a rapid increase of air conditioning of buildings. This is driven by multiple factors, such as urbanization and densification, climate change and elevated comfort expectations together with economic growth in hot and densely populated regions of the world. The trend towards cooling seems inexorable therefore it is mandatory to guide this development towards sustainable solutions.

Against this background, it is the motivation of Annex 80 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 as a whole to withstand, and also prevent, thermal and other impacts of changes in global and local climates. It encompasses the assessment and Research & Development of both active and passive cooling technologies of the following four groups:

- Reduce heat loads to people and indoor environments.
- Remove sensible heat from indoor environments.
- Enhance personal comfort apart from space cooling.
- Remove latent heat from indoor environments.

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

1.2 Objectives and contents

The present review summarizes the state of the art in cooling solutions which may be regarded as resilient. Its main objective is to systematically describe the available cooling solutions, their physical basis, their benefits and limitations, their technology readiness level, their practical availability, and applicability. Doing so, the State-of-the-Art Review forms the basis for the work of Annex 80.

1.3 Scope of the assessment

The focus of EBC Annex 80 is on residential and office buildings. The assessments of the State-of-the-Art Review are based upon extensive and systematic literature research as well as on both scientific and practical expertise of its authors.

2 Reduce heat loads to people and indoor environments

This chapter presents cooling technologies which reduce heat loads both to people and indoor environments. It addresses:

- Advanced window/glazing and shading technologies
- Cool envelope materials
- Evaporative Envelope Surfaces
- Ventilated Envelope Surfaces
- Heat Storage and Release

2.1 Advanced window/glazing and shading technologies

Technology Group A.2

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2.1.1 Physical principles

Building fenestration systems (windows and associated shading) can have a significant influence on overall building cooling energy use, cooling load shapes, peak cooling loads, and the resilience of the building with respect to power interruptions. They also can have a large impact on thermal comfort indoors. Within the window, the technical focus is on the glazing—that is, the transparent element, such as glass, that typically makes up from 70 to 95% of the overall fenestration area, with the remainder taken up by the opaque sash and frame elements. In curtain walls in non-residential buildings, insulated opaque panels may be part of the fenestration system. When considering cooling loads the glazing element is the primary factor so the properties of sash and frame are not considered in depth here. In all heating dominated climates and many temperate climates this simplifying assumption would not be appropriate. Overall solar impacts on building cooling load and comfort include not only the window but the effects of shading systems that are mounted in series with the window—on the outer surface of the building envelope, between glazing elements, or on the inner surface of the building envelope.

2.1.1.1 Primary mechanisms

The primary mechanisms that drive cooling impact are threefold: solar radiation; heat conduction due to temperature differences between indoors and outdoors; and mass transport via air movement, which includes both latent and sensible heat gain. For purposes of this study, we focus mainly on the solar gain element that will dominate in most design applications. Temperature-driven heat transfer can have an appreciable impact in some buildings where single glazing is still common and outdoor temperatures exceed comfort conditions consistently over a 24-hour basis. Natural ventilation, the ability to manage air flow via active or passive control of window opening when outdoor conditions permit, is a classic energy control strategy in some buildings but is not widely practiced and is outside the scope of this report.

Solar radiation through the window system is the dominant driver of cooling load impact for most windows. Since the design essence of a window is for view and daylight, the transparency that makes this possible is always associated with the transmission of solar energy. The primary determinants of solar gain arriving at a window are (1) geometry: latitude, time of year, hour of day, and window orientation; and (2) atmospheric properties: optical properties of the atmosphere and local weather conditions. At any given instant the fraction of incident energy then transmitted through the window into the building is dependent on the spectral/optical properties of the glazing, window, and shading system, as well as the spectral content and angular distribution of the incident sunlight.

The solar radiation intensity and spectrum reaching the earth's surface can be readily calculated with a variety of building energy simulation software tools. Two different approaches are often taken for standards and rating purposes where standard conditions are defined, and for estimating energy impacts and peak loads where data from hourly weather tapes for specific locations is used to calculate performance.

2.1.1.2 Key properties

Several glazing and shading parameters are critical to the contribution that the fenestration system (window plus shading) makes to building cooling loads and occupant thermal comfort.

A wide range of properties are used to characterize the energetic performance of windows but the two most important glazing and shading parameters that effect cooling load are the quantity of solar gain (also known as solar heat gain or passive solar gain) admitted to the building and the transmittance of daylight. Solar heat gain is reported in North America as solar heat gain factor (SHGC) and in Europe as total solar energy transmittance or solar factor ("g-value"), each on a scale of 0–1 [1,2]. These properties are used interchangeably in research and engineering practice. Daylight transmittance is reported as visible transmittance (scale: 0–1) which is the spectral transmittance of radiation weighted over the visible light spectrum by the product of spectral irradiance and the spectral photopic sensitivity of the eye. SHGC is the primary driver of cooling load and accounts for all the solar energy directly transmitted by the glazing as well as absorbed energy in the glazing system that enters the space. The directly transmitted solar radiation component alone, Ts, is sometimes reported but for thermal modeling purposes in energy simulation tools the SHGC is the relevant parameter. SHGC can be defined and calculated for the window alone but an SHGC for the shading system alone is not meaningful – the fenestration system SHGC must be determined for the overall window-shading system, and this may include an interaction between the glazing and shading elements. These calculations can be made in commonly used software packages such as WINDOW [3] which is also used by the National Fenestration Rating Council (NFRC) for rating purposes.

Visible transmittance is defined for each glazing layer, for the overall insulated glass unit (IGU) which may be comprised of two or more glazing layers with associated coatings, for the shading system and for the complete fenestration system. The wide range of glazing technology options is described in more detail in the next section. A comprehensive data base of virtually all commercially available glazing, with verified solar optical properties is maintained by Lawrence Berkeley National Laboratory (LBNL) as the International Glazing Data Base (IGDB) [4] in cooperation with the NFRC. Data entries are peer reviewed and the labs that measure the solar optical properties participate in an Interlaboratory Comparison every three years to help ensure the integrity of the data. The spectral data files are then employed in a variety of software tools. For example, WINDOW can be used to calculate SHGC and visible transmittance, and RADIANCE can compute daylight levels based on this optical data.

The SHGC and visible transmittance of windows includes effects from the glass and framing. Since the ratio of glass area to total window area (glass plus framing) varies widely and depends on operator type it is important to compare like to like. Since frames are opaque the relationship between glass visible transmittance and window visible transmittance is easily computed by the relative areas of the glass to the total window area including frame. The larger the window the greater the importance of its glass properties and the lower the impact of its frame. In assessing the SHGC impacts, while the same trends are true the actual values vary with the detailed thermal properties of the frame. Frame thermal properties and contribution to SHGC depend on the component materials, the cross-section design, dimensions, and external solar absorptance. For example, a thermally unbroken aluminum frame painted black on the outside will contribute significantly to the SHGC; a thermally broken metal frame or a fiberglass frame painted white will have a much smaller contribution.

2.1.1.3 Angle dependence of properties

Published SHGC values for glazing typically report visible transmittance or SHGC properties at normal incidence. In the case of SHGC this evolved from the desire of standards to reflect “worst case” performance and the maximum solar load will normally occur when the sun is perpendicular to the glass. The properties of most clear glass, absorbing glass, and reflective glass can be calculated for any incidence angle if the optical properties at normal incidence are known [5]. At high angles of incidence these models lose accuracy, but overall loads are much lower at such incidence angles, so the overall effects are small. Similarly, a normal incidence property for a shading system with horizontal slats will not be meaningful. Therefore, other approaches are required, as outlined in the optical scattering discussion.

2.1.1.4 Daylight impacts

Visible transmittance by itself has no direct impact on cooling as its thermal impact related to solar radiation is already embodied in the SHGC or in solar transmittance. However, to the extent that the lighting energy use in a room does affect the overall room thermal balance and therefore the result of window solar gain on space cooling, it is important to accurately assess the daylight distribution in a room. If daylighting allows all the electric lights to be dimmed or turned off, this lowers the overall space cooling load. This becomes important in buildings when lighting is an appreciable fraction of the building energy balance. It will thus have greater importance for many non-residential sector building types but not for residential occupancy [6].

To assess the daylight impacts of glazing in a building, the visible transmittance must be known for the complete glazing assembly. The visible transmittance of a layer of glass is determined by applying the photopic weighting function representing the eye's responsiveness to the visible spectrum to the available solar irradiance and then doing a wavelength-by-wavelength integration across the visible spectrum. This value is important both to calculate illuminance in order to estimate electric lighting energy savings and is needed to assess the potential presence of glare. Since most windows use an IGU of two or more glazing layers the overall visible transmittance and SHGC for the glazing assembly must be determined. Once the individual glazing layer properties are known the computation of net thermal and optical properties of the IGU including all the inter-reflectance between layers is readily calculated with tools like WINDOW [3]. The IGU properties are then combined with the frame properties as noted above to determine total window properties. For standardization purposes these properties are typically determined under well-defined "standard" conditions of solar spectrum, temperature, angle, etc., to permit an "apples to apples" comparison between competing products. However, for point-in-time energy impacts and for annual performance assessments these may need to be expanded as noted below.

SHGC and visible transmittance are the two dominant reference standards for reporting relative glazing performance in the context of cooling loads and comfort. However, there are other performance related issues, such as external reflected sunlight and optical scattering, that can play a major role on energy impacts and other performance outcomes in specific cases of building type and climate.

2.1.1.5 External reflected sunlight

While the cooling focus of interest has been the impact on interior thermal loads and glare, windows reflect sunlight back outdoors to varying degrees depending upon solar optical properties of the glass (reflectance) and incident angles. Furthermore, pressure differences due to altitude, temperature, or weather may deform the glass in an IGU and can introduce a focusing effect. Focused reflected sunlight has resulted in melting of vinyl siding on adjacent buildings and other undesired thermal impacts on adjacent buildings and streets [7].

2.1.1.6 Optical scattering

Most glazing reflect and transmit specularly but there is increasing use of diffusing glazing layers in building design. These provide privacy, some degree of solar control (by reducing hot spots), and some glare control; they can also enhance the aesthetics of the room. The diffusing layer can be a surface property of the glass, such as an etched surface; an interlayer in laminated glass; a metal screen or fabric; or other intrinsically scattering materials in the IGU [8].

Most shading systems scatter and diffuse sunlight via two mechanisms: (1) their geometry, e.g., curved parallel slats in a blind; and/or (2) their surface properties, e.g., brushed aluminum finish. The resultant shading system properties depend on the position of the shading system (if operable) and the incident solar angle. The total window system properties also depend on any interreflections between the shading and glazing elements, and on the details of convective and conductive heat flow [9].

Proper definition of the optical properties of glazing and shading materials that are scattering can be very complex. A bidirectional scattering distribution function (BSDF) is needed to characterize both the forward transmitted component and the backwards reflected component of incident solar energy fully and accurately and/or daylight. Unlike SHGC and visible transmittance which are normally defined at one angle—normal incidence—these functions cover the full hemispherical angular input range and the full hemispherical output angular range. The angular resolution of these measurements can vary but rapidly becomes a very large and cumbersome number if high spatial resolution is needed as in glare measurements. For most solar gain studies, a standard 145 × 145 set of incoming and outgoing angles is most used but that set of 21,025 data points is a big increase over a single transmittance value for a layer of glass, complicating sample measurement and data management. These properties are most often measured using complex laboratory facilities. A global effort is underway to further standardize these measurements and to create a shared global data base of materials whose BSDF properties have been determined [10].

2.1.2 Glazing technologies

A wide range of glass technologies and transparent polymers are available from which to construct glazing systems. These vary enormously in terms of their solar control properties, thus presenting a wide range of options to building designers. Research and development continues to add to the portfolio of available options.

2.1.2.1 Clear glass

Clear glass is the cornerstone of most of the glazing, used directly in multipaned units and as a substrate for further coating and processing. Most glass today is made by the float process at very high volume with excellent optical quality and relatively low cost. Traditional window glass varies in nominal thickness from about 3 mm for residential windows to 6 mm for non-residential windows but for large units with high structural loads can be 10 mm thick. Standard annealed glass from a float line can be further post-processed by heat strengthening or tempering to impart added strength. Traditional float glass has a small amount of iron in the mix, imparting a slight green tint when viewed on edge. Low-iron glass eliminates that slight color and boosts visible transmittance by 5% for a typical double-glazed unit with 6 mm glass. The optical properties of clear glass are well documented in the research literature and are detailed in widely used data bases of glass properties [4,11].

2.1.2.2 Thin glass

Thin glass, in widespread use in displays and flat screen televisions, is now being adapted for architectural use. Traditional architectural glazing is 2.3 mm thick for single strength glass used in smaller residential windows. Over the past 10 years a variety of new very thin glass substrates have been developed with thicknesses in the range of 0.3–1.2 mm. Even thinner glass can be made that can be rolled into a cylinder. Glass 0.7–1.6 mm thick is used as the center pane(s) of multipaned triple and quad IGUs [12]. While primarily used to improve insulating value at much lower weight, these multi-glazed assemblies can provide an SHGC as low as 0.15.

2.1.2.3 Tinted glass

Tinted glass is produced in float plants with the use of additives in the float mix. Traditional tints include blue-green, bronze, and grey. Tints function by selectively absorbing portions of the solar spectrum, thus impacting color/visual appearance and reducing solar transmittance and visible transmittance. They will also reduce SHGC but not as effectively as reflective coatings since 20-50% of the absorbed energy enters the building, depending upon the details of the IGU design. Properties of all types of tinted and heat absorbing glass are documented and available for use in window modeling software [4].

2.1.2.4 Reflective glass

Reflective glass uses an applied coating to reflect 20–90% of the incident energy. At the high end of reflectivity, the glass has a mirror-like appearance when viewed from the outside during the day. From the inside it still permits view out during the day when the outdoors is bright but appears as a mirror from the inside at night when the light balance is reversed and the indoors is brighter than outdoors. Mirrored glass with very low visible transmittance and low SHGC was common in the 1980s but is not widely specified now. Properties of commercially available reflective glass are documented and available for use in window modeling software [4].

2.1.2.5 Low-emissivity coatings

Low-emissivity ("low-E") coatings are the dominant coating in use in windows today [13–15].1 They serve two fundamental energy management purposes. All low-E coatings have high reflectance from 4–50 µm and thus decrease overall thermal conductance of the IGU by reducing long-wave radiative heat transfer. The first generation of low-E coatings had a high transmittance in the solar spectrum and was used in solar-heated passive buildings. A second generation of coatings offered since the 1990s followed by further refinements in the multilayer coatings shortened the reflectance transition wavelength to about 0.7 µm from about 4 µm so that most of the near-infrared (NIR) radiation in the sunlight (0.7–2.5 µm) is reflected. Spectrally selective coatings today are the most used low-E coatings. Some are applied directly to the hot glass on the float line (pyrolytic) but most are applied after the glass is made, using magnetron sputtering processes under vacuum conditions. Glass emissivity is 0.84; low-E coating emissivity ranges from about 0.10–0.15 for pyrolytic coatings to 0.03–0.08 for most post-processed sputtered coatings. These sputtered coatings are carefully tuned multilayer optical filters that allow excellent control of the total energy transmitted, typically with low absorptance and high reflectivity in the NIR and varying degrees of daylight transmittance. The spectrally selective coatings that admit daylight but reduce overall solar gain are often characterized by their "light to solar gain" (LSG) ratio expressed as visible transmittance divided by SHGC. LSG ratio ranges from about 0.5 for bronze tinted glazing to about 2.4 for the best spectrally selective "triple silver" sputtered coatings.

2.1.2.6 Transparent polymers

Transparent polymers, such as polycarbonate and acrylic, are used in specialty applications with a similar range in intrinsic optical properties. There are four primary architectural applications and solar-optical properties of those products that are widely used in building applications are available to building designers [4].

- Thin polymer films (e.g., PET) have been used as an intermediate stretched layer in IGUs. These can be coated with reflective and low-E coatings to reduce solar gain and thermal transmittance.
- Thin polymer films (clear or tinted) can be coated with a solar-control coating and then applied to existing clear glass windows as a retrofit measure to enhance solar-control properties of existing clear glass windows. Normally they are glued to the interior of the existing glass

1 In the context of window glass and window coatings, emissivity is evaluated in the 4–50 µm thermal infrared spectrum.

surface. There are many products available with a wide range of solar optical properties that can reduce SHGC to about 0.20 when applied to clear glass.

- Rigid sheet plastics can be tinted or coated although not to the same degree as glass. These are used for security purposes where breakage of glass may be an issue.
- In addition to thin sheet materials, polymers can be extruded as hollow, multi-cavity sheets with a variety of double and triple wall cavity geometries, ranging from 5 to 50 mm in thickness for applications like atria, greenhouses, and conservatories. They may also be used in overhead applications where breakage is a potential safety hazard. The polymers can be dyed to impart color, which also provides some degree of solar control.

2.1.2.7 Laminates

Laminates combine multiple layers of glass with one or more plastic interlayers, typically polyvinyl butyral (PVB), to enhance the strength of the composite glass layer and provide some protection if the glass is broken. In addition to its structural function the intrinsic glass solar properties can be modified by changing the properties of the polymer interlayer, which can be tinted or coated to provide additional solar control, diffuse light, or even include a printed image. The underlying optical calculations to create a wide range of laminates has been documented and embodied in widely available software and databases [3,4,16].

2.1.3 Glazing systems

Over 90% of all windows sold today in the U.S. residential market and 70% of non-residential building windows are double glazed; another 2% of national sales are triple glazed. These multi-glazed, insulating glazing decrease window conductance and lower SHGC. Furthermore, in very hot climates the lower conductance itself reduces window cooling loads. Determining the response of these glazing systems requires that the appropriated optical and thermal properties of the constituent layers are available and that validated thermal/optical models are available to determine the system level properties. Berkeley Lab WINDOW is the most widely used software for these calculations (IGDB | Windows and Daylighting, 2020; Rubin, 1985).

2.1.3.1 Insulating glazing systems

Traditional windows used a single sheet of glass in a frame. In colder climates an inner and outer window sash in parallel were used to reduce overall thermal transmittance. Beginning in the 1960s in the U.S. windows began to incorporate an insulating glass unit (IGU) comprised of two or three glass layers sealed at the edge with a spacer; dead air between the layers imparts additional insulating value. The introduction of double glazing offered advantages for solar control since an absorbing glass layer as the outer glass would reject more absorbed solar energy to the outside, thus reducing SHGC. With the advent in the 1980s of spectrally selective low-E coatings, which were normally placed on the #2 surface (inner surface of outer glass), a low SHGC (about 0.15 to 0.30) could be obtained while still transmitting significant daylight. Further improvements were made by replacing air with argon gas, thus reducing the thermal transmittance and the SHGC. Two factors contribute to the low SHGC: (a) the radiant solar energy is primarily reflected, not absorbed; and (b) radiation absorbed in the outer glass or coating is largely rejected to the outdoors due to the insulating value of the low emittance coating. When triple glazing is used the additional glass layer will normally also have a low-E coating that can further reduce SHGC. It is relatively easy in such a configuration to achieve an SHGC of about 0.15– 0.25 with a visible transmittance or 0.35–0.60. The thermal transmittance of a double-glazed IGU will range about 3.0–1.2 $W/m^2{\cdot}K$, and the thermal transmittance of a triple glazed IGU will range about 1.5–0.6 $W/m^2{\cdot}K$. A quad-glazed configuration further can reduce the thermal transmittance to about 0.4 $W/m^2{\cdot}K$. The properties of these and other IGU configurations can be accurately simulated with validated procedures and software [3,17,18].

2.1.3.2 Special IGUs—vacuum insulating glass, Aerogel

Two other approaches for highly insulating windows are under development or emerging. Both have potentially very low conductance but neither substantially improves solar control. Vacuum insulating glass (VIG) consists of two sheets of glass bonded at the edge with a glass to glass hermetic seal, an internal low-E coating and approximately 0.3 mm thick spacers distributed across the glass to separate the two layers of glass [19–21]. The overall center-of-glass thermal transmittance for the VIG is about 0.8–0.4 $W/m^2{\cdot}K$. Several companies now offer VIG (and some have sold earlier versions for 20 years) but it is expensive and has not yet entered mainstream markets. An alternative low conductance IGU design involves putting a layer of microporous aerogel between two glass sheets. Highly insulating lab samples have been made but size, cost, fragility, and haze have slowed development and market introduction, although potential energy savings appear promising [22]. While each is potentially highly insulating, there is nothing about VIG or aerogel that provides improved solar control beyond what the basic double-pane or triple-pane window will do.

Another option for a double-pane window (and potentially for a triple-pane window) is to embed a shading layer between the glass layers. This is discussed in the shading section.

2.1.3.3 Dynamic/smart glazing

Traditional windows provide dynamic control of solar gain and daylight with the use of extra shading layers that are deployed on the interior or exterior surfaces of the window or are located between glass layers. The newest glazing enhancement to provide control over solar gain is to add an active solar-control layer to the glass itself. Dynamic or smart glazing can be either by passively activated by temperature (thermochromic) or by light (photochromic) or can be actively changed using an applied voltage (electrochromic or liquid crystal). These glazing materials can serve two somewhat distinct functions—solar control and daylight/glare control. In the case of solar control, a smart glazing system with a dark state with an SHGC of 0.15 or below provides a good value proposition for cooling-load management. However, for glare control (without additional blinds or shades) the switchable glazing must provide a low-end visible transmittance below 0.03 and ideally as low as 0.01.

2.1.3.4 Smart passive glazing

Thermochromic (TC) products have been developed and are commercially available from several sources although they have captured only minimal market share to date. Measured and calculated energy savings vary widely depending upon climate, orientation, window area, and base case system [23,24]. There is additional R&D underway to develop better solar control performance [25]. Some thermochromic devices switch sharply over a narrow temperature range while others darken slowly over a wider temperature range. The switching process is temperature based. The temperature of the TC layer is influenced not only by absorbed sunlight but by other factors e.g., the indoor and outdoor air temperatures, the location of the TC layer in a multilayer window, the location of a low E coating etc. The influence of sunlight as a driver for changing the temperature of the TC layer depends in part on the solar absorptance of the coating. TC windows have the cost advantage of not requiring controls and wiring but they have little flexibility to control properties at the behest of the occupant.

Photochromic (PC) products initiate their change in optical properties when triggered by exposure to specific wavelengths of solar radiation. Photochromic materials have been used in sunglasses for years but commercially viable offerings with the required size, durability and optical control requirements for windows have not yet been developed for building applications.

Most of these TC and PC products reduce solar gain by absorbing solar radiation. Therefore, effective solar control for the window system requires an IGU thermal design in which most of the absorbed energy will be transferred to the building exterior.

2.1.3.5 Smart active glazing

The three primary active glazing types incorporate liquid crystal (LC), suspended particle devices (SPD), or electrochromic (EC) layers. Each involves adding a complex series of thin film and other functional layers to a glass or plastic substrate. LC products switch to a diffusing reflective state that also provides some privacy but even in the switched state the overall SHGC is typically not lower than 0.30 due to the scattered transmissive solar component. While the cooling load to the space may be the same as for a specular transmitting glazing, the effect on thermal comfort may be improved since the flux is spread over a wider area. Newer versions with enhanced solar control are under development. SPD products have had limited applications in buildings to date and require moderate switching voltage which makes their application more complex. Electrochromic coatings have attracted the most investment over the last 30 years and the best market reception to date (Casini, 2018; Piccolo & Simone, 2015; S. E. Selkowitz et al., 1994). The available commercial products reduce solar gain by absorption. A typical IGU with an EC layer will switch visible transmittance from 0.60 to 0.02 with an associated change in SHGC from 0.40 to 0.09. Most early building applications involve non-residential buildings but there is growing interest in residential applications as well [29–31].

New research is extending the potential performance of this class of smart coatings. One approach is to replace the active absorptive layer with an active reflective layer, further reducing visible transmittance and SHGC [32].ref. Another approach is to switch visible transmittance and NIR transmittance independently. This allows better performance in northern climates, and the window can reduce SHGC in warmer climates but still admit daylight [33,34]. A key driver of market interest in electrochromics is their glare control capability. Initial testing and modeling shows that the products can deliver good glare control and cooling load reduction although often at the cost of higher lighting energy use [35]. As with thermochromics the savings vary widely depending upon other building design and operational factors. Despite the initial market introductions and interest, and the promising early test and analytical results, market impact remains small as the technology is costly and requires integration with other building systems. For electrochromic windows to become more widely specified in buildings, the challenges that remain include lower cost; faster switching speed; more color-neutral appearance; and easier, more foolproof integration into building control systems. There is a significant global investment in RD&D in new or enhanced electrochromic solutions, as well as other active glazing technologies, which should provide new market options in the near term [36,37].

2.1.4 Building integrated photovoltaics

Building integrated photovoltaics (BIPVs) are traditionally opaque PV panels that are arrayed on the roof of a building to optimize solar access and minimize shading effects. There is growing interest, particularly in high rise buildings where roof area is limited, in placing these panels on the vertical façade, either as wall panels or as part of the window/facade system. The initial solutions utilized elements of conventional opaque cells integrated into the IGU and covering 20 – 80% of the window area, thus partially obscuring view and reducing light transmittance. If designed and integrated into the window effectively these BIPV-integrated IGUs can not only generate power for the building but serve a shading function [38,39]. Any energy in sunlight that is converted to electricity and extracted from the window represents a net reduction in solar load to the space.

A second-generation product utilizes a visibly transparent PV coating design which converts UV and NIR light to electricity [40]. While this approach allows daylight transmittance and view it also reduces the total power generated by the unit, decreasing it by roughly a factor of two compared to conventional cells since visible light comprises about 50% of the solar spectrum. In all cases extracting electrical power from the sunlight passing through the glazing will reduce the SHGC of the glazing. There has been continuous technical progress on the properties of these approaches but there are limitations as well. In addition to the reduction in efficiency, the vertical orientation of the window and its orientation with respect to south generally limits exposure to sunlight and therefore total power output. Output is also potentially compromised by shading from adjacent buildings. Generation of electricity by the windows or their shading systems would be useful during any power interruption and thus enhances the resilience of the building.

2.1.5 Shading devices and systems

Shading products to manage solar entry to buildings predate glass and windows. Today a wide range of products and systems are available to operate in conjunction with windows to provide excellent solar control under a variety of sun and climate conditions. The system properties depend largely on the location of the shading device relative to the window: (1) interior to the window, (2) between glazing layers in the window, or (3) exterior to the window. All of these devices and systems impact daylight transmittance and view as well as managing solar gain. There is extensive ongoing innovation in development and refinement of shading devices and systems as evidenced by trends in the global patent literature, which show not only improvements in shading element design but a new emphasis on control and automation [41].

Three sets of factors determine the overall impact of the shading system on the building cooling load and occupant comfort: (1) the intrinsic solar-optical properties of the shading materials, (2) the manual or automated operation of the system (if operable), and (3) the properties of the associated window system.

2.1.5.1 Interior operable shading systems

A wide range of interior operable shading products are employed in homes and office buildings. They are designed to be modulated by the occupants to control solar gain, daylight levels, thermal comfort, and visual comfort. Most interior devices are less efficient than similar external or between-glass solutions since the absorbed energy contributes directly to the space-cooling load. Most shading systems involve fabrics or slats that reduce cooling and improve comfort by reflection and absorption of the sunlight being transmitted through the window. Fabric roller shades and venetian blinds dominate this market segment. For vertical or horizontal blinds, the solar properties of the wood, metal, or plastic slats are determined by the surface finish, the geometry of the slats (flat or curved) and the position of the slats relative to the plane of the window. A closed-slat system with high reflectivity can reject 60-70% of incident sunlight. A partially open, dark-colored slat system will have almost no impact on solar gain although it may enhance local thermal comfort by diffusing the sunlight beam. Likewise shading fabric performance is influenced by the overall optical properties of the fabric. Some fabrics are opaque to the full solar spectrum (i.e., blackout screens) in which case their reflectance and absorptance are the key performance parameters as transmittance is zero. Other types of fabrics have a total transmittance with one component directly through gaps between the fibers, termed Openness Factor by the shading industry, with additional transmittance by diffusion through non-opaque fabric materials. The performance range of roller shades with these different fabrics is just as broad as that of blinds. Interior shading design and selection has focused on delivering aesthetics, privacy, and a glare control/light management function, and the solar control functionality has lagged in terms of optimizing performance. Furthermore the effectiveness in cooling load reduction is highly dependent on the operation of the moveable shading and numerous studies have shown that occupants are not reliable operators of manually controlled shading systems [42–44].

The solar-optical properties of these interior shading systems are far more complex than those of specular glazing materials. While a full bidirectional scattering distribution function (BSDF) may be required for some daylighting glare calculations a simpler data set usually suffices to assess solar gain. Researchers have extensively studied the methods to characterize these shading product with integrated measurement and modeling processes [45–48]. This research is now being adapted for product rating purposes by groups like the Attachment Energy Rating Council (AERC) in the U.S. [49] and the European Solar Shading Organization, ES-SO [50]. There have been two challenges: (1) developing the underlying product data for each shading layer, and (2) developing a methodology to produce a system BSDF when the BSDF of each component layer is known. One set of widely used calculations is embedded in the WINDOW software suite available from LBNL [3]. This allows the BSDF of a multilayer system to be computed once the properties of each layer are defined. The product data and their underlying materials properties are essential to performance assessment, to standards, and to product ratings globally. Since many of the product suppliers have global supply chains, there is a concerted international effort underway to develop and make available a global data base on the properties of shading system materials and systems properties, with supporting software tools. The collaborative effort between the Fraunhofer Institute/ISE in Germany and Lawrence Berkeley National Laboratory (LBNL) began in 2019 and should have an initial data base available in late 2020 or 2021.

Between-glass shading solutions

Two types of system design solutions involve shading devices operating between glazing layers. In the simplest case the solar control layer is embedded within a sealed IGU. In the more complex case, a shading system is incorporated into a double-skin façade, DSF. DSFs will normally have a passive or active shading layer between inner and outer glass layers and may also utilize natural or forced ventilative air flow between the glazing layers to manage heat transfer more effectively.

Shading in sealed IGU

The simplest case involves a solar energy management layer such as a woven metal screen or honeycomb panel inserted into the conventional insulating glass unit. The shading layer is protected from dust and disturbance so that optical surfaces do not need cleaning and properties persist over time. If the layer is static the BSDF of the assembly can be determined using the approach described in Section 2.3.1 and the overall properties calculated using the WINDOW software. If the layer is active— e.g., thin venetian blinds between glass [51]—or a thermotropic bi-metal layer, then the characterization becomes more complex but there is no heat transfer via mass exchange between the IGU and the indoors or outdoors.

Double-skin façade with shading

The double-skin façade solutions typically combine air flow management with the passive or active operation of the shading system. This entails more design and operational complexity and cost but potentially a higher performance solution. DSFs are commonly described as adaptive façades, emphasizing their ability to change thermal and solar optical properties in response to changing weather conditions or occupant and building needs. DSFs can include external and internal shading but the classic case involves shading between the glazing layers. In the summer cooling mode, air flow over the shading system in the glass cavity removes heat from the cavity and exhausts it outdoors. In the winter on a sunny day the energy absorbed in the shading element is captured in the air stream and delivered to the building HVAC system to offset heating needs. Variants of these systems have been extensively modeled and tested in testbeds [52–56] and assessed in a more limited way in several occupied buildings [57,58]. Although they are the subject of much research and interest, their actual field application to date has been limited in terms of overall market penetration. They typically require integration with a sophisticated HVAC system with extensive controls optimization so that shading operation and HVAC functionality are coordinated.

2.1.5.2 Exterior shading

Shading exterior to the sealed building skin is potentially the most effective strategy to reject incident solar energy if measured as the ability to reduce total solar heat gain. Solutions fall into two broad categories: fixed solutions and operable solutions.

Fixed exterior shading

Overhangs and fins are attached to the building envelope and sized to block direct sun from entering the building under summer cooling conditions. The design of these systems is always a compromise in terms of the time of day and day of year when the geometry of the shading will provide the desired functionality. There are normally tradeoffs that must be made between competing performance demands. For example, fixed shading used in some locations may increase the heating load (heat that must be added to the space to maintain set point) during the heating season if the shading design blocks solar gain that would otherwise have been transmitted through the windows [59].

To respond to this possibility these fixed systems can be redesigned to be adjusted several times a year to improve performance [46,59–62].

Operable exterior shading

Motorized shades, shutters, and blinds are widely used in climates and countries where air conditioning is not routinely available to help maintain comfort conditions in homes and offices. Systems that are motorized and automated have the greatest potential for reliably minimizing cooling impacts and enhancing comfort under a wider range of weather conditions, and during unusual events such as failure of the building HVAC [63,64]. The systems are more complex and costly than interior systems and need more maintenance over time given their outdoor exposure.

2.1.5.3 Shading system controls and operations

While we can hope that building occupants will effectively and consistently manage operable shading, experience suggests that occupants are notoriously unreliable as a consistent optimal operator of shading system performance [43,44,65,66] With the advent of wireless communications; the introduction of low-cost, low-power sensors; and an investment in the IOT infrastructure in many buildings it seems plausible that a smart, automated system to control shading could become the norm for new buildings. Lab testing suggests the value of these systems and several high visibility building projects prove that the strategies can be implemented [67–69]. However, the industry is not yet at the point where it can reliably deliver these solutions at scale.

2.1.5.4 Solar shading integrating renewable energy technologies

The integration of solar thermal components into solar shading devices is a challenging task aimed at improving both the cooling energy performance of buildings and the renewable energy harvesting though building integrated systems. Building-integrated solar thermal shading (BISTS) refers to shading systems, usually louvers, which embed solar collectors in each slat. The louvers are fixed, while the single slat may rotate across its axis to maximize the collected irradiation. The main challenges are related to the manufacturing of the solar thermal slats and the piping connections between the slat system and the rest of the building.

Integrating solar photovoltaic components is easier, and this is reflected by the number of available studies and applications. Photovoltaic integrated shading devices (PVSDs) refer to the replacement or coating of part or all the solar shading device (e.g., panels, louvres, blinds, and overhangs) with PV components or materials. Zhang et al. [70] provide a systematic review of technological and design solutions, but not energy performance.

2.1.6 Benefits and limitations

Fenestration systems encompass a very wide range of glazing, framing, and shading elements, which when incorporated into the building envelope impact heat transfer, solar gain, daylight, view, ventilation, comfort, and power generation. When trying to assess the benefits and limitations of these solutions on energy, comfort, and resilience the literature results are sometimes seemingly contradictory. This is largely because there are numerous parameters that determine overall performance—sometimes clearly defined, but often ambiguous or different between studies. Specific decisions about optimizing the solar control functions of window and shading systems can create benefits or have negative effects at four different physical and operational scales:

- Occupant. At this scale the key effect is on thermal comfort, including the direct impact of solar radiation on an occupant as well as a secondary effect on mean radiant temperature, and air flow. Clothing and activity level can also influence thermal comfort. For an occupant, daylight levels and visual comfort often take precedence over solar control when implementing a shading strategy.
- Building. At this scale the focus is on the thermal dynamics in the spaces in the building, influenced directly by glazing/shading properties, by thermal properties of the space, and by HVAC response (e.g., radiant vs. air systems, precooling strategy). In summer the concern is solar impact on cooling, but in winter the fenestration solar impact may usefully offset heating loads
- Urban context. At this scale the concern is the role the building has on other nearby buildings, on vehicles and on people outdoors. Solar energy reflected from glass facades has created significant thermal problems on adjacent buildings, and on people and vehicles at street level.
- Electric grid effects. Cumulative solar effects on building cooling load—particularly on hot days—will typically define systemwide electric load shape and peak electric loads. The primary building electric loads influenced by shading are cooling and lighting.

While the key performance metric that determines overall solar gain in the building is the SHGC of the glazing/shading system, the magnitude of potential savings depends on many factors. It is thus dangerous to make blanket statements about benefits or performance of glazing and shading systems without specific reference to these key parameters. The overall effectiveness of solar management strategies must therefore be assessed in the context of these topics:

- Glazing and façade elements, and full integrated façade systems: specific glazing properties and framing used, integrated or internal or external shading, integrated systems such as double envelope or ventilated facade systems, power generation options, and sensors and controls for operable systems if present.
- Glazing role in the building envelope: areas and locations of windows, skylights, and other glazing [71].
- Site and climate: City location and latitude impacting solar conditions and associated annual climate impacts. Site location within a city, surrounding site albedo, and the geometry and proximity of adjacent buildings may also influence solar access and wind. Important climate details include not just annual average conditions, also but monthly and hourly patterns of sunlight and temperature [72].
- Building type and characteristics: A unit of solar energy entering a building via fenestration can have a wide range of net effects on cooling, lighting, load shape, etc. depending upon key building characteristics. These include (1) type—residential vs. non-residential with associated operating hours; (2) building size; (3) thermal mass; (4) operating conditions and occupancy (density, hours); (5) HVAC system type, part load operating characteristics, and thermal zoning, and (6) HVAC downsizing potential with high performance solar control [73].
- Human factors: Occupant interactions, including the effects on task performance and productivity, thermal comfort, glare and visual comfort, view, health, and well-being [74].

These five factors interact in both simple and complex ways to determine the overall cooling impact on a building. A strategy that works very effectively for the west façade in one climate zone may not have the same performance on the west in a different climate. Strategies that are effective for small window areas may not scale well as solutions for highly glazing facades. The underlying solar gain metrics discussed earlier are the starting points for assessing impacts on building performance and occupant comfort. But it should be clear that there are many modifying circumstances that taken together will collectively determine actual cooling impacts and savings in any given building example. This helps explain why research papers sometimes report apparently contradictory results if these qualifying circumstances are not explicitly defined and accounted. It is thus critical to review and make transparent the assumptions, limitations, and boundary conditions associated with all performance assessments [75].

2.1.7 Performance

2.1.7.1 Overview

Numerous studies over many years have assessed the impact of façade and shading systems on building energy performance, with a focus on cooling impacts as a subset of overall performance. More recent studies have expanded the scope to include HVAC system size, occupant comfort, and tradeoffs with other building systems such as daylighting/lighting energy use. The body of these studies can be divided into three large categories: (1) modeling, simulation, and optimization; (2) test labs and test beds; and (3) measured performance in buildings. Some studies involve more than one of these. Each of these approaches has its strengths and weaknesses, and combinations can be very powerful as well. For example, a field study with measurements of one system in one building and one location can be extended with simulation tools to explore other technology options, other building types, and other locations.

From a performance perspective, windows are often perceived as the weak thermal link in the building envelope both in winter and summer. The winter case is easy to make as the typical thermal transmittance of a window may have only 10-20% of the thermal transmittance value of the adjacent wall or roof. Prescriptive non-residential building codes in the U.S. for example have consistently limited window area to 40% of the gross wall area although a walk through any major urban downtown area will show a preponderance of office space with fully glazed facades. The discrepancy here in part is the large gap between what is technologically available as outlined in Section 2.1.9 and what is routinely specified and delivered to building projects to meet code.

Extensive field testing in a full scale, partial floor mockup of the New York Times building in Manhattan in 2003 demonstrated that a fully glazed, high-performance façade design with dynamic shading controls could deliver annual energy performance that is better than the energy use of 40% glass code compliant envelope design [76]. Looking at new emerging technology solutions, research supports the thesis that in many cases it is technically possible to design a façade system, including glazing and shading, that uses less energy on an annual basis than an insulated wall [77]. These performance levels are rarely achieved in practice but the technology and design guidance to achieve them exist for many applications. At the same time the window provides a range of other important benefits—daylight, view, connection with the outdoors, and ventilation—in exchange for a small increase in cooling load.

A series of key studies of the three types identified above is summarized below. We note the differences between studies that measure typical solutions that are deployed today, and research studies that identify evolving or future solutions, as outlined in Section 0. We also note there are a growing number of simulation tools that allow an architect or engineer to optimize the role of glazing and shading in terms of building performance; shading and daylighting tradeoffs; and occupant thermal and visual comfort [78].

2.1.7.2 Modelling and simulation studies

Over the last decade there has been a significant increase in the number and types of simulation software tools available to researchers and practitioners to assess and/or optimize the performance of window and shading solutions. Simulation tools are versatile, powerful, and faster than lab and field testing. Even when the underlying algorithms have been validated there is sometimes uncertainty as to how well the tools can adequately represent and simulate the complexity of real-world installations. Simulation studies that assess energy impacts will generally use an annual energy simulation model. In cases where the existing simulation tool lacks the required modeling capabilities, the primary tool may link a variety of pre- and post-processing engines to extend the functionality of the suite of tools. This is often useful to address performance issues such as accurate glare assessments that may not be adequately modeled in the primary energy simulation models.

Earlier studies used the DOE-2 whole-building energy model [29,79–81] while more recent studies utilize other whole-building energy models, such as EnergyPlus, IDA ICE, TRNSYS, and eQUEST. Some studies focus on the effect of specific solar control technologies on prototypical buildings [55,82,83] while others address energy savings potentials of a technology on national building stock [33]. Other studies focus on the sensitivity of building energy use to key window design variables or compare specific solar shading strategies against each other. Many recent studies operate an annual energy model as an element of an optimization tool to seek optimal designs that trade off cooling energy use, lighting energy use, and visual comfort [53,84].

2.1.7.3 Shading devices without integrated renewable energy technologies

Ali Ahmed [85] explored the effect of vertical shading devices on the thermal performance of residential buildings in Egypt. The outcome suggested the potential for a 2 K indoor temperature reduction by using exterior vertical louvers.

Other studies showed that a good shading design combined with appropriate control can reduce the cooling energy consumption and also maintain good indoor illuminance conditions [86].

However, the performance of the shading systems depends on the location of the building. Palmero-Marrero & Oliveira [59] studied the influence of fixed louver shading devices on the energy requirements of buildings in different locations (Mexico, Cairo, Lisbon, Madrid, and London). For this purpose, they simulated the cooling and heating loads for different scenarios (changing the window areas and louver angles). The louvers were used as overhangs over the windows on the south façade. For the east and west façade, they were placed in front of the window. The results showed that the louvers lowered energy consumption and cooling needs in all locations, particularly in cities with high solar radiation and ambient temperatures. For one of the scenarios, estimated energy savings were 60%, 50%, and 9% in Cairo, Lisbon, and Madrid, respectively. Simulated cooling load (heat that must be removed from the space to maintain set point) in London was reduced to zero. However, the results showed an increased heating load. This may be avoided by using movable shading devices.

Table 2-1 summarizes some studies with regards to the performance of solar shading technologies (based on information provided by Bhamare, Rathod, & Banerjee [87].

Table 2-1 Studies with regards to the performance of solar shading technologies

Publication	Location	Building Type	Shading device	Indoor temperature reduction [K]	Load or energy savings [%]
Ali Ahmed [85]	Egypt	Residential building	Fixed vertical louvers	2	
Wong & Li [88]	Singapore	Residential building	Horizontal shading device		2.6 to 10.1 (annual cooling load)

Shen et al. [89]	Baltimore, London, Abu-Dhabi	Residential building	Movable blind system		4.9 - 48.8 (annual cooling load)
Tzempelikos & Athienitis [90]	Belgium	Office	Movable roller shade		12 (annual heating, cooling, and lighting energy use)
Palmero-Marrero & Oliveira [59]	Mexico, Cairo, Lisbon, Madrid, and London	Test Box	Exterior louvers		3 – 60 depending on scenario for Cairo, Lisbon, and Madrid (annual heating and cooling load)

2.1.7.4 Shading devices with integrated renewable energy technologies

This section explores the performance of solar thermal and photovoltaic (PV) components used as shading systems for windows and facades.

Shading devices with integrated solar thermal collection

The performance of a window-integrated solar air collector with a black blind was assessed by Onur et al. [91]. The system available on the market consisted of a double-glazing unit (120 cm × 80 cm) with vertical slats in the air gap, with air recirculation provided by fans and apertures coupled to the windows. Each slat could rotate around the vertical axis. This was an early windows-integrated solar system, but the research focused on solar energy gain rather than shading performance.

Extensive experimental and simulation campaigns were carried out by a research group at the University of Porto (Portugal) on building-integrated solar thermal shading (BISTS) systems [59,92,93]. The basic idea was to develop louvre shading devices (overhang type), in which the horizontal slats were conceived as solar collectors. Initially, a detailed testing analysis was carried out on the solar collector. In a second phase, the work focused on the numerical analysis of a building-integrated solar thermal system. These collector configurations were analyzed: (1) tube, (2) larger channels, and (3) smaller channels with a transparent cover. In Lisbon, Portugal, the best louvre inclination for the solar performance in summer was 5-10°. The reduction of the transmitted solar energy was 21% for louvers tilted at 45°. It was also found that, assuming hot water use of 200 L/day, 4.5 m^2 of louvers provided an annual solar fraction (fraction of water-heating energy that is supplied by the solar system) of 52-83% in Lisbon and 57-94% in Tenerife, Spain. The economic payback of the system was about 6 years compared to conventional gas heaters.

Chou et al. [94] conducted an experimental study on the performance of solar thermal collectors integrated in louvres. The louvres array was not horizontal but tilted 30° downward; each slat could rotate around the horizontal axis from vertical to horizontal inclination. The study was tailored to Taiwan climate as pre-normative work, to support the definition of policy measures related to building-integrated solar systems. The solar collector efficiencies were suitable for south facade applications only. The impact on the building energy performance was not studied. The design of a solar collector to be integrated into louvers was also studied by Abu-Zour et al. [95]. The core of their work was the development of the collector; they did not analyze the collector's influence on building energy performance.

Louvre-integrated solar collectors were also the objective of a numerical study for the city of Los Angeles, California (USA) [96]. The study included daylighting analyses and considered two louver configurations: (1) overhang for the south orientation and (2) venetian blind for east/west orientation. Calculations were carried out for a 5000 m² office building and 0.33 window to wall fraction, with solar shading installed only one façade at a time. Small total primary energy savings were calculated: 1.4% for south installations, and 1.8-2.1% for east or west installations. Simulation were also run with solar shading installed on three facades of the building, with 5.3% primary energy savings for heating, cooling, and lighting. More significant benefits were detected for daylighting, with increases in useful daylight index (500-1000 lux range) ranging from 5.8% (south) to 28.7% (east). The same authors investigated the active energy production by BISTS in [97]; this second study included technical and economic analyses. The main outcome was that 10 m² on the east facade or 33 m² either on the east and west facades achieved the recommended target of 75% of solar fraction for domestic hot water production. Using the same design principles of the previous cases, Luo et al. [98] described a novel application for a hot summer and cold winter climate zone in China. The idea was to replace the slat with a system consisting of shading reflecting plates (produced in three different section profiles) and vacuum heat collecting tubes. Parametric analyses were carried out by numerical and experimental activities. The study showed that this system can meet 100% of hot water demand in summer and 10% of hot water demand in winter. It also reduced indoor temperature about 2 °C in summer.

Ng et al. [99] studied a shading façade-integrated solar absorber system in hot and humid climates. The horizontal louver was a single plate collector instead of an array of slats. The experiment evaluated the energy efficiency of the collector (ratio of collected energy to incident energy) rather than whole building performance. The system achieved daily efficiencies ranging from 45% to 60%, and maximum daily water temperature ranging from 45 °C to less than 60 °C.

A final remark is that many recent studies about the integration of solar thermal collectors with the building's transparent envelope have focused on solar or thermal gains rather than solar shading [100,101].

Shading devices with integrated solar photovoltaics

Sun and Yang [102] simulated the performance of a shading-type cladding with integrated PV in Hong Kong. Calculations considered the window (6.75 m²) and its shading components but not the whole building. Several geometric configurations were defined for the PV shading. Maximum annual electricity generation was obtained at 20° tilt (about 80 kWh/m²). The effect on building cooling depended strongly on the selected geometry, but higher-performance configurations yielded annual energy savings of 1200-1400 kWh per window.

Bahr [103] studied horizontal PV panels as partial shading of a transparent facade for a building in Abu Dhabi, including energy, daylighting and financial calculation analyses. The study was carried out as a function of several variables. The highest annual electric savings for cooling per square meter of facade area respect to the base case (no PV shading) were about 70 kWh/m² for both mono-crystalline and amorphous silicon panels. The profit rate, defined as the ratio of cost savings to cost investment, was less than 1% due to the very low local energy cost. The low latitude made PV applications on the roof more effective than those on the facade.

Mandalaki et al. [104] simulated the heating, cooling, and lighting energy uses of a reference office room with several PV shading configurations. Scale model measurements in Athens and Chania (Crete Island, Greece) were performed to support the calculations analyses. For an office room with 45% window-to-wall ratio and initially unshaded windows, adding PV shading yielded 60 and 80% total energy savings (heating, cooling, and lighting) for Athens and Chania, respectively. The same authors further investigated the trade-off between energy performance and daylight provision, concluding that egg-crate configurations should be considered as the preferred solution as PV shading devices in south-oriented office buildings in the Mediterranean climate [105,106].

A simulation study accompanied and calibrated by the monitoring of a PV panel, installed as building-integrated shading system, was conducted for Hong Kong, and not limited to the south orientation as in previous cases [107]. An office room was simulated, varying the orientation of the room, and tilt of the PV panels. Results proved that best electric energy performance for air conditioning and lighting was achieved by a horizontal PV shading panel tilt installed on a southwest facade, with 46% savings respect to the no-shading base configuration.

These studies included parametric analyses of several PV shading solutions. A first attempt to optimize the design with respect to energy use, electricity generation, and daylighting was carried out by Taveres-Cachat et al. [108]. The study sought to identify the best configuration for an array of fixed PV louvres in Nordic climate conditions. It avoided typical approaches, as parallel blades, while allowing the optimization process to find the most efficient tilt for each element. The strength of this study is its methodology and its consideration of the importance of advance modelling tools to design and predict optimized performances. The best performing solutions used fewer and more widely spaced louvers.

Optimized parametric analyses of PV louvres in multi-story buildings were also carried out for several Chinese cities [109]. The optimization focused on electricity generation, with limited analyses of building energy performance and cost. The study sought to yield the optimal design of the louvres to avoid self-shading between an element and the one at the level below. The best solution outperformed the usual rooftop configuration.

Some studies aimed to identify the potential of PV blinds. A double-skin facade with a PV venetian blind in the gap was studied by experimental and numerical analyses, first in Changsha, then in other Chinese cities [110–112]. The studies focused on the accurate modeling of thermal, luminous, and electrical performances at the component level. The predicted cooling electricity savings of 12% and 25% relative to a double-skin facade with conventional shading and no shading, respectively. The effect of the PV blind's self-shading on the electricity production was investigated as a function of many geometric and climatic parameters.

Hong et al. [113,114] explored improving of the performance of PV venetian blinds by using "bi-directional" slats. Such slats are tilted against the sun but also admit the sun, to avoid self-shading and to admit daylight under some circumstances. Experimental and numerical studies demonstrated that the conventional tilt of slats provided 22-39% of the average illuminance achieved by the bi-directional tilt movement; the power electric generation of the conventional slats was 85-110% that of the bi-directional slats, depending on the geometry of the PV system. Building energy performance was also analyzed by comparing the results of identical two mock-up rooms with a 3.3 m^2 window, in which conventional and bi-directional PV slats were installed. Bi-directional slats reduced electric demand for lighting and heating by 5-35% and 2-11% respectively. Conversely bi-directional blinds underperformed during the cooling season by 6-14%. Authors claimed that bi-directional slats outperform conventional slats for most of the year, excluding sunny and partly cloudy days in summer in the experiment climate conditions. The same research group recently prototyped an advanced smart window that includes PV blinds, a ventilation system, and a controller developed to optimize the performance smart windows [115]. The study mainly focused on hardware and software; it did not include building energy performance analysis or comparison with other technologies.

2.1.7.5 Discussion

The use of solar renewable energy systems (thermal or electric) to be integrated in or serve as shading devices has been investigated in many studies. Various solutions were found to be feasible, though building integration is easier for PVs than for solar thermal devices. Most of the studies are based on simulations, sometimes calibrated with experiments; system performance is evaluated by comparison to reference cases with similar geometries. In all cases the use of solar energy brings energy advantages. However, the use of the solar renewable energy system generally has not been compared to the more conventional practice of using conventional shading systems supplemented with rooftop renewable electricity or heat generation. Therefore, it is not possible to assess whether solar renewable energy systems are more effective. Also, few cost analyses are available because these systems are not on the market.

Glazing

Multiple studies have been conducted regarding the performance of different glazing technologies. A wide range of glazing types and multi-glazed configurations, e.g., double or triple, are available in most global markets. The solar heat gain of each window varies with the type of glazing selected and with the configuration of the various glazing layers within the window system. Thus, it is not surprising to see a wide range of simulated performance outcomes, that will vary with climate, building type, orientation, etc.

Jaber and Ajib [116] explored the influence of window orientation, size, and type on buildings' annual heating and cooling loads. They conducted a simulation analysis for different types of windows (single, double, and triple glazed) in three different locations (Amman, Aqaba, and Berlin). The outcome showed the importance of matching window properties (e.g., size, or glazing type) to the buildings' location and orientation. The estimated annual conditioning (heating + cooling) load saving potential due to optimized window designs were estimated to be 21%, 20%, and 24% for Amman, Aqaba, and Berlin, respectively.

Various research efforts showed that cooling load could be reduced by using specific glazing types at a certain location. Sadrzadehrafiei et al. [117] explored the effect of triple glazing on the cooling energy load of an office building in Malaysia. For this purpose, they simulated the annual cooling energy and compared it to a scenario with single clear glass instead of triple glazing. The simulation results showed an estimated reduction of 6.3%.

Table 2-2 shows a summary of some studies with regards to the performance of glazing technologies (based on information provided by Bhamare et al. [87].

Table 2-2 Studies regarding the performance of glazing technologies, based on information provided by Bhamare et al. (2019)

Author	Location	Type of glazing (base case)	Alternative glazing options	Best performing glazing type	Load or energy saving [%]
Tahmasebi et al. [118]	Kauala Lampur, (Malaysia)	Double glazed window	Triple glazed window	Triple glazed window	5.5 – 8.5 (annual cooling energy use)
Sadrzadehrafiei et al. [117]	Malaysia	Single clear glazing	Triple glazing	Triple glazing	6.3 (annual cooling energy use)
Sadrzadehrafiei et al. [119]	Malaysia	Single clear glazing	Single low-E pane glazing, double low-E pane glazing, double clear pane glazing	Double low-E pane glazing	6.4 (annual cooling energy use)
Sbar et al. [120]	USA	Electrochromic double glazing (SHGC: clear state, 0.47; tint state, 0.09)	ASHRAE 2007 Compliant glazing (SHGC: 0.4/ 0.25), Single Pane glazing (SHGC: 0.82)	Electrochromic glazing	> 20 (annual conditioning [heating + cooling] and lighting site energy)

Author	Location	Type of glazing (base case)	Alternative glazing options	Best performing glazing type	Load or energy saving [%]
Jaber & Ajib [116]	Amman, Aqaba, and Berlin	Single glazed window (SHGC: 0.855)	Double glazed (SHGC: 0.775/0.589), Triple glazed window (SHGC: 0.407)	Triple glazed window	21 (Amman) 20 (Aqaba) 24 (Berlin) (annual heating and cooling load)
Li et al. [121]	Shanghai, Shenzhen, Harbin, (China)	Single PV glazing	Double PV glazing, Natural ventilated PV glazing, Single clear glazing, Double clear glazing	Double PV glazing for Harbin; natural ventilated PV glazing for Shanghai, Shenzhen	12.3 (Harbin), 4.8 (Shanghai), 10 (Shenzhen) (annual electricity use)

Laboratory and testbed test studies

Laboratory testing provides critical performance data for validating simulation models, provides feedback to manufacturers to enhance their products, and helps build confidence in decision makers to adopt and deploy emerging technology in buildings. Some labs are set up to test product or device properties while others measure performance in the context of a room. Limited testing can be conducted in indoor testbeds with simulated outdoor conditions, but more realistic and challenging tests are conducted in outdoor testbeds. In large test cells, occupancy can be simulated with a thermal manikin or can be provided by human subjects. Size and scale range from a test box to a small room to larger spaces and some testing can be done in actual buildings in a “living lab” configuration with occupied or unoccupied spaces. The duration of testing varies widely. The ideal for testing a solar shading system would be to ensure that testing is conducted over the seasons and solar angles of interest to the study and ideally to compare alternate systems on a side by side basis to a base case window design [77]. Some adjustments can be made with some facilities to extend the range of test conditions. For example, a rotating outdoor testbed can be used to test low angle solar performance in summer by facing east or west.

Monitored building test studies

Field tests of the effects of windows and shading systems on cooling loads can also be carried out in monitored buildings. In most cases this involves adding additional test and measurement equipment at the building and inside the spaces to measure site radiation as well as detailed thermal effects more accurately in the spaces and energy consumption of the HVAC. Testing has focused on validating the expected performance of a shading system or comparing the relative performance of alternative systems, either when both are installed on different parts of the building, or they are sequentially replaced over time. Longer term studies might collect data for one year to establish a baseline, then replace systems and collect data for a second year. In most cases a variety of data will be of interest: hourly load shapes, peak loads, overall building cooling impacts, and occupant comfort. An extensive year-long field test at the New York Times headquarters building reported 24% savings in total measured energy use for HVAC and lighting when compared to a simulated code-compliant base case with smaller windows. The building utilized a sophisticated façade with fixed external shading, low-E glazing, and automated interior blinds, linked with daylight dimming to manage energy use and occupant comfort [122].

Daylighting vs. cooling loads in non-residential buildings—glazing/shading tradeoffs

While our focus here is cooling loads, the effect of the fenestration design on the overall building energy use during both normal use and during extreme events that test resilience will depend on two other major energy consuming building systems: heating and lighting. A high-performance window with operable shading can deliver thermal benefits of passive solar heating in winter as well as effectively managing summer cooling loads. The appropriate use of daylight in non-residential buildings to reduce electric lighting loads is another major building level energy effect has been a theme of many research studies over the last 30 years. There has been a large increase in recent years specifically looking at the controls tradeoffs involved in maximizing lighting energy savings while minimizing cooling and glare [123–128].

The influence of daylight on overall non-residential building energy use and its effect in energy optimization considering cooling loads has been changing over time. Several important caveats must be made when assessing the impact of daylighting from windows and skylights on cooling loads in non-residential buildings:

- Admitting daylight to a room saves no energy—energy is only saved if electric lights are dimmed or turned off. The magnitude of the total energy saved, and thus the reduction in thermal load in the conditioned space, is determined by the floor area over which daylight is controlled; the type of control—dimming vs. on-off; the reliability of the control, e.g., the probability that electric lighting use will be modified when daylight is available via manual or automated control; and the lighting power density (W/m2) of the installed electric lighting [81,129].
- If daylight from windows is adequate to dim or extinguish electric light, then there will be lighting energy savings. Reduced lighting energy use will also reduce space cooling. However, the daylight admitted by the window also contributes to the cooling load, so the challenge is to replace a lumen of electric light by a lumen of daylight with an equal or lower impact on space cooling loads. The luminous efficacy of sunlight and daylight varies by a factor of about 3 to 1 ranging from 50 lm/W for sunlight at low solar elevations to as high as 150 lm/W for diffuse daylight from a blue sky. The optical properties of the glass then determine the luminous efficacy of the transmitted daylight (luminous flux per unit radiant flux) that enters the space—this could raise or lower the efficacy depending upon the glazing LSG ratio. After accounting for room size and optical properties, the “effective” luminous efficacy accounting for non-uniform distribution of light in the room will be even lower [130].
- Lighting power density was reduced in the 1940s and 1950s when fluorescent lighting replaced incandescent lighting, but the design criteria for preferred lighting levels increased as it became possible to deliver illuminance at much higher efficacy. Continued improvements in fluorescent and high intensity discharge lamps reached efficacies of (80–120 lm/W) over the following decades making it possible to reduce installed lighting power

density (electric power demand per unit floor area) for typical offices from about 30–50 W/m2 down to about 10 W/m2. During this period non uniform, task-based lighting became more common, further reducing electric loads. Over the last decade a revolution in solid state lighting (light-emitting diodes, or "LEDs", with luminous efficacies now approaching 200 lm/W) has further reduced installed lighting power density below 5 W/m2. The growing use of occupancy-based controls means that the lights are off a greater fraction of the day, further reducing the thermal impacts, but also reducing the potential savings from daylighting.

- These trends have led to the conclusion for some that the role of daylighting as an energy saving strategy to offset highly efficient electric lighting is minimal and that windows may no longer be needed and could even be replaced by a wall-mounted, LED-driven artificial window [131]. But over the last decade there has been a growing recognition that windows play a key role in comfort and productivity in workspaces and that view, the higher illuminance levels, and the unique spectrum of daylight provides health well-being benefits to occupants [132]. Thus the new specification challenge becomes to design windows and shading to admit adequate daylight without excessive solar gain and without thermal and visual discomfort [46,133,134].

2.1.8 Application

2.1.8.1 Overview

Glazing and shading solutions must be optimized in design and tuned in operation to meet the needs of occupants and the building operators, with attention to the climate and local site conditions. The technology alone does not define performance—it is the applications context for the use of these glazing and shading technologies that determines energy use, load shape, and occupant comfort. One set of market drivers relates to features of the residential and non-residential buildings in which the glazing and shading solutions are located. The other set of drivers is influenced by climate and site.

2.1.8.2 Market drivers that impact design decisions

Window and shading designs can differ significantly between adjacent buildings. These differences are driven by many factors and can best be understood by outlining some of the market drivers that influence both the final selection of glazing and shading strategy and the technologies that are specified. Each of the following market characteristics can influence the selection of specific windows and shading systems.

<u>Residential buildings</u>

1. Single family vs. low-rise multifamily vs. high-rise multifamily
2. New construction vs. additions vs. retrofit

3. Building size and construction cost
4. Construction type vs. climate region
5. Urban vs. suburban vs. rural

Non-residential buildings

- Building type and size
- New construction vs. retrofit
- Construction cost
- Ownership model: owner occupied vs. lease/rent
- Construction type: curtain wall vs. punched opening windows
- Glazing location/orientation: atria, sloped glazing, skylights
- Site solar access

At the high end of both residential and non-residential markets globally there is a rapidly growing interest in zero energy buildings that require higher-performance solutions than do typical code compliant designs. There is also a recognition that resilience in the face of short-term events, such as power failures, and longer-term trends, such as global warming, will increase interest in and demand for high-performance window and shading options to minimize the capacity and energy use of size of cooling systems.

2.1.8.3 High performance buildings

There are small but important subsets of the residential and non-residential sectors that strive to deliver very high-performance buildings. This includes the U.S. Passive House movement [135], Passivhaus Institut [136], Zero Net Energy homes and buildings, the US Green Buildings Council (USGBC) LEED Gold and Platinum buildings [137], and the Living Building Challenge [138]. Each of these programs emphasizes occupant health and comfort as well as energy performance.

Traditional passive solar homes are highly insulated and airtight. If glazing is not properly shaded occupants can experience high solar gains and thermal discomfort. Biophilia (connection with nature) is a recurrent theme in many of these programs. The new interest in biophilia and the renewed interest in daylighting for health and wellbeing has created a new motivation for more glazing. Larger glazed areas will increase the importance of dynamic shading solutions that minimize solar loads, reduce HVAC system size, optimize load shape on hot summer days, and reduce peak electric demand. Responsive shading systems will also support new demand response programs that seek to shift and shed summer peak cooling loads.

2.1.8.4 Climate

While solar gain is the primary source of window-related cooling load in most climates, temperature-driven heat transfer will increase cooling in some buildings, particularly where single glazing is still common. The effect varies widely by climate, both in terms of design peak cooling load and in terms of annual cooling energy use. Equatorial climates (both humid and arid) generally experience year-round cooling loads from high average temperatures that are at or above the comfort level most hours of the year. Peak outdoor air temperatures can reach 50 °C. In high-latitude and temperate climates cooling conditions based on air temperature are experienced primarily in summer months and typically for a short hourly duration during a day. Over the next decades the impacts of climate change will generally drive these outdoor air temperatures higher over most parts of the planet and will likely increase the frequency and duration of periods with unusually high cooling loads.

2.1.9 Technology readiness level

2.1.9.1 Overview

There has been an enormous industry investment over the last 50 years to improve the ability of building fenestration systems to effectively manage solar gain. This encompasses both the glazing solutions and shading solutions. It involves (1) technical enhancement of the properties of glazing and shading elements; (2) changes in the design and delivery of integrated, adaptive solutions; and (3) new control capabilities for dynamic control of smart glazing and shading for occupants, for building operators, and for the utility industry. These changes were driven by a slow tightening of building codes and standards globally, by owner recognition of the importance of providing thermal comfort to occupants, and by significant population growth in global regions where cooling is the dominant HVAC load.

New technological solutions are a necessary but not sufficient condition for market availability, affordability, and widespread utilization. If the supply chain is inadequate, the price is too high, or the complexity of building integration is too great, then the technology will have little real-world impact.

Product availability is driven by multiple forces on the supply and demand side of the market. The window and shading industry has a complex business and technological structure with component suppliers, fabricators of subsystems, integrated product suppliers, contractors, systems integrators and building operators. The markets are differentiated across many different characteristics that share some common features but differ in others. Each of these different building factors below can have a direct influence on whether a particular window or shading product option is available for each major building type.

Residential buildings

- Single family vs. low-rise multifamily vs. high-rise multifamily
- New construction vs. retrofit
- Construction cost
- Construction type vs. climate region

Non-residential buildings

- Building types and size
- New construction vs. retrofit
- Construction cost
- Construction type: curtain wall vs. punched opening window
- Glazing location/orientation: atria, sloped glazing, skylights

The supply chains that provide product to each of the building categories in Section 2.1.8.2 have some commonalities but can also be fundamentally different, having evolved over time to meet the unique needs of each market. For example, the supply chain that provides an all-glass curtain wall on a 40-story office tower in Beijing has few similarities to the industry infrastructure that supplies the windows in a single-family home in Los Angeles.

The glass industry has developed and implemented a series of refinements to the solar control properties of glass over the last 50 years. Starting with a market which offered only clear glass, heat absorbing glass, and highly reflective coated glass, the options have now expanded enormously to include hundreds of glazing offerings combining numerous innovative coatings deposited on three types of glass substrates—low iron, clear, or tinted—in double- and triple-glazing packages. The industry produces an almost unlimited range of optical properties to meet any market need.

For static glazing the single most important innovation to help manage solar gain has been the development of spectrally selective low-E coatings with moderate to high daylight transmittance but very low overall SHGC. These multilayer coatings are tuned to transmit visible light (wavelengths 0.4 —0.7 µm) and reflect most of the near-infrared radiation in sunlight (0.7 – 2.5 µm). The light to solar gain ratio is a good relative indicator of the solar control capability of the glazing. While conventional tinted and clear glazing have LSGs of 0.6–1.0, the best spectrally selective glazing can be three times better with LSG near 2.4. Equally important these coatings are available from multiple manufacturers; for glazing of all sizes, thicknesses, and types (e.g., tempered, laminated); and at affordable cost.

2.1.9.2 Availability

The ease of specifying, procuring, and successfully deploying solar control solutions for windows differs widely across global markets for the five main categories of glazing and shading systems outlined below. The data shown below for each are thus illustrative of trends and typical practice but will not be definitive in all locations. Low cost is meant to suggest that the products are readily affordable and thus may constitute standard practice. Moderate and high-cost products will capture smaller market shares.

Spectrally selective static glazing

- Product availability: widespread
- Cost: low to moderate
- Design support/expertise: widely available to architects, engineers
- Utilization: widespread, often mandated by code

Ongoing R&D continues but mostly to make these spectrally selective low-E coatings more robust and durable, to improve clarity, and to lower cost. Spectral selectivity and emittance have been optimized to the extent technically possible and are not likely to show any further significant improvements. These products should be used in virtually all windows in climates with significant cooling loads, unless there are also high heating loads that would benefit from a higher SHGC.

Highly insulating glazing

1. Product availability: widespread
2. Cost: moderate
3. Design support/expertise: widely available to architects, engineers
4. Utilization: limited

In very hot climates with many days and weeks with elevated outdoor temperatures, the glazing's conduction contribution to the building cooling load can be large. Innovations for low-conductance windows developed originally for very cold climates can provide energy savings and enhanced comfort. Conventional triple-glazed windows could help reduce cooling loads but have only a tiny market share in the U.S. since they are not mandated by code. Since sales volume is low, production efficiency may not be optimized resulting in high costs. In some northern European climates triple glazing is now mandated by code, making it readily available from multiple suppliers and keeping costs low. Triple-glazing IGU designs are becoming available in a lighter, thinner format to make it easier to incorporate into windows designed to hold double glazing [12]. A concerted research effort is underway to bring a new generation of vacuum insulated glazing (VIG) to markets, with several recent new product introductions. Some commercial products (mostly manufactured by companies in Asia) have recently become available [139]. However, VIG remains a relatively high-cost option today with limited market availability.

Active and passive smart glazing

- Product availability: limited to several companies globally
- Cost: high, but may offset some HVAC cost

- Design support/expertise: limited, controls integration is a challenge
- Utilization: limited, perhaps 1,000 projects worldwide

Current markets are expanding rapidly but from a small initial sales base. R&D continues in four key areas: (1) new materials and coating types that can be fabricated at lower cost, (2) improved durability, (3) more neutral color, and (4) faster switching. To effectively deliver energy efficiency and comfort, and thus increase market adoption, the controls for active smart glass must be properly integrated with building control systems. New results from simulation based optimization studies and field studies are helping to define how to tradeoff daylighting performance against solar-gain control and how to balance glare control with overall lighting energy use [140,141]. Work has continued refinement of passive smart coatings, but the largest body of ongoing R&D is focused on active glazing systems since the performance potentials are thought to be larger.

Fixed exterior shading systems

1. Product availability: widespread globally, although not used commonly in many countries or building types
2. Cost: low to high
3. Design support/expertise: extensive for conventional simple systems with respect to blocking sunlight; less well developed for comprehensive energy optimization
4. Utilization: limited—varies widely by climate and design style

Fixed exterior shading solutions are some of the oldest solutions in buildings. Their use declined over time as air conditioning became widely available. However, there is renewed interest with current environmental concerns to reduce energy use and carbon emissions. More effort is now being placed on design optimization to maximize solar rejection while admitting daylight and view, and to admit sunlight in winter to offset heating loads. Optimization for latitude and building orientation is very important. External shading solutions should be attached to the building structure without thermal bridging.

Operable Interior/Exterior Shading Systems

1. Product availability: interior systems widespread globally; exterior systems in use in Europe but not as widely used in the U.S. Manual operation is common; automated/motorized solutions are limited but coming to the market in greater volume.
2. Cost: low to high for interior; generally high for exterior but can offset HVAC cost. Automation adds significantly to cost but prices are declining as volume and experience increase.

Design support/expertise: extensive for conventional interior systems; more limited for exterior systems; very limited for automated solutions

3. Utilization: suitable for any building, orientation, and climate, although details will vary with each. Exterior systems have best performance but higher cost.

Most solutions today are manually operated interior shades and blinds. Since interior solutions generally do not reject a large fraction of the incident solar load, some research effort is focused on developing higher-reflectance shading materials that provide lower SHGC. Most interior systems are not operated optimally so there is a big push to add motorization and automation to both residential and non-residential products. For retrofit applications these can include a photovoltaic panel with battery backup so that new wiring is not needed. There are numerous simulation studies and limited field studies that explore the advantages of motorizing and automating these systems. As cost is reduced and the performance is validated the markets are expected to grow.

There is an entire class of integrated façade solutions for non-residential buildings with automated shading incorporated into the façade system described in Section 0. These double-envelope systems can operate in different modes based on season (summer/winter) and sky condition (clear/cloudy). They can also be operated to optimize comfort and/or building energy use. They show promising results in modeling studies and in testbeds but have only been used in a small number of buildings to date. Most are complex systems requiring full integration with building HVAC and lighting controls.

2.1.10 References

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2.2 Cool envelope materials

Technology Group A.2

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2.2.1 Physical principle(s)

2.2.1.1 Definition of a cool envelope material

The following discussion assumes that the solar ("shortwave") spectrum is 0.3 - 2.5 µm [1], the ultraviolet (UV) spectrum is 0.3 - 0.4 µm, the visible spectrum is 0.4 - 0.7 µm[2], the near-infrared (NIR) spectrum is 0.7 - 2.5 µm, and the thermal-infrared (TIR, or "longwave") spectrum is 4 – 80 µm.

Cool roofs and walls reduce radiative heat gain at the building's opaque envelope to decrease heat flow into the conditioned space [5–9].

We define a cool envelope material (CEM) as a solar-opaque surface whose net radiative heat gain, equal to [absorbed solar radiation - emitted shortwave radiation (fluorescence)] + [absorbed TIR radiation - 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.

2.2.1.2 Key radiative properties

The surface's solar absorptance (fraction of incident solar radiation absorbed; scale 0-1) is typically calculated by subtracting its solar reflectance (SR, or fraction of incident solar radiation reflected, or

2 Some standards specify the visible spectrum as 0.38 – 0.78 µm [2–4], but we use the simpler range 0.4 – 0.7 µm because the human eye has limited response outside this band [1,2].

“albedo”; scale 0-1) from unity. Its absorption and emission of TIR radiation are each proportional to its thermal emittance[3] (TE, or ratio of TIR radiative flux emitted by the surface to that emitted by a black body at the same temperature; scale 0-1). If the material fluoresces (quickly emits at a longer wavelength light absorbed at a shorter wavelength), the fraction of incident solar radiation so emitted is its fluorescence benefit (scale 0-1), and its ability to reject incident solar radiation is gauged by its effective solar reflectance (ESR, or solar reflectance + fluorescence benefit; scale 0-1) [10–12].

If an envelope product transmits sunlight its radiative properties must be evaluated over the solar-opaque substrate to which it will be applied. For example, since a thin layer of white exterior wall paint may transmit a substantial portion of incident NIR radiation, its radiative properties should be measured over a representative wall substrate.

Solar reflectance can vary with the geometry and spectral power distribution of incident sunlight. The geometric dependence is usually addressed by approximating surface reflection as Lambertian (fully diffuse, and thus independent of incidence angle), specular (fully mirrorlike), or glossy (specular at the air-surface interface and Lambertian below this interface). The spectral dependence can be addressed by measuring solar spectral reflectance (variation of reflectance with wavelength over the solar spectrum) and calculating solar reflectance as the average of solar spectral reflectance weighted with a representative solar spectral irradiance [4,13]. The solar reflectance of a horizontal or near-horizontal surface, such as a low-slope roof, can also be measured directly under certain solar and sky conditions [14]. We are usually most interested in the global (a.k.a. hemispherical) solar reflectance, or fraction of all incident sunlight that is reflected into the hemisphere facing the surface.

Thermal emittance can vary with the angle of emission or absorption, and with surface temperature (though it is usually evaluated near 300 K). TIR radiative exchange between an envelope material and its environment is typically assessed from the material’s hemispherical thermal emittance [Appendix X.1 of 15].

Outer space is colder than the Earth’s atmosphere. Therefore, under a clear sky-high emittance in the atmospheric window (the 8 – 13 µm band in which the atmosphere is highly transmissive) coupled with low emittance in the rest of the TIR spectrum (4 – 8 µm and 13 – 80 µm) may yield more net longwave radiative heat transfer from a low-slope roof to its environment (TIR emission – TIR absorption) than achievable with uniformly high TIR emittance [16,17].

Solar reflectance and thermal emittance can be combined to compute solar reflectance index (SRI). SRI gauges “coolness” by comparing the temperature of a horizontal, adiabatic test surface on a reference sunny summer afternoon to that of a reference black surface (SRI 0) and to that of a

3 The synonym “thermal emissivity” is also used.

reference white surface (SRI 100) [18]. SRI can be lower than 0 if the surface is exceptionally hot or exceed 100 if the surface is exceptionally cool (Table 2-3). SRI is calculated rather than measured and characterizes only quasi-adiabatic (well-insulated) roofs. It does not apply to walls because it assumes radiative and convective boundary conditions typical of horizontal, rather than vertical, surfaces.

Table 2-3 Examples of roofing products sorted by solar reflectance index (SRI). Parenthetical codes identify each product in the Rated Products Directory of the Cool Roof Rating Council (CRRC) [19]

Product (CRRC Product ID)	Initial Solar Reflectance	Initial Thermal Emittance	Initial SRI
Black Asphaltic Membrane (0616-0018)	0.03	0.93	-1
Black EPDM (1090-0002)	0.12	0.87	7
Concrete Tile (Grey) (0942-0086)	0.11	0.92	9
Clay Tile (Red) (0942-0179)	0.25	0.86	24
Shasta White Asphalt Shingle (0890-0002)	0.26	0.90	27
White Painted Metal Roof (0810-0040-008)	0.55	0.83	63
White EPDM (0738-0008)	0.76	0.90	94
White PVC (1032-0010)	0.86	0.86	108

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 change in solar reflectance than to the same change in thermal emittance [Appendix A of 20].

The sensitivity of the envelope's surface temperature to its thermal emittance also depends on the difference between the envelope's surface temperature and that of its radiative exchange surface.[4] Therefore the effect on envelope temperature of changing the thermal emittance of a vertical wall

4 Strictly speaking, the longwave radiative heat exchange between two surfaces depends on the difference between the fourth powers of their absolute temperatures, but it is usually reasonable to treat the heat transfer as proportional to the simple temperature difference.

that sees both ground and sky (or ground, sky, and neighboring buildings) will typically be less than that of modifying the emittance of a horizontal roof that sees only the sky.

Natural exposure (weathering and soiling) tends to change the solar reflectance and thermal emittance of a building envelope surface over time. Since most changes to these properties take place within the first year or two of exposure, and the service life of a roof or wall product is about 10 – 50 years, radiative heat flows are evaluated from aged solar reflectance and aged thermal emittance.

Color and glare may be important for roofs or walls visible to pedestrians or neighbors. Where light-colored surfaces with high visible reflectance and high NIR reflectance are aesthetically undesirable, high spectral selectance (NIR reflectance minus visible reflectance) permits a “cool colored” dark surface (low visible reflectance, high NIR reflectance) to stay cooler in the sun than a conventional dark surface (low visible reflectance, low NIR reflectance) [1,21,22]. “Directionally reflective” steep roofing materials that exhibit high directional selectance (solar reflectance viewed from above minus solar reflectance viewed from the street) may also provide dark-looking surfaces with higher-than-usual solar reflectance [23].

Glare from bare-metal surfaces with high specular reflectance or bright-white surfaces with high Lambertian reflectance can be problematic. Mirrorlike envelope surfaces may pose the greatest concern, especially if a surface is vertical and concave and can focus reflected light.

Meanwhile, roughly half the sunlight reflected from a Lambertian wall will strike nearby walls and ground surfaces, diminishing the ability of a cool wall to mitigate the local urban heat island effect. Wall materials with high solar retro-reflectance (ability to return sunlight toward the sun) could be used to reduce both building and urban radiative heat gains [24].

2.2.1.3 Solar heat gain at the envelope

The solar heat gain of a horizontal or near-horizontal surface can be computed from its air mass 1 global horizontal (AM1GH) solar reflectance [25,26]. The solar heat gain of a vertical surface, such as a wall, can be evaluated from its air mass 1.5 global vertical (AM1.5GV) solar reflectance [Appendix I of 27].

The ability of a cool envelope material to reduce hourly solar heat gain will scale linearly with both envelope albedo rise [9,28] and the hourly global solar irradiance at each modified surface. The effects of these gain reductions on annual cooling and heating energy uses or annual unmet cooling and heating hours will depend on concurrence with hours in which the building needs cooling or heating.

Raising the albedo of the opaque envelope tends to reduce demand for cooling in summer and increase demand for heating in winter. Therefore, the utility of a fixed-albedo cool envelope material may scale with the surface-specific ratio of mean solar irradiance in summer to that in winter [7]. A variable-albedo cool envelope material intended to minimize the winter heating penalty should be characterized by both its high albedo in the cooling season and its low albedo in the heating season.

2.2.1.4 Non-radiative properties affecting performance of cool envelope materials

An envelope product's thermal resistance, thermal capacity, and envelope ventilation (if present) can affect both heat transfer to the conditioned space and the influence of a cool surface on that heat transfer.

High thermal resistance across the cool envelope material impedes conduction, reducing the influence of the envelope's surface temperature on heat transfer to the conditioned space [29]. Envelope material ventilation—e.g., the flow of air between a roof product and the roof deck, such as that in the space below a batten-mounted tile roofing assembly—can also reduce heat transfer to the conditioned space [30]. Thus, each feature can decrease the benefit of reducing the building's surface temperature with a cool envelope material.

High thermal capacity in a cool envelope material slows heating and cooling, delaying heat transfer to and from the conditioned space. This lag can help increase the cooling benefit of a reflective roof by reducing space cooling load when electric power demand peaks in late afternoon on a summer day. It can also diminish the penalty of a reflective roof by keeping the roof and attic warmer overnight, decreasing space heating load on a winter morning [31].

The thermal resistance and thermal capacity of the building envelope (roof and wall assemblies) affect heat flow to the conditioned space, and the efficacy of cool surfaces, in manners similar to the thermal resistance and thermal capacity of the cool envelope material itself.

Cool-roof and cool-wall benefits scale with roof area and net wall area (gross wall area - window area - door area), respectively. If the roof is pitched, ceiling area (roof plan area) may be a better scaling factor for solar heat gain, though TIR exchange will still scale with roof area.[5]

2.2.2 Typologies (classifications) and design parameters

While there are no universal specifications for cool envelope materials, the general principle is that a cool envelope material is one whose enhanced solar reflectance—or enhanced effective solar reflectance if the material is fluorescent—keeps it cooler under the sun than a less-reflective conventional envelope material. Thermal emittance is a relevant but secondary consideration.

Cool envelope materials can be classified by the cooling strategy or by the technology used to achieve this goal.

5 This distinction is often minor because the ratio of roof area to ceiling area for a roof with typical pitch of 5:12 (23°) is 13/12 = 1.08.

2.2.2.1 Cooling strategies

Each of the following strategies uses nonselective high thermal emittance unless otherwise specified.

A. Static6 high solar reflectance. This approach uses a light-colored material of high visible reflectance, high NIR reflectance, and high solar reflectance. It maximizes savings in the cooling season but may incur a penalty (increased heating load) in the heating season. The bright color of this surface may pose aesthetic or glare concerns if the surface can be seen by pedestrians or neighbors.

B. Static high NIR reflectance. This approach uses a cool-colored material of low to medium visible reflectance, high NIR reflectance, and medium solar reflectance. It offers a wide color palette but yields cooling savings and heating penalties smaller than those generated by maximizing both visible and NIR reflectance.

C. Static high NIR reflectance + static NIR fluorescence. This approach uses a fluorescent cool-colored material. It is analogous to strategy B (static high NIR reflectance) but yields greater cooling savings and heating penalties because some of the absorbed visible light is rejected by emission as invisible NIR light.

D. Temperature-sensitive high solar reflectance. This approach uses a thermochromic material whose reflectance increases with temperature. In warm weather, the material can act as a light-colored or cool-colored surface; in cool weather, it can behave as a conventional low-albedo material. This avoids the heating penalty associated with using a material whose reflectance is elevated in both the cooling and heating seasons.

E. Angle-sensitive high solar reflectance. This approach uses a surface that exhibits high solar only when the surface is illuminated by light whose diffuse reflection will not be observed by pedestrians or neighbors. This approach reduces concerns about the use of bright colors by employing a sloped material that appears dark when viewed from below—e.g., from street level—but bright when viewed from above. It will incur both cooling savings and a heating penalty, but the albedo in summer typically exceeds that in winter.

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6 "Static" indicates that variations in reflectance are not intentional. Few materials exhibit truly constant reflectance—for example, that of a glossy dark surface can increase substantially as the incidence angle approaches 90° [25].

F. Static solar retroreflection. This approach strongly retroreflects beam sunlight to the solar disc, or at least in its general direction. This is analogous to static high solar reflectance (strategy A) but allays concerns about glare and downward reflection that can arise from use of a light-colored, diffusely reflecting surface on a tilted roof or a wall.

G. Static near-unity solar reflectance + static selective thermal emittance. This approach seeks to provide negative net radiative heat gain during the day by (a) using near-unity solar reflectance to minimize solar heat gain and (b) using selective thermal emittance (high emittance in the 8 – 13 µm sky window and low emittance in the rest of the 4 – 80 µm TIR spectrum) to maximize long-wave radiative loss to the sky. This is analogous to strategy A (static high solar reflectance) but increases cooling savings, heating penalties, and potential concerns about glare and aesthetics.

2.2.2.2 Cooling technologies

Here we classify materials according to the technology used to make them cool.

Light-colored CEMs are roof and wall products that use white or other light-colored pigments to attain high visible reflectance and high NIR reflectance.[7] White products typically incorporate the highly reflective pigment titanium dioxide rutile [34]; other highly reflective pigments under investigation include nanostructured zinc aluminate [35] and bismuth titanate [36].

Light-colored options are available in most roofing product categories, including built-up, clay tile, concrete tile, liquid applied coating, metal, modified bitumen, spray foam, and single-ply membrane [20,37–39]; and in most wall product categories, including exterior wall paint (field-applied coating), painted metal cladding (factory-applied coating), vinyl siding, and architectural membrane [Appendix J, 27]. The notable exception is asphalt roofing shingles—nominally white asphalt shingles look grey and have modest solar reflectance [40].

The performance of a light-colored CEM is characterized by its solar reflectance and thermal emittance; values for roofing materials are usually reported in the Rated Products Directory of the Cool Roof Rating Council [19]. The European Cool Roofs Council also specifies a program for

7 The radiative power in the air mass one global horizontal (AM1GH) solar spectral irradiance recommended for evaluating the solar reflectance of roofing materials is 6.6% UV, 44.7% visible, and 48.7% NIR [32]. Nearly all envelope materials other than bare metal, light-colored clay, and light-colored cement concrete exhibit low UV reflectance [1], as do non-metallic pigments; indeed, the ubiquitous white pigment, titanium dioxide rutile, strongly absorbs UV light [22,33]. High UV reflectance can also accelerate the photochemical formation of ozone in urban areas. Since (a) UV radiation comprises less than 7% of global horizontal solar radiation, (b) high UV reflectance is uncommon among high TE (non-metallic) envelope materials, and (c) high UV reflectance may degrade local air quality, light-colored CEMs typically do not incorporate high UV reflectance.

measuring the solar reflectance and thermal emittance of roofing products [41,42]. Building energy efficiency standards, such as ASHRAE 90.1 [43] and California Title 24 Part 6 [44]; energy efficiency product qualification programs, such as the U.S. Environmental Protection Agency's ENERGY STAR® [45]; and green building programs, such as the U.S. Green Building Council's Leadership in Energy and Environmental Design (LEED) [46] that promote the use of light-colored materials on low-slope roofs (pitch ≤ 2:12) typically require such products to exhibit a minimum aged solar reflectance circa 0.55 – 0.65 and an aged thermal emittance of at least 0.75 [29].

There are few performance specifications for light-colored materials on walls, but Levinson et al. [Appendix P of 27] proposed that "higher-tier" cool walls should be required to demonstrate an aged solar reflectance of at least 0.60 and an aged thermal emittance of at least 0.75. The Cool Roof Rating Council plans to launch a wall-product rating program by 2022 [47].

Cool-colored CEMs are analogous to light-colored materials but use spectrally selective pigments with high NIR reflectance or high NIR transmittance[8] to produce a dark-to-medium colored surface with high NIR reflectance [1,21,22,33,48–50]. One might create a cool-colored material by applying to a conventionally colored envelope product an NIR-reflective clear topcoat or film [40], analogous to a "heat mirror" solar-control window film [51].[9] Cool-colored options are available in essentially all roofing and wall product categories, apart from slate roofing [Appendix P of 27,38].[10]

The performance of a cool-colored CEM is characterized by its solar reflectance and thermal emittance; color is also important to the consumer. Building energy efficiency standards, such California Title 24, Part 6; energy efficiency product qualification programs, such as ENERGY STAR®; and green building programs, such as LEED that promote the use of cool-colored materials on steep roofs (pitch > 2:12) typically require such products to exhibit a minimum aged solar reflectance circa 0.15 – 0.30 and an aged thermal emittance of at least 0.75 [29]. There are few performance standards for cool-colored materials on walls, but Levinson et al. [Appendix P of 27] proposed that "lower-tier" cool walls should be required to demonstrate an aged solar reflectance of at least 0.40 and an aged thermal emittance of at least 0.75.

Fluorescent CEMs incorporate fluorescent cool pigments that emit some absorbed visible light as NIR radiation and reflect or transmit incident NIR radiation. A topcoat colored with the fluorescent cool pigment is applied over a substrate with high visible and NIR reflectance (e.g., a white envelope material, or a white basecoat) to (a) enhance fluorescence by increasing optical path length through the fluorescent topcoat and (b) reflect upward both incident NIR radiation that passes through the

8 A spectrally selective pigment with high NIR transmittance must be applied in a color topcoat over a NIR-reflective substrate, such as a white envelope material or a white basecoat.

9 While such coatings and films are not yet available for opaque envelope products, painted optical films are under development [52].

10 Some naturally colored envelope materials, such as terracotta clay roofing tiles and wood shakes, happen to have high NIR reflectance and low visible reflectance, and thus qualify as cool colors [1].

topcoat and downward-emitted NIR radiation. The fluorescence raises the CEM's effective solar reflectance, or fraction of incident sunlight rejected via reflection or fluorescence, above that of a non-fluorescent cool colored CEM of the same color and NIR reflectance.

Fluorescent cool pigments include ruby (Al_2O_3:Cr) and Egyptian blue ($MCuSi_4O_{10}$, M = Ca, Sr, Ba). Additional colors can be created by mixing (e.g., fluorescent cool blue + non-fluorescent cool yellow = fluorescent cool green) or layering (fluorescent cool blue coating over non-fluorescent cool orange coating = fluorescent near-black) [10,11].

The performance of a fluorescent CEM is characterized by its effective solar reflectance and its fluorescence benefit (effective solar reflectance minus solar reflectance). Color is also important to the consumer. ESR can be measured by comparing the temperature in the sun of the fluorescent material to those of two non-fluorescent reference specimens of known solar reflectance [12]. Performance standards for cool-colored CEMs should also apply to fluorescent CEMs since both technologies seek to provide cool, non-white surfaces for the building envelope.

Thermochromic CEMs incorporate a temperature-sensitive surface coating whose solar reflectance flips from low to high when the material exceeds its transition (switching) temperature [37,53–56]. Garshasbi & Santamouris [53] subdivide these technologies into dyes (e.g., Leuco dyes) and non-dyes (e.g., quantum dots, plasmonics, photo crystals, conjugated polymers, Schiff bases, and liquid crystals). They note that only the former have been tested in building envelope applications. The switchable dyes are applied over a bright substrate, such as a white concrete tile, since they can transmit or absorb light, but not scatter light [55]. Thermochromism may also be used to modulate a CEM's thermal emittance [57].

The performance of a thermochromic CEM is characterized by its transition temperature, transition time, low solar reflectance, and high solar reflectance [58,59]. We are not aware of performance standards for this technology.

Directionally selective reflector CEMs (also known as directionally reflective materials) are steep roofing products designed to appear dark from below ("view direction") but bright from above ("sun direction"). One approach is to apply a white coating to only one side of each granule on an asphalt roofing shingle, then install the shingle on a steep roof with the shingle's bright side facing away from the street [60–62].

The performance of a directionally selective reflector CEM is characterized by its "summer reflectance" (maximum near normal-hemispherical solar reflectance), "winter reflectance" (mean near normal-hemispherical solar reflectance), and "annual reflectance" (average of summer and winter reflectances) [23,63]. Performance standards for cool-colored CEMs on steep roofs should also apply to directionally selective reflector CEMs since both technologies seek to provide cool, non-white surfaces for steep roofs.

Solar-retroreflective CEMs are surfaces intended to reflect beam sunlight toward the solar disc to minimize unwanted reflection from cool walls or cool steep roofs toward neighboring people or buildings. The extensive literature on this technology is summarized by Yuan et al. [64] and Levinson, Chen, et al. [24].

The performance of a solar-reflective CEM is characterized by its solar spectral bi-directional reflectance distribution function. We are not aware of performance standards for this technology.

Daytime sky radiator CEMs are surfaces that combine near-unity solar reflectance, high emittance in the 8 – 13 µm sky window, and low emittance in the rest of the TIR spectrum (4 – 80 µm, excluding the sky window) to attain a modest net radiative heat loss during the day. Sky radiators intended to attain sub-ambient (lower than air) temperatures should be shielded from the wind to minimize convective warming [16,17].

This technique was first demonstrated over 40 years ago [65] but is enjoying renewed attention. Santamouris & Feng [16] identified 22 different technologies, including 8 multilayered planar photonic radiative structures, 12 metamaterials or 2D/3D photonic structures, and 2 paints.

The performance of a daytime sky radiator CEM is characterized by its solar reflectance, emittance in the sky window, emittance in the rest of the TIR spectrum, daytime radiative heat loss rate, and daytime sub-ambient temperature depression. We are not aware of performance standards for this technology.

2.2.3 Benefits and limitations

2.2.3.1 Benefits and penalties

Cool materials can decrease envelope surface temperature and diminish heat conduction into the occupied space. This lowers surface, radiant, and air temperatures inside an unconditioned building, and decreases cooling load (heat that must be removed from the occupied space to maintain setpoint), annual cooling energy use, and peak power demand in a conditioned building. Apart from thermochromics, CEMs also tend to increase heating load (heat that must be added to the occupied space to maintain setpoint) and annual heating energy use in climates that have a heating season.[11]

Direct benefits and penalties. The “direct” cooling benefits and heating penalties of CEMs—meaning those attained by reducing the building’s net radiative heat gain—have been assessed in over 30 countries and regions, including

- Australia [66–68]
- Brazil [69–71]
- Canada [72–78]
- China [28,79–93]

11 Installation of a CEM may incur little to no heating penalty if the building is sufficiently warmed by internal thermal loads.

- Egypt [94–98]
- United Kingdom [86,99]
- France [97,100]
- Ghana [70]
- Greece [50,86,97,101–103]
- Haiti [104]
- India [94,105–111]
- Iran [112,113]
- Israel [114]
- Italy [58,98,115–123]
- Jamaica [70]
- Jordan [124,125]
- Kenya [126]
- Kuwait [127,128]
- Malaysia [129]
- Mexico [130–132]
- Middle East [133]
- Morocco [134]
- Netherlands [135]
- Pakistan [136]
- Portugal [137]
- Singapore [85,138,139]
- Southeast Asia [140]
- Spain [98,141,142]
- Sri Lanka [143]
- Sweden [144]
- Thailand [145,146]
- Tunisia [147]
- Turkey [148]
- United States [6–9,20,27,30,31,76,78,85,149–163]

- many world cities [164]

Hernández-Pérez et al. [165] reviewed over 100 such works, including 16 roof heat transfer studies, 18 test-cell measurement studies, 5 computational fluid dynamics (CFD) studies, 21 building energy simulation studies, 10 whole-building measurement studies, 8 calibrated simulation studies, and 4 large-scale cool roof studies.

In hot-summer climates, the energy-cost or source-energy annual cooling savings provided by a static-albedo CEM (e.g., a light- or cool-colored roof or wall) typically exceeds the corresponding heating penalty [9,20,27,28,31,81,86,91,98,99,102,103,106,114,141,148,152,166–172]. Several studies have found that cool roofs yield annual energy cost savings in office and retail buildings across nearly the entire United States [6,152,173]. 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 [76].

A few studies have compared the life-cycle operational energy savings and carbon emission reductions from cool roofs to those from garden roofs [91,174], or those yielded by cool roofs, garden roofs, and photovoltaic roofs [74]. Pushkar & Verbisky [114] assessed the life cycle sum of production, operational, and maintenance-to-disposal energy uses for red and white roofs in Israel, finding that white roofs were best.

Increasing the albedo of building facades can increase the mean radiant temperature experienced by nearby pedestrians, with net changes to thermal comfort that depend on season and concurrent changes to ambient air temperature [Appendix D of 27,175–177].

Indirect benefits and penalties. Citywide application of CEMs can cool the outside air by reducing convection of heat from the building envelope. This mitigates the urban heat island effect, or elevation of urban air temperature above rural air temperature [178–193] and provides “indirect” cooling savings and heating penalties to buildings throughout the cooled city [72,155,166,168,169,184,194–201]. Cooling the urban air can slow the temperature-dependent chemical reactions that form smog [184,188,202–205] but may also increase the concentration of particulate matter by reducing planetary boundary layer height [202,205].

Global cooling benefit. CEMs induce “global cooling” (negative radiative forcing), or a reduction in the global mean atmospheric temperature, by reflecting sunlight out of the Earth system [206–209].

2.2.3.2 Limitations

Since the most important function of a CEM is to reduce solar heat gain, decreases in solar availability or solar reflectance will limit its utility.

Solar availability. Shadows cast by trees or neighboring buildings can decrease the sunlight incident on the roof or walls of an individual building [158,210], while air pollution (e.g., aerosols) or cloud cover can reduce the sunlight incident on all buildings citywide [28,211,212].

Solar reflectance. Soiling and weathering can reduce the solar reflectance of a CEM. Roof albedo is especially sensitive to soot deposition and biological growth [133,154,171,213–227], while wall albedo is less affected by natural exposure [Appendix J of 27,228]. Cleaning can restore the initial albedo of some roofing materials [220], but this does not appear to be a common practice.

The following examples are representative but not exhaustive.

The loss of reflectance caused by aging (weathering, soiling, and biological growth) depends on the initial reflectance value, the type of coating, and climate characteristics. Sleiman et al. [225] analyzed the reflectance loss of roofing products in different locations in the USA. For initial reflectance values of 0.60–0.80, the authors report a mean absolute reflectance loss after three years of 0.13, 0.05, and 0.10 in a hot-humid climate (Florida), a hot-dry climate (Arizona), and a temperate but more polluted climate (Ohio), respectively. For initial reflectance values above 0.80, the mean reflectance loss is higher, namely 0.24, 0.08, and 0.17 in the aforementioned climates. The authors also report that the solar reflectance reduction is more evident on field-applied coatings, modified bitumens, and single-ply membranes and smallest for factory-applied coating and metal products.

Levinson et al. [220] found that five to eight years of natural exposure increased the solar absorptances of initially light-colored, single-ply PVC roofing membranes by factors of 1.4 – 3.5. In accelerated bio-ageing experiments, Ferrari et al. [219] studied the effect of biological growth on the solar reflectances of different polymeric coatings and roofing membranes, finding small absolute reductions of solar reflectance for colored single ply membranes (0.01 to 0.05) and a maximum absolute reduction of 0.30 for a white field applied polymeric coating. In hot humid climates, aged field-applied, white-coated roofs showed a drop in solar reflectance of about 0.16 (to 0.59 from 0.75) [229]. Similarly, in Athens, Greece, the albedos of white-coated roofs on two schools fell by 0.24 (to 0.50 from 0.74) and 0.17 (to 0.54 from 0.71), respectively, after four years of exposure [221].

2.2.4 Performance, with a focus on robustness and resilience

2.2.4.1 Overview

The performance of a CEM is typically gauged by its initial and aged radiative properties; decrease in envelope surface temperature; annual cooling site energy savings, annual heating site energy penalty, annual HVAC source energy savings, annual HVAC energy cost savings, and peak-power demand savings in a conditioned building; and by temperature reduction in the occupied space of unconditioned building.

2.2.4.2 Aged radiative properties

The Rated Products Directory of the Cool Roof Rating Council (CRRC) reports for roofing materials both initial and 3-year-aged values of solar reflectance and thermal emittance. The 3-year-aged values in this database average properties measured after three years of natural exposure at U.S. sites in Arizona, Florida, and Ohio [19]. Solar reflectance losses after three years depend strongly on material type, exposure site, and initial solar reflectance [225]. The CRRC also reports for some products “laboratory-aged” values of solar reflectance measured after exposing materials to a laboratory practice that simulates the radiative property changes that would occur after three years of natural exposure [226,227,230].

All solar reflectances in the Rated Products Directory are based on a beam-normal, rather than global, solar spectral irradiance. Use of this irradiance spectrum can overestimate the solar reflectance of a spectrally selective “cool colored” material [22,25,32].

Lawrence Berkeley National Laboratory is exposing wall products for five years (2016 – 2021) at the Arizona, Florida, and Ohio sites to assess changes to their solar reflectances and thermal emittances [Appendix J of 27,228]. The LBNL study reports a global vertical, rather than beam-normal, solar reflectance.

2.2.4.3 Envelope surface temperature reduction

The extent to which a CEM lowers envelope surface temperature depends primarily on the albedo gain (increase in solar reflectance) attained by switching to a CEM, and on solar irradiance. Envelope surface temperature and surface temperature reduction can be measured [28,31], or simply estimated under sunny summer afternoon conditions following the protocol used to compute SRI from solar reflectance and thermal emittance [18].

2.2.4.4 Energy savings in a conditioned building

The energy efficiency benefit of substituting a CEM for a conventional envelope material is usually based on its annual HVAC source energy or energy cost savings.[12] The resilient cooling benefit of a CEM depends more on its ability to deliver reliable passive cooling; small annual HVAC energy savings or even a modest annual HVAC energy penalty might be acceptable.

Annual cooling site energy savings from light-colored or cool-colored roofs and walls have been simulated by many workers. Hernández-Pérez et al. [165] summarize cooling load or cooling energy savings simulated in over 20 studies; additional simulations can be found in later studies [7,28,37,54,67,70,76,81,91,97,114,121,122,133,135,194].

These savings vary strongly with envelope albedo gain, climate (e.g., hourly solar irradiance and air temperature), envelope construction (e.g., thermal resistance and capacitance), and building operation (e.g., occupancy schedule). Choice of savings metric is also important. For example, whole-building fractional savings gauge the fraction of the building’s cooling energy use that can be addressed by installing a CEM, but typically do not apply to a building with a different geometry; they

12 Energy efficiency can also be gauged from annual HVAC site energy savings if the building uses only electricity for heating and cooling.

may be high simply because the building requires little cooling. A more transferrable metric is savings intensity, or savings per unit envelope surface area modified.

Example 1. Rosado & Levinson [7] simulated cool-wall and cool-roof energy savings for 10 different building types of three different vintages across California and the United States. Table 2-4 summarizes annual site cooling energy savings and peak power demand[13] savings for a two-story single-family home and a three-story medium office building in ASHRAE climates zones 1 – 4, these climates map roughly to the southern half of the United States. The savings were evaluated with TMY3 weather files based on observations from 1991 to 2005 [231]. Cooling savings in current or future climates should be greater as global warming increases the number of hours each year during which buildings require cooling [232–235].

Example 2. Hernández-Pérez et al. [165] carried out a detailed review of the thermal performance of cool materials applied to the building envelope (roof and facades), including monitoring and simulation studies. The authors reported that the daily cooling energy decrease varied between 1% and 80% depending on the climate and the building construction characteristics.

Example 3. Synnefa & Santamouris [42] evaluated the cooling potential of cool roofs applied to real buildings with different uses (schools, laboratories, offices, and dwellings) and located at different latitudes (from Crete at 35.2 °N to London at 51.5 °N). They reported cooling energy saving of 10–40%.

Example 4. Zinzi [97] carried out simulation studies in the Mediterranean zone reporting annual cooling energy savings up to 2.9 kWh/m² floor area per 0.1 increase of façade albedo. This reduced building annual cooling energy use by 10–20%, depending on envelope construction, cooling system, and facade albedo [121].

Table 2-4. Cool-roof and cool-wall annual cooling site energy savings in ASHRAE climates zones 1 – 4, derived from the Cool Surface Savings Database in Rosado & Levinson [7]

	Annual cooling site energy savings intensity [kWh/m²]	Annual building cooling site energy fractional savings [%]	Annual-average HVAC site peak power demand savings intensity [W/m²]	Annual-average building HVAC site peak power demand fractional savings [%]
Cool roof [a]				

13 Peak demand hours were defined as those between 12:00 and 18:00 local time on weekdays, June through September.

Single-family home, old (pre-1980) [b]	1.5 - 5.5	3.5 - 11.8	1.1 - 2.5	3.8 - 10.2
Single-family home, new (2006-2012) [c]	0.5 - 2.4	2.2 - 9.3	0.2 - 1.0	2.2 - 7.2
Medium office building, old (pre-1980) [b]	0.8 - 7.3	2.5 - 5.2	1.1 - 3.9	2.4 - 3.6
Medium office building, new (2004-2013) [c]	0.6 - 4.4	1.8 - 3.7	0.5 - 1.9	1.8 - 3.9
Cool walls [d]				
Single-family home, old (pre-1980) [b]	3.0 - 8.2	7.9 - 24.7	1.9 - 2.8	7.2 - 18.8
Single-family home, new (2006-2012) [c]	1.0 - 4.8	7.0 - 23.5	0.5 - 1.6	5.6 - 16.0
Medium office building, old (pre-1980) [b]	1.7 - 10.9	3.0 - 8.8	1.9 - 4.3	2.4 - 4.9
Medium office building, new (2004-2013) [c]	0.6 - 4.3	1.6 - 2.8	0.5 - 1.9	1.5 - 2.9

[a] The cool-roof scenario increases roof albedo to 0.40 from 0.10 on the single-family home, and to 0.60 from 0.20 on the medium office building.
[b] "Oldest" vintage in simulations by Rosado & Levinson [7], corresponding to pre-1980 construction.
[c] "New" vintage in simulations by Rosado & Levinson [7]; year of construction corresponds to statewide building code enforced circa 2016 in the city used to represent the climate.
[d] The cool-walls scenario increases wall albedo to 0.60 from 0.25.

Shading and reflection by adjacent buildings can diminish cool-wall energy savings and penalties [158]. If a substantial fraction of light reflected from exterior walls is transmitted through the windows of neighboring buildings, the use of cool walls may increase neighborhood cooling energy use [236].

2.2.4.5 Thermal and comfort improvements in an unconditioned building

The improvement to the thermal environment within an unconditioned building is gauged by reduction in the air, operative, and/or environmental temperature in the occupied space, or by decrease in annual discomfort hours. Hernández-Pérez et al. [165] summarize space temperature reductions measured or simulated in over 30 studies and discomfort hour reductions simulated in 4 studies. Later works also report reductions in space temperature [58,95,108,119,126,134,137,236–239] or discomfort hours [70,87,95,108,119,134,194]. Thermal and comfort improvements depend strongly on envelope albedo gain, climate (e.g., hourly solar irradiance), and envelope construction (e.g., thermal resistance and capacitance).

Example. Synnefa, Santamouris, & Akbari [164] reported annual hours in which the indoor air temperature exceeded various thresholds for a single-story, flat-roof house simulated in 27 world cities. Increasing the albedo of the modestly insulated roof (RSI-1.2) by 0.40 reduced annual hours exceeding 27 °C by about 20% (Figure 2-1).

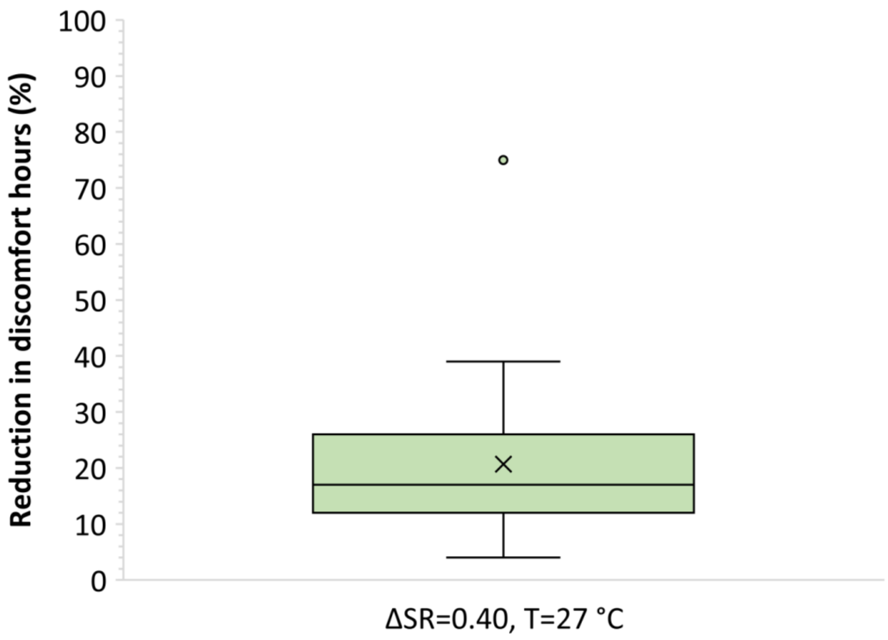

Figure 2-1. Fractional reduction in 27 world cities in the number of hours each year during which the air temperature inside a single-story home exceeds 27 °C, upon raising by 0.40 the albedo of a modestly insulated roof on a single-story unconditioned home. Data source: Synnefa, Santamouris, & Akbari [164]

2.2.4.6 Cool roof case studies

This section reports the main findings of full-scale cool roof deployments, to better understand energy and thermal performances in real operational conditions. Only the solar reflectance (SR) of the cool roof application is reported for the different applications; all products were non-metallic, with high thermal emittance (0.88 – 0.90).

Early cool-roof applications in real buildings were carried out in Florida, USA and documented by Parker & Barkaszi [160]. The first case described a one-story detached family home with a 158 m^2 pitched roof, which had the initial roof (SR 0.20) covered with a white elastomeric coating during summer 1993. Temperature measurements showed a maximum reduction of 18 °C on the roof surface and 11 °C in the attic air. The calculated average daily reduction of electricity use for cooling was 11.6 kWh, corresponding to 20% in typical summer days, keeping the cooling set-point unchanged at 27.5 °C. Also, the peak power demand was reduced by almost 1 kW (23%). The second demonstration was another one-story single-family home, 84 m^2 conditioned floor area, with an asphalt shingle roof (SR 0.08). A white elastomeric coating was placed on the existing roof. After this application, the maximum surface temperature reduction of the roof was 18 C, while the peak air temperature drop in the attic was 16.6 C. This yielded a 25% reduction in cooling energy use on typical days, with 47% reduction during the warmest hours. Before the white coating was applied the cooling system was not powerful enough to maintain the thermostatic setpoint; after, the setpoint was always maintained.

A cool roof case study was carried out in an experimental detached house, built in the northern outskirts of Rome, Italy [123]. The building was funded by the Italian Ministry of Industry as a state-of-the-art demonstration for building technologies. It consisted of two identical floors, the first above an unheated basement and the second below a flat roof that was finished with dark red clay pavers. The monitoring was carried out in free-floating conditions in summer 2006, during which a white cool coating (SR 0.86) was applied to the 50 m^2 roof. Before the coating was applied the average air temperature on the second floor was 1.8 °C higher than that on the first floor. After the coating was applied the temperature difference inverted, making the temperature on the second-floor cooler than that on the first floor 90% of the time. The effect of the cool roof was estimated by regression, resulting in an average air temperature reduction of 2.1 °C on the second floor during the monitoring period.

A set of five demonstrations was implemented in the framework of the Cool Roofs (CR) project funded by the European Commission in 2009 and 2010 [42,240]. Each case study was implemented using the following methodology, based on calibrated simulations: (1) the building is monitored in free-floating conditions for limited periods before and after the cool roof application; (2) the indoor air, outdoor air, and outdoor surface measurements are used to calibrate a numerical model; and (3) simulations are carried out to estimate annual energy and thermal performances. Energy performance is calculated as annual thermal load, which refers to the heat energy that must be supplied to or removed from the occupied space to maintain its operational set-point(s) during both the heating and cooling seasons. No energy monitoring was carried out in the buildings because they were not mechanically cooled in summer.

The first CR case study was a two-floor school building in Athens, Greece, where a 410 m^2 section of the school's cement and gravel screed flat roof was treated with a white elastomeric coating (initial SR 0.80) [103]. The building structure was reinforced concrete. The envelope had no thermal insulation, and the building was naturally ventilated through windows. In summer, the cool coating reduced the roof surface temperature by 12 °C during the morning hours and lowered by 1.8 °C the average hourly air temperature in a monitored room below the cool roof. Calculations were carried out to estimate energy savings in the building as it was, and in the same building with the envelope thermally insulated. The cool coating reduced annual cooling loads by 40% and 35% for the reference building and the thermally insulated configuration, respectively. It also increased their annual heating loads by 10% and 4%, respectively. Also, the peak cooling power demand decreased by 20% for the real building.

The second CR case study was carried out in Greece, namely in Iraklion, Crete Island [102]. Here a small one-floor laboratory/office building (roof area 50 m^2) was equipped with the same cool material used in the Athens study. This building was well insulated and was naturally ventilated with windows. Calibrated simulations in free-floating conditions predicted an indoor temperature reduction of 1.5 °C during the summer months. They also predicted 27% cooling load savings.

The third CR case study was a single-story building containing offices and laboratories in a secondary school campus in Trapani, a city on the western part of Sicily Island in Italy [120]. The structure had no thermal insulation and was naturally ventilated with windows. The flat roof surface (706 m^2) was treated with a natural coating based on milk and vinegar (initial SR 0.86). The cool coating was applied to concrete pavers (pre-coating aged SR 0.25). Measurements in summer 2009 found that the indoor air was 1.8 °C warmer than the outdoor air before the cool roof application, but

1.1 °C cooler than the outdoor air after the application. Calculations were carried out to estimate thermal load savings in the building as it is, and in the same building with the envelope thermally insulated. The cooling load savings were 54% and 24%, respectively. Calculations also showed that when the building temperature is free floating, the cool roof would reduce the fraction of summer hours with the indoor operative temperature above 27 °C to 15% from 55%.

The fourth CR case study was a 27 m^2 cool-roof application carried out on top of a duplex apartment in a social housing complex in La Rochelle, France [100]. The building was highly insulated and equipped with mechanical ventilation. Supply air was delivered to the living room and bedrooms, and exhausts were in the kitchen, water closet, and bathroom. The roof, initially finished with a dark waterproof asphalt coating, was retrofitted with a white coating (SR 0.88). Simulations predicted that the operative temperature in the attic fell to 22.4 °C from 30.8 °C. Due to the presence of both the attic and the thick insulation layer, the mean operative temperature reduction on the second floor was only 0.7 °C (to 24.2 °C from 24.9 °C). More relevant improvements (up to 9 °C) were calculated for uninsulated configurations, but these are not common in the region.

The fifth CR case study carried out was implemented in London, United Kingdom [99]. A 137 m^2 section of the roof of a university building, over an open office area and three office rooms, was made cool. The building's roof and walls were insulated, and the building was naturally ventilated. Since the United Kingdom is a heating-dominated climate with significant cooling loads in office buildings, a pink cool coating (SR 0.70) rather than a white cool coating was selected to balance this mixed thermal requirement. Calculations showed that the cool coating significantly improved thermal comfort, reducing summer maximum and average values of operative temperature by 2.2 °C and 5.3 °C, respectively.

A case study compared innovative off-white clay tiles (SR 0.77) to conventional brown tiles (SR 0.19) for pitched-roof applications [119]. The monitoring focused on a 42 m^2 section of the roof on a three-story detached house and on the attic below the roof section. Daily peak surface temperature reductions of 18 °C and 15 °C were measured in June and July, respectively. The ceiling surface temperature also decreased by 6–9 °C in summer. The attic average operative temperature decreased by 2 °C in the June-August period, with a daily peak reduction of 4.7 °C in July. Corresponding temperature reductions were much smaller in winter.

Another study evaluated the impact of cool roofs in a school building in Athens, Greece, using monitoring followed by calibrated simulation [241]. The building's thermal behavior was compared to that of a nearby school with similar thermal, use, and geometric characteristics. A cool roof coating (SR 0.89) was applied to a section of the roof covering several classrooms and a stairwell. Measurements showed that peak roof surface temperatures dropped to 40.4 °C from 54.6 °C, while a 2.5 °C peak difference of the ceiling temperature was measured before and after the cool roof application. The peak indoor temperature was 34.5 °C before the application (25.9 °C average outdoor air temperature over the pre-coating monitoring period), dropping to 32.4 °C after the cool coating, despite warmer weather (29.5 °C average outdoor air temperature during the post-coating monitoring). Calibrated calculations showed a potential 30% reduction of electricity use for ceiling fan operation in the building.

A full-scale comparison between cool and green roofs was carried out in an unoccupied office building in the city of Chongqing, China, characterized by hot summers and cold winters [81]. Three identical top-floor rooms (each 21.4 m^2) had the following roof finishing layers: black coating (SR

0.20), white coating (SR 0.84), or sedum garden roof (SR 0.36). During summer, it was found that the mean ceiling temperatures below the garden and white roofs were 8.7 °C and 5 °C lower than that below the black roof. When unconditioned (on weekends), the mean cooling-season indoor air reduction with respect to the black roof was 3.2 °C for the garden roof and 1.8 °C for the white roof. Per unit roof area, the white roof also provided 4.8 kWh/m^2 annual cooling energy savings and 3.9 kWh/m^2 annual conditioning (cooling + heating) savings with respect to the black roof, outperforming the garden roof as well.

The application of a cool roof to a low-income house in a country with high solar irradiance was documented in a case study in Portmore, Jamaica [70]. A single-story semi-detached house with a flat roof (40 m^2) received a white coating (SR 0.82). The ceiling and indoor air temperatures were monitored before and after the cool roof application, which took place in March–April 2016. Comparing two days with similar average ambient temperature and solar irradiation, it was found that the ceiling temperature dropped by 6.8 °C on average with 18.6 °C maximum temperature reduction; the averaged reduction in indoor air temperature was 2.3 °C. Calibrated calculations were implemented starting from the monitoring data, estimating a cooling load reduction of about 37%.

The integration of cool roofs with the night ventilation was the objective of a case study implemented in the cooling dominated city of Xiamen, China [242]. On the roof of a six-story office building the surfaces above three identical top-floor rooms (31.5 m^2 each) were coated: one black (SR 0.05), one yellow (SR 0.57), and one white (SR 0.79). The rooms were fully equipped to monitor indoor air temperatures during the March–April transition season when the rooms were free floating, and to monitor cooling energy use in summer when the rooms were fully air conditioned. Measurements were also used to calibrate simulations. In the transition season, the peak surface temperature of the black roof was 68.6 °C; the peak surface temperatures of the white and yellow roofs were 27 °C and 20 °C lower than that of the black roof. The air temperatures in the offices with the white and yellow roofs were 1.2 °C and 0.9 °C lower than that in the black-roofed reference room in this period, but both the white-roof room and the yellow-roof room registered the same maximum air temperature drop of 1.3 °C when the night ventilation was added. The measured cooling energy uses in summer of rooms with the white and yellow roofs were about 30% and 25% less, respectively, than that of the room with the black roof. Simulation showed that combining the white cool roof and natural ventilation can reduce annual heating and cooling site energy use by 27% compared to the black roof.

2.2.5 Application

2.2.5.1 Overview

The ability of a CEM to reduce radiative heat gain depends on the solar availability of the building envelope and thus on the latitude and climate type of the site location, the surrounding urban geometry (e.g., shading and reflection from surrounding buildings), and the building orientation. The higher the solar availability, the greater the potential benefit of a CEM.

2.2.5.2 Climate

Light- or cool-colored roofing and wall products are generally well-suited to climates with hot, sunny summers, with diminishing annual cooling and annual HVAC savings as one moves to cooler climates. They provide substantial annual HVAC source energy savings in ASHRAE climate zones 1 – 4,[14] and modest annual HVAC energy savings or penalties in ASHRAE climates zones 5 – 8 [7]. As remarked earlier, a CEM that yields an annual heating penalty comparable to its annual cooling savings may still be useful as a source of resilient cooling, even if the annual HVAC energy savings are a wash. Also, CEMs are expected to grow more useful as the global warming increases the numbers of hours each year during which buildings require cooling.

Cool roofs are particularly effective in climate regions with high solar radiation and no heating requirement [70,95,108,244,245]. This technology has also proved to be more resilient in hot-dry climates than in hot-humid ones, where the solar reflectance losses due to weathering were found to be 2–3 times greater [225]. The lower performance of CEMs in tropical regions is also due to a smaller sky radiative cooling effect due to high average cloudiness [246].

CEMs are effective on both residential and commercial buildings, though space available for cool roofs and cool walls can be limited by the presence of solar equipment on the roof and windows on the facades. Cool roofs benefit only the top floor of a multi-story conditioned building, making cool-roof savings per unit floor area greater in low-rise buildings than in high-rise buildings. Cool walls are most effective on east, west, and equator-facing facades [7]. Since total wall area is proportional to building perimeter length while total floor area is proportional to building footprint area, cool-wall savings per unit floor area are higher in buildings with a small footprint than in buildings with a large footprint.

CEMS are ideal for older, poorly insulated buildings since their benefits are inversely proportional to envelope thermal resistance [7]. Therefore, they are most helpful for retrofits.

The areal density (mass per unit area) of a roofing product is an important consideration if the roof deck can support only lightweight products. This issue often arises in warm-winter climates where roofs are not built with extra weight tolerance for snow. For example, a roof deck in Los Angeles designed to support asphalt shingles may be unable to carry concrete tiles or clay tiles, which can be 3–5 times heavier [40].

14 CEMs should also be useful in ASHRAE climate zone 0, which comprises the hottest portions of ASHRAE climate zone 1 [243].

2.2.5.3 Urban environment

Shading by neighboring buildings and trees can reduce the solar availabilities and cooling benefits of cool roofs and walls [158,210]. Soiling by soot, such as that from vehicle exhaust, is one of the factors that tends to degrade the reflectance and performance of CEMs [226].

Studies have found that increasing the albedo of building facades in cities may increase the mean radiant temperature of urban canyons, reducing outdoor thermal comfort in summer [175,176].

2.2.5.4 Installation strategy

Since the cost of a CEM is often the same as that of an otherwise comparable conventional (warm) envelope material, a low-to-no cost way to introduce CEMs is to specify their use in place of conventional envelope materials for new construction or end-of-service replacement. Installation during regularly scheduled retrofits is an especially attractive strategy in places like the United States that have an aging stock of poorly insulated buildings and little new construction. If envelope surface materials are replaced on average after 20 years of service, the envelopes of most buildings could be made cool within two decades.

2.2.6 Technology readiness level

Both white and cool-colored roof materials are mature technologies that are widely available to both building owners and building contractors [38,247], and identifiable via mature product rating systems provided by the Cool Roof Rating Council [19] and the European Cool Roofs Council [41,248]. Cool wall materials, such as light-colored paints, claddings, and sidings, and some cool-colored wall products, are similarly mature and available [Appendix P of 27]; a wall-product rating system is scheduled to begin in 2022 [47].

The dominant residential roofing product in the USA is asphalt shingles, but nominally “cool” asphalt shingles are not very reflective; substantial improvement is needed [40].

Some novel CEMS such as directionally selective reflectors are specialty products with limited availability; other CEMs, such as daytime radiators, solar retroreflectors, fluorescent cool colors, and thermochromics remain under development.

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2.3 Evaporative Envelope Surfaces

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2.3.1 Physical Principles

Water retention on external envelopes is a passive cooling solution. This passive technique is mainly used through vegetated surfaces like green roofs and green façades [1–3], or water surfaces like roof ponds and water spray façades [4]. Figure 2-2 shows the thermal flux for the main typologies of evaporative surfaces. The primary difference between façades (green or watered) and roofs (green roof or roof pond) is linked to the vertical water runoff, which amplifies the water effect in the thermal balance due to gravity. However, the retention of runoff depends on the seasonal variation in rainfall. Storm water events with heavy rainfall are managed by partial retention on green roofs or roof ponds. Evaporative techniques for façades require continuous water spray or water supply to permanently irrigate the upper part.

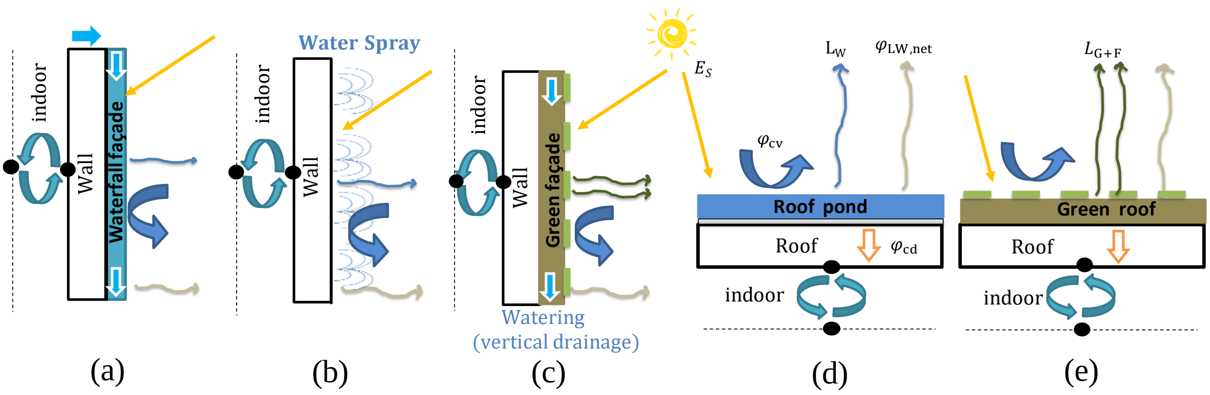

Figure 2-2 Heat transfer in evaporative envelope surfaces, including (a) a waterfall façade, (b) a spraying system, (c) a green façade, (d) a roof pond, and (e) a green roof.

All these systems have a water retention or watering technique supplied by regular rainfall or controlled watering devices. On the external envelope, the evaporative process absorbs the sensible heat fluxes that are derived mainly from solar irradiance (ES), conducted heat flux (φcd), and convective heat flux (φcv) with outdoor air. Thus, the cooling effect on the outside is mainly due to the latent heat flux (LW) resulting from surface water evaporation, or from growing medium (LG) and foliage (LF) evapotranspiration, and longwave radiation to the sky (φLW,net). The evaporative process is amplified by direct solar gains for open wet surfaces (e.g., roof ponds), compared to vegetated surfaces (Figure 2-2 a, b, d). The external evaporative system limits the transferred and stored heat in the wall and the roof, reducing the indoor surface temperature.

The cooling potential of evaporative envelope surfaces depends on the availability of water, which may be limited in some places that are increasingly dry due to climate change [5,6]. Thus, water balance must be modelled together with thermal balance, considering watering and rainfall, retention potential during rainfall events, runoff, and the evaporated water quantity.

For coupled thermal effects, new techniques have been developed to control the dynamics of the evaporation process, such as covers for roof ponds, high albedo claddings, or added porous materials for water storage [7,8].

2.3.2 Typologies and Design Parameters

2.3.2.1 Typologies

The cooling potential of evaporative surfaces depends on their water retention capacity. This is the main difference between the two types of green roof [9]:

- 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.

Green façades with substrates behave similarly to green roofs but require regular watering and fertilizer to counteract the drainage effect. Green façades can also be designed with climbing plants, which have a low evaporative potential but have the advantage of providing a shading effect [10].

Several configurations of roof ponds have been proposed and classified depending on thickness, thermal mass, insulation properties, and the addition of shading elements or reflective materials [4,11]. The roof pond system was first studied in 1920 at the University of Texas [12]. An evapo-reflective roof pond typology was developed to prevent vapor loss with a reflective cover that limits solar gain. At night, the vapor condenses and falls back into the pond. Heat loss is amplified by the radiation between the humid surfaces, and this drives the cooling process, which is based on heat moving outwards and cold inwards [13]. Tang & Etzion (2004) designed a roof pond system with absorbent materials filled with water. This typology has a buffer effect and behaves like a buffer tank, storing the energy from the excess heat as hot water; it can be designed according to water resources and cooling needs. Various typologies have been developed with both reflective cover and absorbent materials [15,16].

Water spraying is another controlled method that can be used to increase cooling and the evaporation process for a roof pond. Erell et al. [17] recommended droplet sizes of 0.5 to 1 mm, spray rates of about 1-1.5 volumes of the roof pond per hour, and a spray height of 50 cm.

2.3.2.2 Design Parameters

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.

For roof ponds, water level is a key design parameter. Raeissi and Taheri [18] demonstrated that a lower water depth could be more efficient due to both the increased evaporation rate and the decreased temperature of the bottom layer of the pond. This parameter can be adjusted by overflow outlet design but is constrained by rainfall management requirements.

For green roofs, the water capacity and therefore the evaporative cooling effect are mainly determined by the soil thickness. Wong et al. [19] compared a bare roof with a humidified green roof (40% moisture content) and with a dry green roof, considering various soil thicknesses on the roof (from 10 to 90 cm). For 90 cm dry clay soil, the annual cooling energy use for the building was reduced by 64% and the annual cooling peak demand was reduced by 71% compared to a reference bare roof. For the same green roof, fully watered, the energy use and peak demand were both reduced by 22%, compared to the same reference bare roof.

For green roofs and façades, there are also other key design parameters, such as plant physiology, color, type, and morphology. Liu et al. [20] demonstrated that plant height can have a significant effect on roof cooling potential. With B. pinnatum, which is an herbaceous plant, a comparison of 10, 15 and 35 cm high plants showed that the lowest rooftop temperatures were obtained with the tallest plants.

2.3.3 Benefits and Limitations

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. Moreover, they help mitigate the urban heat island effect and may eventually create local cool islands.

Water retention systems such as green roofs and roof ponds reduce the risk of water flooding and are used to prepare for the potential impacts of changing rainfall patterns that could overwhelm the capacity of existing drainage systems [21]. Indeed, a well-designed system can have positive effects on urban hydrology, avoiding sudden discharges of storm water to the sewers when rainfall water is harvested on the roofs to irrigate the living wall, especially if it is combined with green roof technologies that act as water buffers. Mentens, Raes, & Hermy (2006) showed that rainfall-retention capability may be around 75% for intensive green roofs with a growing medium thickness of 150 mm and 45% for extensive green roofs with 100 mm growing medium thickness.

However, 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 [23]. This could be also a solution for greywater treatment by drainage or infiltration through living wall and green roof systems.

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

2.3.4 Performance

2.3.4.1 Key Performance Indicators for Evaporative Envelope Surfaces

The performance of evaporative surfaces can be assessed in terms of a decrease in surface temperature (external or internal), or by reduction in the temperature of the indoor environment. Indoor cooling performance depends on the indoor air temperature (T_i) or operative temperature (Top) or the cooling energy consumption of the building. The main physical parameters for the calculation of key performance indicators (KPIs) are represented in Figure 2-3, which illustrates heat transfer for evaporative envelope surfaces compared generally with either a reference bare roof (ref 1) or a galvanized iron roof (ref 2). The latter is the worst case, with a maximum ceiling temperature ($T_{c,max}$) equal to the sol-air temperature (T_{sa}).

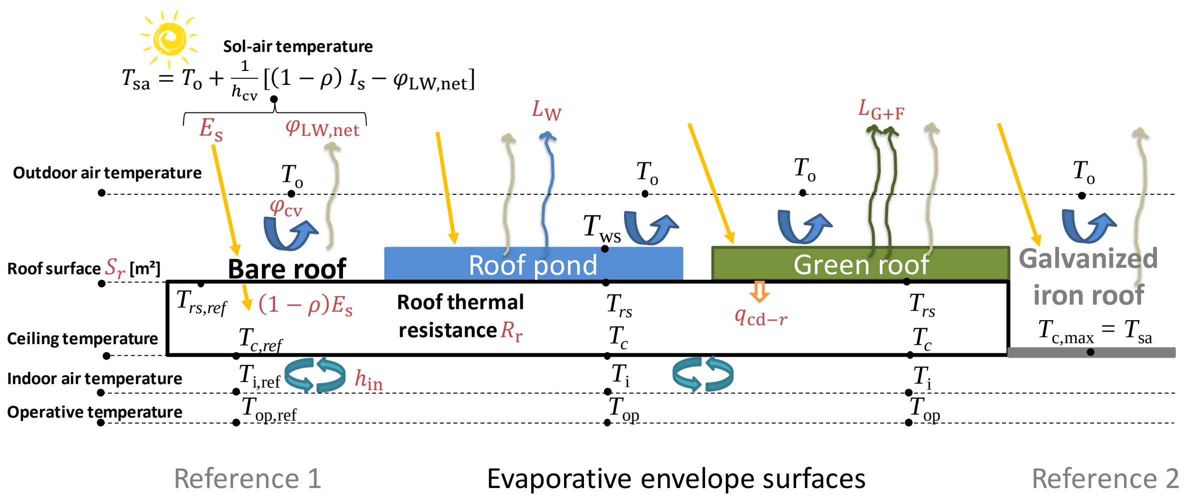

Figure 2-3 Heat flux and temperature of a reference bare roof and evaporative envelopes

A first KPI can be defined as the temperature reduction of the roof (Trs) or the ceiling (Tc). A comparison of the daily extrema of both internal and external surfaces was defined as the decrement factor $DF_s = (T_{c,max} - T_{c,min})/(T_{rs,max} - T_{rs,min})$ by Barrios et al. [24], where Tc,min is the ceiling temperature limit for thermal comfort. The smaller the decrement factor, the better the thermal performance. Another KPI, the thermal performance index TPI (%), is also used for evaporative techniques by Barrios et al., and Kabre [24,25].

For the overall cooling performance of an evaporative surface without an air-conditioning system, a coefficient of performance [COP = (Ti,ref1 – Ti) / (To,avg – TWB)] was defined by Krüger el al. [26]; where To,avg is the daily average outdoor temperature, and TWB is the outdoor wet bulb temperature. Indeed, the minimum indoor air temperature that can be obtained with an evaporative cooling system is the outdoor wet bulb temperature.

2.3.4.2 Roof Pond

Spanaki et al. [27] studied the impact of a roof pond, with natural ventilation through the airspace between a cover and the water surface, on indoor temperature. The simulation results showed that the daily amplitude of indoor air temperature variation decreased by 30%, compared to a bare roof. This is mainly due to the high thermal capacity of water. The effect on indoor temperature reduction can be assessed by the COP of the roof pond, which was studied experimentally for an evapo-reflective roof pond by Krüger et al. [26] in Maracaibo, Venezuela (north of South America) during summer. This study [26] highlighted the cooling performance of the roof pond system, even for a hot and humid climate. The cooling performance determined by the coefficient of performance by Krüger (around 0.3) is comparable to the values obtained (around 0.45) for a hot and dry climate (Negev region, Israel). This approach characterizes the system performance and enables comparisons to be made for different experiments under various climates.

Raeissi et Taheri [18] studied various roof ponds for an air-conditioned building in Shiraz, Iran. For typical summer days, the daily cooling loads were reduced by around 79%, 58% and 44% for a shaded roof pond, open roof pond, and shaded bare roof, respectively.

2.3.4.3 Green Roof and Façade

To study the green roof effect on roof slab cooling, S Onmura et al. [28] assessed lawn gardens planted in non-woven fabric, during a very hot summer in Osaka, Japan in 1991. The results showed that roof surface temperature decreased to 30 °C from 60 °C during daytime. Similarly, Jaffal et al. [29] simulated the temperature with a detailed model. For a temperate climate (France), in summer, the daily amplitude of the roof slab temperature was reduced by 30 °C compared to that of the bare roof (Figure 2-3, ref1). The summer indoor air temperature decreased by 2 °C in the temperate climate of La Rochelle (France).

Spala et al. [30] simulated an office building located in the greater Athens area to examine the impact of a green roof on cooling load and found that the cooling loads were reduced by 40% during summer, compared to a bare roof (Figure 2-3, ref1). Santamouris et al. [3] demonstrated that green roofs could reduce cooling load in summer in a two-story nursery school building in Athens, Greece. The cooling reduction varied between 6 and 49% for the whole building, compared to a bare roof (Figure 2-3, ref1). Wong et al. (2003) studied various roof top garden strategies for a five-story commercial building in Singapore. Compared to a bare roof (Figure 2-3, ref1), annual energy savings in reducing total air conditioning energy consumption varied from 0.6 to 14.5%, and shrub plants were found to be the most effective. Susca et al. [31] observed that energy savings could increase 40-110% by using a green roof rather than a white roof.

For green façades, the interactions are more complex, especially in a dense urban context. Alexandri & Jones [32] found that the cooling effect due to green walls and urban canyon orientation was more significant for hot and dry climates. Compared to a bare roof (Figure 2-3, ref1), their numerical results showed that cooling energy savings varied from 32% to 100% during a typical day of the hottest month with an average temperature and solar radiation. Djedjig et al. [33] simulated orientation impacts for the summer climate in Athens and concluded that green walls on east and west façades could reduce the cooling load by 37%, compared to bare walls.

2.3.5 Application

The effectiveness of evaporative envelope surfaces depends on the climate. Simulations showed that green roofs are thermally beneficial for hot, temperate; and cold European climates [29]. Alexandri & Jones [34] studied the performance of green roofs and walls in diverse climates and highlighted their effectiveness in hot and dry climates for indoor and outdoor urban temperature mitigation. A combination of green roofs and green walls led to the best mitigation of temperature inside the canyon and achieved cooling energy savings of between 32% and 100% in hot climates. Green roofs are now widely used in Toronto (Canada) intending to meet the urban environmental challenges, as reported by Doug et al. [35].

The benefit in terms of thermal comfort of a shaded roof pond was tested in a warm and temperate climate in New-Delhi, India [36], and the results showed that the indoor temperature was reduced to 35.4 °C from 40 °C during May. Ben Cheikh & Bouchair (2004) found that, in a hot and arid climate, an evapo-reflective roof pond made it possible to reduce the indoor temperature by 6-10 °C.

2.3.6 Technology Readiness Level

Water retention on flat roofs is widely used in rainfall management, especially considering the increasingly restrictive urban construction rules for storm water. Storm water management is also a common concern with adaptation to climate change. Green roofs and roof ponds could meet the challenge of both rainfall management and passive cooling. However, their thermal benefit is not widely acknowledged and is almost absent from the regulations and standard design rules.

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 have also social benefits such as urban food production, social networking, and access to nature in a workplace [37]. 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.

Roof ponds are commonly used for water retention in standard flat roof design. The technology includes typical bare waterproof membranes, gravel roofs, and more recently alveolar systems like Nidaroof© [38]. However, roof ponds are not commonly used, but there are many lab studies. Various full scale and working prototypes have been set up by researchers under different climates [39], and these studies highlight possible typologies and the future potential of roof ponds as a cooling solution.

2.3.7 References

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2.4 Ventilated Envelope Surfaces

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2.4.1 Physical Principle

For conventional facades and roofs, conductive heat transfer within the envelope (φcd) is the result of three forms of thermal exchange with the external environment: convective heat transfer (φcv) between the surface and outdoor air, longwave radiation (φLW,net) between the envelope and the external environment (building, street and sky), and solar irradiance gain (Es) during the day.

With the aim to improve heat recovery for winter or dissipation for summer, there has been a surge in the development of ventilated roofs and facades in the construction and refurbishment sectors. These systems are characterized by a ventilated double-skin within which the outside air circulates (Figure 2-4). In summer, these structures work as a cooling system, and can thus reduce the surface temperature of the inner skin (wall or window) and heat gain. This reduces the need for air conditioning or helps maintain indoor thermal comfort.

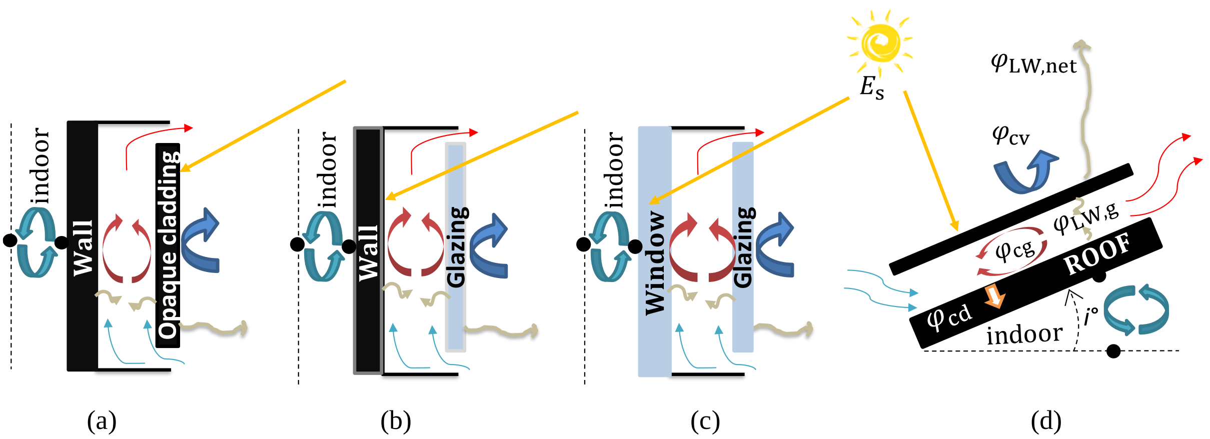

Figure 2-4 Heat transfer in ventilated envelopes - (a) opaque façade; (b) ventilated double-skin façade with a glazed outdoor layer and inner wall; (c) ventilated double-skin façade with a glazed outdoor layer and an inner layer as a window; (d) ventilated double-skin roof.

Within the air gap, two transfers take place: convective heat transfer (φcg) and longwave radiation interchange (φLW,g). The stored heat within the wall, from both indoor wall and external heat fluxes on the outside, is transmitted by convection (φcg) to the air circulating within the double-skin and can be extracted to the outside. The two main driving forces for air movement within the cavity are the wind and thermal buoyancy.

For vertical façades (or pitched roofs) the natural ventilation mechanism is increased by the natural upward convection of hot air within the gap, which increases fresh outdoor intake. This natural upward ventilation effect can be increased by heat sources such as longwave heat exchange (φLW,g) within the gap, and additional shortwave irradiation for transparent double-skin façades (Figure 2-4 b, c). Radiative contributions increase the temperature of the cavity surfaces and thus increase the pressure gradient between the bottom and the top of the cavity (solar chimney principle). For flat roofs (slope i = 0°, Figure 2-4 d), the wind is the main driving force for cavity ventilation.

For a better control of heat transfer within the double-skin cavity, the natural ventilation can be replaced by mechanical ventilation. Natural or mechanical ventilation of a ventilated façade can also be coupled with the building ventilation system itself.

The cooling potential of these techniques depends on the interaction between thermal buoyancy and wind effects. In addition to ventilation mechanisms, some transparent double-skin façades incorporate solar shading such as venetian blinds within the gap to limit solar gain. Another variant is the use of latent heat transfer with added components within the gap, such as a vegetated surface, water misting, phase change materials, or water retention (flat roofs only), that can offset the heat peaks in summer conditions.

2.4.2 Typologies and Design Parameters

2.4.2.1 Typologies

Ventilated roofs and façades are widely used, and innovative configurations have been investigated to improve their performance. For example, Liu et al. [1] studied the various typologies of double-skin façades: opaque ventilated façades that are composed of the main wall and an additional external cladding; and an opaque wall combined with external glazing and a transparent façade with multiple glazing layers. Apart from the composition of the façade or roof, different ventilation strategies can be found in the scientific literature.

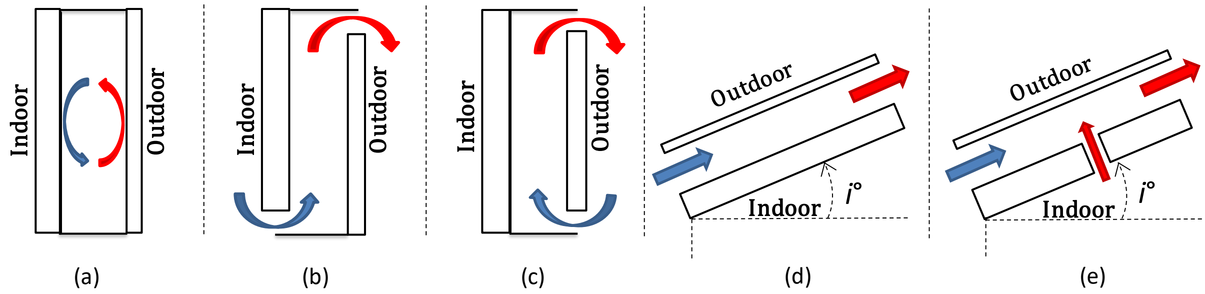

Figure 2-5: Typologies of ventilated envelope surfaces: (a) closed cavity façade; (b) exhaust air façade; (c) outdoor air curtain façade; (d) ventilated roof; (e) ventilated roof coupled to a natural ventilation of the building.

Figure 2-5 presents the specific ventilation strategies in the cavity to reduce solar gain and extract heat from the building. They can be classified into two categories [2]:

- Exhaust air façade/roof (Figure 2-5 Figure 2-5b, e). The building ventilation is designed with an air outlet through the wall, which can reduce heat transfer from the outside to the inner wall.
- Outdoor air curtain façade/roof (Figure 2-5 c, d), without coupling airflow with the indoor environment.

Additional strategies (not represented here) are designed for air preheating in winter (Trombe wall):

- the air circulates in a closed loop between the inside of the building and the cavity of the double-skin
- the outside air enters the cavity and then enters the building.

In these façade configurations, the external skin is generally glazed (Figure 2-5 b, c). The incoming fresh outdoor air (or indoor air) is preheated by heat loss recovery from the building and by the solar radiation absorbed by the external surface of the inner skin (greenhouse effect). In summer, these devices can be controlled according to cooling requirements by means of by-passes.

Closed cavity façades (Figure 2-5 a) act as insulators by reducing the consumption of air conditioners in summer, and they can be combined with solar protection and controllable ventilation openings such as roller blinds, vertical louvre blinds, or curtain panels for periods of overheating [3]. In addition, Pflug et al. (2015) simulated a closed translucent façade to control convection with varying thermal transmittances to prevent overheating in summer.

Pitched ventilated roofs (Figure 2-5 Figure 2-5d) have a good cooling potential in hot climates [5]. Ventilated roof techniques, which are less widely used than façades, can also be employed as solar collectors to increase natural ventilation through the roof structure (Figure 2-5e). Indeed, the thermal draft in a ventilated roof increases the air flow rate of natural ventilation inside the building by the chimney effect [6].

Other designs have been proposed. For example, perforated outside cladding (

Figure 2-6 b) can improve the ventilation efficiency of double-skin façades (Başaran et al., 2016; Blanco et al., 2014; Srisamranrungruang et al., 2020). Another innovation has been developed with Venetian blinds (

Figure 2-6 a), which allow shading to be adapted to sunlight conditions by varying the inclination of the slats (Ji et al., 2008; Velasco et al., 2017; Wang et al., 2019; Xu et al., 2008).

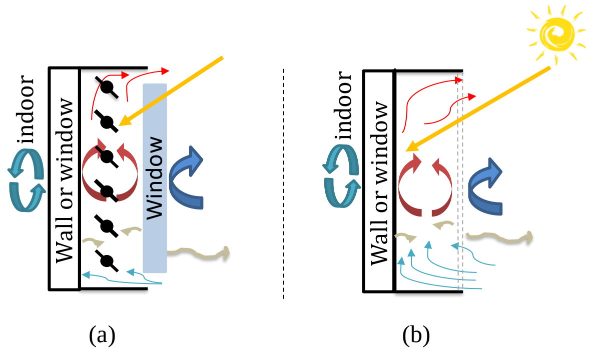

Figure 2-6: Ventilated double-skin façade: (a) with Venetian blinds; (b) with a perforated external façade.

We can also find various additions on the external side, and within the façades, such as semi-transparent photovoltaic panels for the exterior glazing which shade the façade [16–18]; vegetated surfaces on the external/internal façades (Yang et al.,2018); and the incorporation of microalgae [20] or water misting systems [21].

2.4.2.2 Design Parameters

Cooling potential is mainly linked to the ventilation rate of the double-skin air gap, which depends on geometric parameters such as the façade or roof air inlet geometry, the tilt angle of the cavity, and the air layer width. Ciampi et al. [22] simulated the energy savings in summer with different air channel thicknesses and tilt angles for a ventilated roof. They demonstrated that a channel thickness exceeding 8 cm provoked turbulent airflow for angles between 20° and 60°. The heat transmitted to the building was reduced by 35% with turbulent airflow compared to 30% with laminar airflow.

More specifically, perforation rate is a significant parameter for ventilated double-skin perforated façades (

Figure 2-6b). Srisamranrungruang et al. [9] modelled this system with various screen perforation fractions demonstrated that 50% perforation was optimum for natural ventilation in Japan.

Double-skin façades with Venetian blinds (

Figure 2-6a) are designed with specific slat angles, air cavity thicknesses, and façade heights. Wang et al. (2019) studied this configuration and the temperature variation of the inner glazing for slat tilt angles of 0° to 90°. Increasing the slat tilt angle from 0 to 60° reduced airflow and increased the temperature. For a slat tilt angle above 60°, the air pressure loss in the cavity decreased, which increased the airflow and reduced the temperature of the inner glazing.

The thermophysical properties of wall materials are also decisive design parameters (e.g., thermal inertia, insulation layer position, albedo, and thermal emissivity). Ciampi et al. (2003) demonstrated that ventilated façades with reflective outer cladding (steel or titanium alloy) can strongly reduce solar gain.

2.4.3 Benefits and Limitations

The benefit of ventilated surfaces for cooling is mainly driven by the air ventilation rate within the double-skin air gap. Outdoor air is, then, the main heat sink that prevents excessive heat transfer inside a building. The cooling potential and the limits of the system are thus linked to the ventilation rate and temperature difference between indoor and outdoor air. These systems are more efficient with high radiative gains and moderate air temperatures. The addition of natural nocturnal ventilation within the double-skin can evacuate the heat stored in the walls and mitigate diurnal temperature peaks. Indeed, there is a risk of overheating in hot seasons. The results of the study of Khoshbakht [24] showed that transparent double-skin facades have the potential to reduce cooling energy demands (2 weeks in summer) by approximately 50% in temperate climates and 16% in the subtropical region. Indeed, most double-skin façades were designed for temperate climates and guidelines should be developed for other climates [24].

Ventilated double-skin façades act as a thermal buffer in all seasons, minimize heat loss, and provide insulation for summer and winter by adapting the ventilation strategy. Additionally, there are thermal benefits on the outside envelope, such as the thermal insulation layers of the outer skin that limit thermal bridging and prevent surface condensation.

From an acoustics point of view, ventilated double-skin façades limit indoor noise even with high exterior noise levels. Moreover, several studies have been carried out on the acoustic performance of various types of double-skin façades [25]. The type of double-skin façade and the number of openings can be critical for the insulation to internal and external noise pollution [26].

For building renovation, a double-skin façade has both the benefit of adding insulation and keeping the existing wall structure. The constraint 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 material [27]. Therefore, for building renovation and even for new constructions, it must be verified that the original facades can support double-skin facades; otherwise, they must be hung, and pillars added to fix them to the ground.

2.4.4 Performance

2.4.4.1 Key Performance Indicators for Ventilated Envelopes

The effectiveness of ventilated envelopes is assessed either from the cooling energy consumption and peak-power demand savings for air-conditioned buildings, or the operative temperature Top and indoor temperature Ti for non-cooled buildings. The key performance indicators (KPIs) commonly associated with ventilated envelopes are either directly evaluated with these cooling performance indicators or assessed in comparison with references such as a bare roof (ref1) and an insulated double-skin roof (ref2), as illustrated in Figure 2-7.

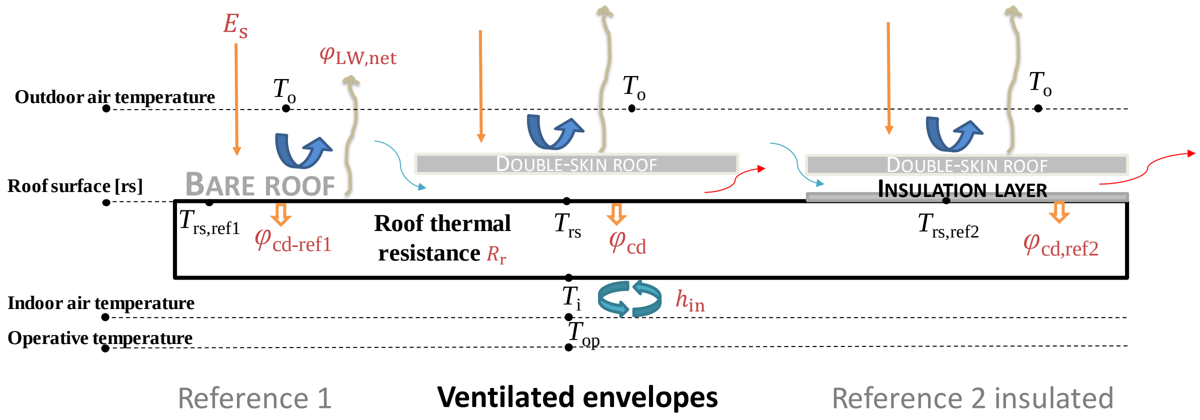

Figure 2-7 Heat fluxes and temperatures for a reference bare roof, and ventilated envelope surfaces

A direct performance indicator can be derived from the temperature variation between the outside surface Trs and indoor air Ti, as proposed by Yang et al. [28]. They expressed the transmitted heat flux as (Trs – Ti) / (Rr + 1 / hin), with Rr the bare wall thermal resistance and hin the indoor convective heat transfer coefficient hin.

However, the relative performance is generally assessed based on a reference, such as the ratio of transmitted heat flux with a bare wall reference (φcd / φcd,ref1). Omar et al. [5] proposed another reference (ref2) with an added insulation layer for the double-skin roof, as shown in Figure 2-7, and this new KPI is defined by the ratio (φcd,ref2 / φcd). For non-cooled buildings, indoor temperatures are a more relevant way to define the KPIs.

2.4.4.2 Ventilated Roof

Gagliano et al. (2012) analyzed the thermal behavior of ventilated roofs and showed that the system can reduce the transmitted heat flux by 50% in hot climates during summer. Omar et al. (2017) compared a reference bare roof (ref1, Figure 2-7) to non-insulated and insulated ventilated roofs, and found that the performance expressed as (φcd / φcd,ref1) was 50% (to 60 W/m² from 116 W/m²) and 85% (to 17 W/m² from 116 W/m²), respectively, in the hot, and arid climate of Djibouti in summer. This KPI expressed as transmitted heat flux reduction has a direct impact on air-conditioning energy savings. For example, Ciampi et al. [22] found that energy savings for cooling needs reached 30% for a naturally ventilated roof compared to the same non-ventilated roof in summer (To = 28 °C).

Furthermore, Dimoudi et al. [30] studied the effect of adding a radiant barrier that could block thermal radiation and keep a ventilated roof 14 °C cooler than a typical roof for a typical day in the summer period in Greece. They also investigated the effect of the air gap height, the air inlet and outlet opening dimensions. For a 6 cm air gap, they measured higher roof temperature differences with the reference bare roof (Trs,ref1 – Trs = 9.5 °C) than with an 8 cm air gap (8 °C).

In regions with a hot climate, a ventilated roof is an efficient and non-invasive technique to improve energy performance. Gagliano et al. [29] obtained reductions of 46% and 57% of transmitted heat flux when comparing a ventilated roof to a bare roof with either low or high thermal resistance (0.35

or 1.31 m²·K/W). Based on an experiment with a ventilated roof, Dimoudi et al. (2006) have shown the effectiveness of this technique in Mediterranean countries during summer due to the optimum interaction between the air gap layer and the external ambient conditions. The observed energy saving for cooling needs over 24 hours was greater than 49% compared to a typical roof.

2.4.4.3 Ventilated Facade

The cooling performance of ventilated façades varies with wind and natural convection potential, which are related to the local climate conditions and building orientation. Increasing wall height improves the thermal performance of ventilated façades as the airflow due to the stack effect and the convective transfer's increase. However, the airflow and performance are also increased by perpendicular winds for upwind or downwind façades, compared to parallel winds [31,32].

Based on simulations of a double-skin façade in Belgium in June, Gratia and De Herde [33] concluded that, for a 4 m/s wind speed, the temperature in the double-skin was 10.2 °C lower than for no wind.

A numerical study of a ventilated façade on a typical summer day in Wuhan (China) showed that increasing the air velocity of the cavity to 0.5 m/s from 0.25 m/s could reduce transmitted heat flux through the envelope by 45% [1].

For the subtropical climate of Hong-Kong, Chan et al. [34] have experimented and simulated a transparent double-skin façade composed of an inner-glazing pane and an outer double reflective glazing pane. The annual cooling energy saving was 26% higher than a conventional simple glazing façade.

For the Mediterranean climate of Florence in Italy, an opaque ventilated façade was simulated by Balocco [35]. The results demonstrated that this configuration could reduce summer overheating by 7% and 27.5% at cavity widths of 7 cm and 35 cm, respectively.

2.4.5 Application

Ventilated envelope surfaces can be used to adapt building envelopes to climate change. Experiments have shown that this technique is efficient in mitigating indoor temperatures and the urban heat island effect [23,29,34].

Ventilated double-skin façades have also been developed for cold climates, especially in commercial buildings across Europe. This technique was developing in China for hot-summer and cold-winter zones and has gained acceptance in Europe, North America, and Japan since 1980 [36]. However, the use of some configurations depends on climate change, which modifies the process and the design of the product. For a perforated double-skin façade, Blanco et al. [37] concluded that the optimum rate of perforation depends on the climate conditions. Numerical results for cold and hot climates highlighted an optimum perforation of 30% and 20%, respectively. In addition, the effectiveness of a ventilated double-skin façade depends on its orientation. For example, Barbosa & Ip (2014) recommended a southern orientation (±45°) for the northern hemisphere intending to promote natural ventilation and intensify indoor cooling.

Additionally, ventilated double-skin façades are an efficient passive cooling design for commercial buildings in hot climates as they attenuate solar gain. Based on simulations and performance assessment calculations and measurements in Germany, ventilated double-skin façades are now used in high-rise office buildings. In Belgium, the ventilated double-skin façade is an industrialized concept for which modules are inserted per story [38].

2.4.6 Technology Readiness Level

Envelope ventilation systems are increasingly found as architectural elements in commercial and residential buildings as well as offices.

In recent years, ventilated facade systems have become widespread in various climate zones due to their high energy performance, rich variety of available design solutions, the reduced effect of solar radiation on indoor microclimate, good noise reduction properties, and the possibility of rapid building repair and reconstruction. These systems are mainly used in office buildings, as analyzed in the BESTFAÇADE project [38]; their transparency and lightness make them particularly appropriate for Swedish conditions.

Recently, double-skin façades with venetians blinds have been developed and commercialized. In Austria, double-skin facades with venetian blinds have been used for the refurbishment of a three-story office building in Graz to improve noise and thermal efficiency [38]. Aluminum louvers may also be used given their thermal and architectural advantages (e.g., Glasscon [39]). Ventilated perforated double-skin façades also constitute an emerging technique for advanced buildings. This technique combines a high-quality aesthetic aspect with a high thermal performance to reduce cooling loads during summer (e.g., Accurate Perforating [40]). Perforated cladding is available in different thicknesses and can even be customized to suit a particular construction project. By balancing light and ventilation, perforated facades allow architects to manage the accumulation of interior heat due to solar radiation.

Closed cavity façades (air-tight double-skin façades) have recently been developed [41] and are available on the market (e.g., Linder-Group [42]). This technique increases acoustic efficiency and limits maintenance resulting from damage due to moisture and dust.

Opaque ventilated façades are more common for single-family houses. Their use has been promoted by local standards, like the UNI 11018 [43], together with the assessment of thermal and rain screen performance.

Ventilated roof systems are mainly still in the development phase; nevertheless, some companies offer certified roof ventilation systems for commercial and residential buildings (e.g., Vent-A-Roof [44]).

Ventilated envelope surfaces with phase change material (PCM) are still at the technological development level with macro-encapsulated PCM. Experiments and simulations have highlighted the potential of this system as a cold storage in reducing cooling loads [45,46]. Another technique that is being developed is the naturally ventilated solar roof with a PCM heat sink, which is effective in lowering cooling load by about 50% [47].

2.4.7 References

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2.5 Heat storage and release, including thermal mass, phase-change materials, and ice storage

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2.5.1 Physical principle(s)

A thermal energy storage system stores thermal energy [1] to regulate temperature and improve thermal comfort in a building. In summer it absorbs heat during the day and releases it outside at night, so the building can stay comfortable. In winter it stores the heat during the day to release it at night inside the building to keep the warmness. Thermal energy can be stored as a change in internal energy of a material as sensible heat, latent heat, or thermochemical energy. Sensible heat storage is due to temperature change of material while latent heat storage is due to the phase transformation [2], thermochemical storage depends on the energy absorbed and released in breaking and reforming molecular bonds in a reversible chemical reaction. A thermal energy storage system can use the building's structure (floors, walls, ceilings) as radiant emitters and permit low temperature heating and high temperature cooling [3].

Thermal mass utilization schemes including phase-change materials (PCMs) and off-peak ice storage can be classified as thermal energy storage (TES) systems. By storing and discharging thermal energy (heat), they can reduce peak power demand for heating and cooling, shift peak heating and cooling loads to the low tariff hours, shift indoor air temperature peaks to non-working hours, improve the indoor environment, and efficiently use passive heating and cooling loads [4].

TES systems can also be further distinguished based on whether the heat storage is sensible, latent, or both. Ordinary (single-phase solid) building materials such as concrete and gypsum only storage sensible heat, and their specific heats range from 0.75 to 1 kJ/kg·K. Phase-change materials can store latent heat. For example, paraffin has a latent heat storage capacity of 110 kJ/kg. Therefore, to store the same amount of energy, PCM requires much less mass than single-phase solid materials. Besides the large heat storage potential, the other advantage of PCM is that the temperature remains almost constant during the phase change. This characteristic limits the temperature stratification in the space [4].

2.5.1.1 Thermal mass

In thermal mass heat storage technique, the sensible heat is stored leading to gradual temperature change in the storage medium. The amount of heat that causes a certain temperature change is called heat capacity. Thus, to store high amounts of heat energy, it is desirable that the storage medium has the high thermal capacity and low conductivity. Almost in all building typologies, the sensible heat storage (thermal mass) can be applied as all the material stores the heat when the temperature increases and releases the heat when the temperature decreases. However, it is mainly thermally heavyweight materials that can store high amount of heat such as concrete [5]. In sensible heat storage technique, the heat is stored during the elevated temperatures and released during the relatively colder periods dampening the peak temperatures during a day.

2.5.1.2 PCM

A phase change material (PCM) thermal energy storage system can store more thermal energy per unit volume than a sensible heat storage system [1]. PCMs are capable to reduce the temperature variations by absorbing and releasing the heat from/in an environment. The operating principle of PCMs relies on the state modification in temperature gradients: as the temperature increases, the PCMs are changed from solid to liquid state absorbing and storing the heat energy. Differently, when the temperature drops, the PCMs can release the stored heat to pass from liquid to solid state [6]. The transition can be to the same physical state (i.e., solid to solid) if the crystalline structure of the material changes. Substances are considered PCMs if they satisfy some or all the PCM requirements [7]: (1) a high value of the heat of fusion; (2) a high value of specific heat capacity, which provides additional heat storage and avoids subcooling; (3) chemical stability; (4) a melting temperature which matches the required application; and (5) a high thermal conductivity.

2.5.1.3 Ice storage

The ice-storage cooling device uses chiller to make ice during the off-peak periods when the energy is cheaper and melts during the peak period to fulfil the cooling needs. Thus, it consists of two operation modes namely, charging (off-peak period) and discharging (peak period). During the charging mode, the ice-making chiller produces low temperature glycol loop to freeze the water inside the tank. The glycol loop consists of ice-storage tanks, heat exchangers and pumps. During the discharging, the produced ice starts to melt as the building cooling load increases.

2.5.2 Typologies (classifications) and design parameters

Different types of energy storage systems are shown in Figure 2-8.

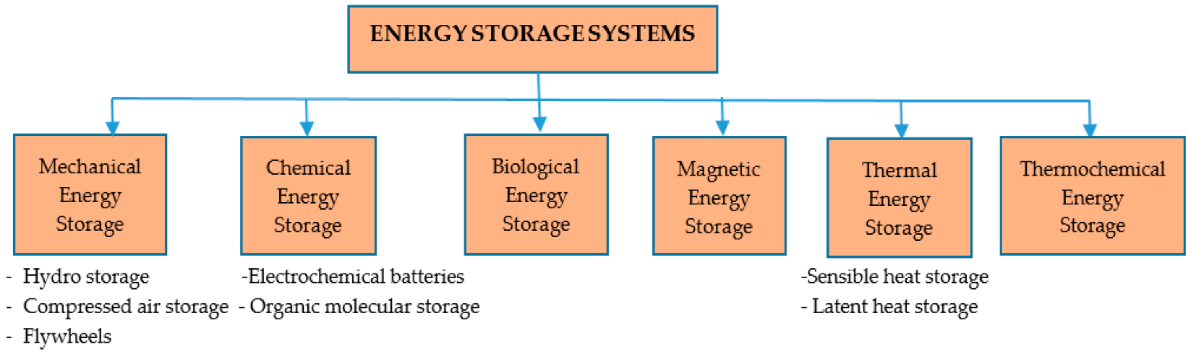


Figure 2-8 Classification of energy storage systems [8]

In addition to the different types of energy storage systems, a comprehensive classification of energy storage materials was developed by Zalba, Marín, Cabeza, & Mehling [9], as shown in Figure 2-9. It classifies solid-liquid PCMs as organic or inorganic, and then according to thermophysical properties and grade (commercial/analytical).

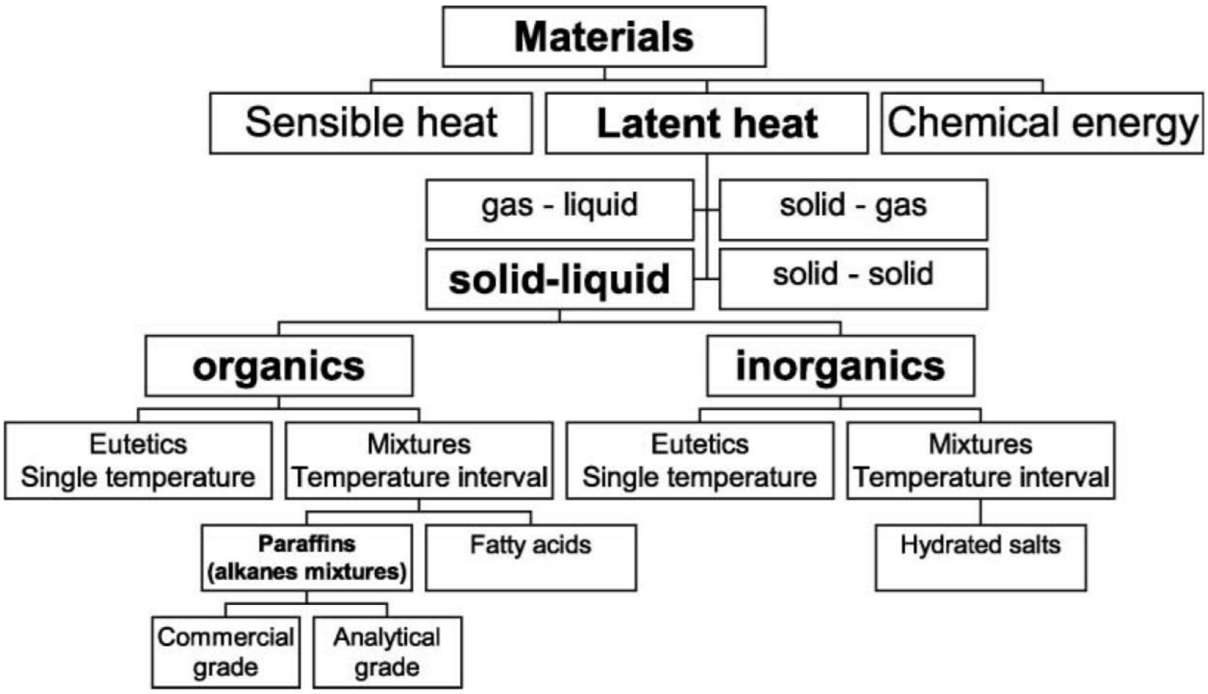


Figure 2-9. Classification of energy storage materials. [9]

Osterman, Tyagi, Butala, Rahim, & Stritih [10] proposed a classification of PCMs used to store thermal energy for cooling (Figure 2-10); this application is also known as “cool storage”, “chill storage”, or “cool thermal storage” [11]. In this study, PCMs are categorized as organic, inorganic, and eutectic materials. Organic materials are further described as fatty acids, paraffin, and non-paraffins. Inorganic materials are divided into salt hydrate and metallics. A eutectic material is a composition of two or more organic or inorganic PCMs. Osterman et al. [10] stated that materials with a melting point between 15 °C and 30 °C are suitable to store chill from air conditioning and free cooling, and to use it to maintain the room temperature. Besides melting point, the authors discussed the following important properties for selecting PCMs to use in cooling storage systems:

- Thermo-physical properties
- Melting point within the range of desired operating temperature
- High latent heat of fusion per unit mass
- High specific heat per unit mass to provide additional sensible heat storage
- High thermal conductivity in both solid and liquid phases
- Small volume change during the phase change process
- Chemical properties
- Completely reversible freeze/melt cycle
- Long term chemical stability
- No corrosiveness to the construction materials
- Non-toxic, non-flammable and non-explosive
- Kinetic properties
- High crystallization rate to meet demand for heat recovery from storage system
- High nucleation rate to avoid supercooling of the liquid phase

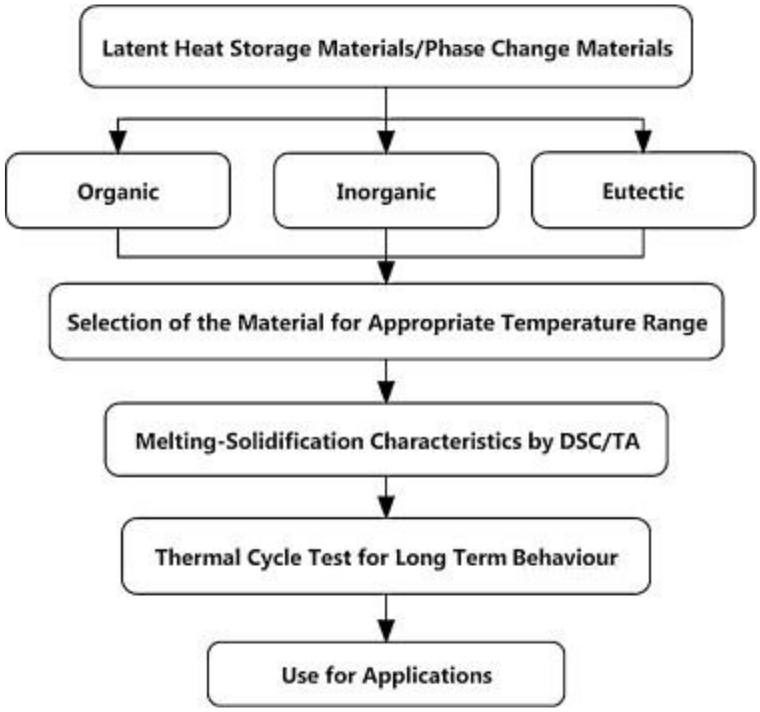


Figure 2-10. Classification and selection process of phase change materials for applications. [10]

2.5.2.1 Thermal mass (without phase change)

Thermal mass can be classified by location (building exterior or interior) and material. For example, walls and roofs are exposed to the outside environment, while internal concrete partitions are not [12]. The simplest form of thermal mass is a concrete slab floor; concrete blocks, tiles, brick, rammed earth, and stone can also be used. Several factors influence the ability of the material to absorb and store heat: (1) high specific heat capacity, which increases the ability of the material to store thermal energy; (2) high thermal conductivity, which keeps the rate at which heat flows in and out in step with the building's daily cycle of heating and cooling; and (3) high density, which increases both mass and thermal mass.

Optimization of thermal mass levels depends on different parameters such as building material properties, building orientation for its location and distribution, thermal insulation, climate condition, occupancy patterns and ventilation [13].

2.5.2.2 PCM

Physical Principle

PCMs can be categorized as organic compounds, inorganic compounds, and eutectics. Each group has its typical range of melting temperature and its range of melting enthalpy [14]. There are several ways to enhance the performance of the PCMs. For example, using metallic fins enhance the thermal conductivity of PCM and the use of suitable PCM thickness can prevent incongruent melting [14].

PCM classification is shown in Figure 2-11. Organic phase change materials can be used as latent heat storage in buildings as they are available in wide range of melting temperatures. Inorganic materials have good thermal conductivity. Eutectics mix different components to produce a material with tailored phase-change properties. Eutectics are divided into three groups according to their component materials: organic–organic, inorganic–organic, and inorganic– inorganic [14].

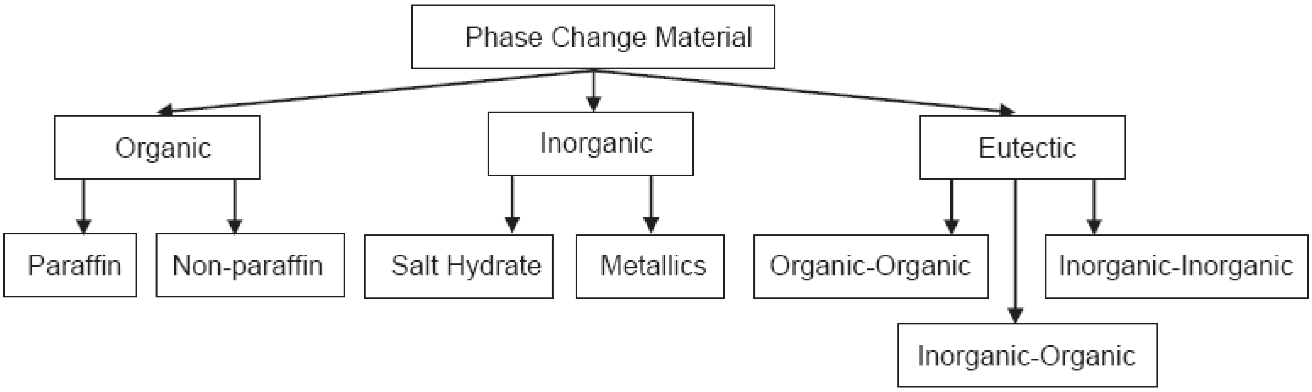


Figure 2-11: PCM classification [14].

Integrating PCM in buildings increases the thermal energy storage capacity of construction elements. PCMs can be installed in wallboards, floors, roof, concrete, and other elements to improve the thermal performance of the building [6] which provides indoor thermal comfort and reduces the energy consumption. The selection of convenient PCMs for different applications depends on several parameters [14]: (1) outdoor climate conditions; (2) characteristics of the PCM, including its melting point and thermo-physical properties; (3) purpose of PCM application; (4) quantity of PCM (effective volume and PCM layer thickness); (5) building operation, including heating and cooling set points, air infiltration rates and internal gains; and (6) orientation and solar reflectance of the surfaces [15].

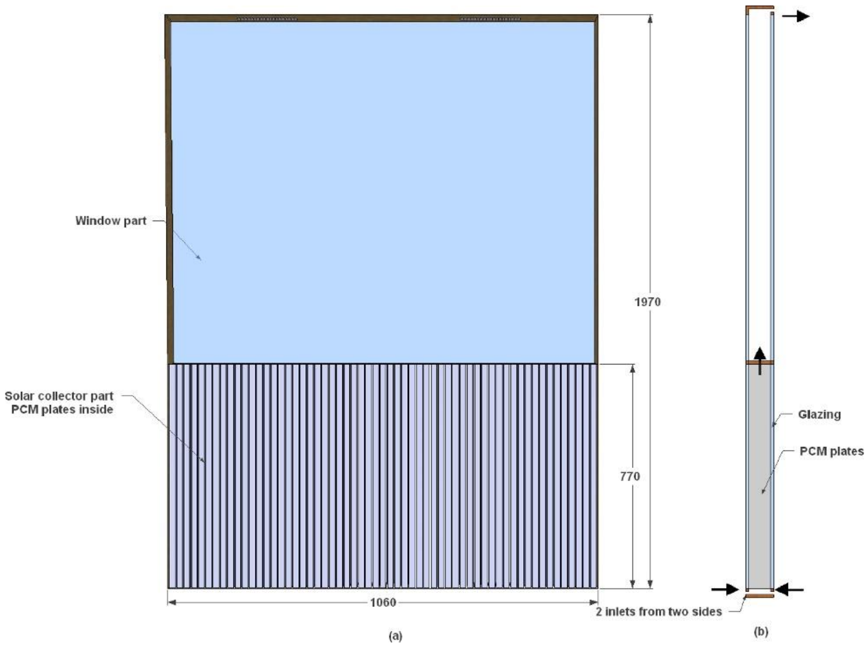
Application of PCMs in building components

Based on several literature reviews [4,16,17], the applications of PCMs in building to reduce cooling demand are listed below.

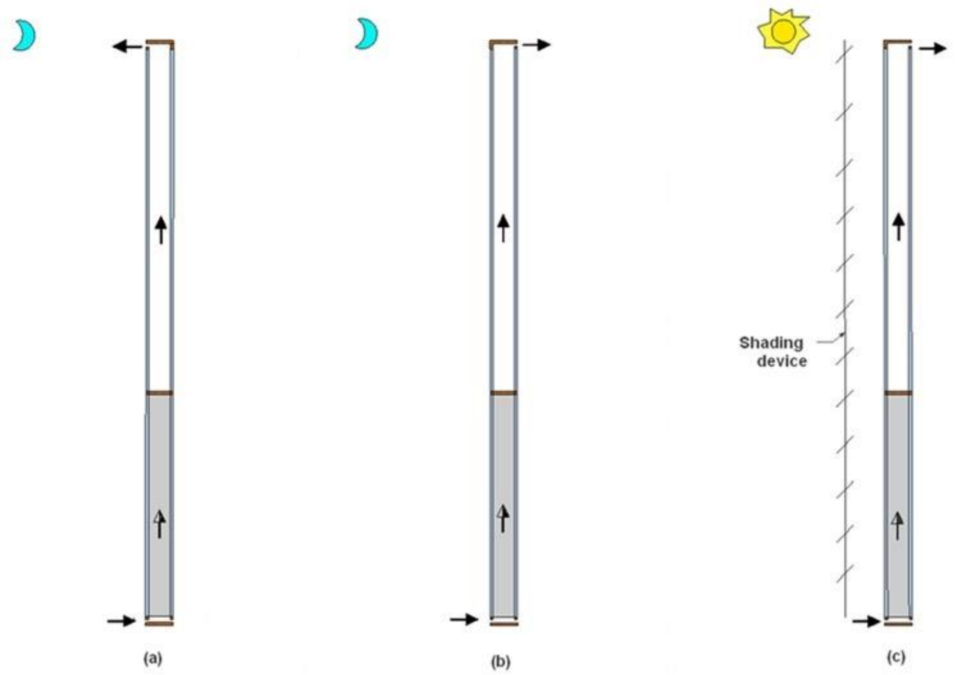
PCMs in construction elements (passive and active). Most studies focus on integrating PCMs with construction elements, such as walls, ceilings, and floors, because large surface areas allow efficient heat transfer within building enclosures. Depending on the approaches to activate the latent heat storage, Pomianowski et al. [4] divides PCM in construction materials into passive and active activation. The passive activation represents that thermal mass is heated or cooled only by indoor temperature fluctuations and does not rely on any mechanical facility or additional energy. The active approach is to embed the water-carrying pipe in the construction elements and use water to remove absorbed heat from thermal mass.

PCMs in glazing, shadings, and blinds. Glazing units, such as conventional windows, glazing façades, and glazing roofs are an essential part of buildings, providing vision, daylight, ventilation, and passive solar gain. However, compared with other building construction, glazing generally has a lower thermal resistance and is a large source of heat loss or heat gain. At the same time, to provide a comfortable indoor environment or achieve energy saving, windows need to block solar heat gain in summer and maximize solar heat gain in winter. One promising technology is to integrate transparent PCMs in the glazing units and ordinary PCMs in solar shading components to absorb part of the solar heat gain.

A new PCM solar air heat exchanger integrated with a ventilated window was developed by Aalborg University [18,19]. In summer, night ventilation is part of the control strategy. Heat is released from the PCM heat exchanger to cold ambient air during the night, and the PCM freezes (solidifies), or "charges". In the daytime, the PCM heat exchanger is used to cool the outdoor air supplied to the room, and the PCM melts (liquifies), or "discharges". Meanwhile, a shading device is used to prevent overheating of the system. The prototype was tested in the laboratory and optimization processes were conducted by a validated numerical model in COMSOL Multiphysics (finite-element analysis physics software). In the climate of Copenhagen (Denmark), the PCM heat exchanger with 10 mm plate thickness shows a stable precooled air temperature and reduce heat gain by ventilation of 3.2 MJ/day. A thinner heat exchanger is recommended for climates in which the duration of outdoor temperature suitable for night cooling is shorter.



(i)



(ii)

Figure 2-12 Ventilated window with a PCM heat exchanger showing (i) Structure of the system; and (ii) Operation strategies of the system in summer with different ventilation modes: (a) night ventilation; (b) night free cooling e; (c) daytime ventilation. [18]

PCMs in furniture. Many current studies on building energy systems assume empty rooms and do not account for the internal thermal inertia, such as that provided by furniture. Johra & Heiselberg [20] pointed out the furnishing elements and other internal content present a large surface area for heat exchange with the indoor environment and the large surface area can be used for latent heat thermal energy storage with the integration of PCM. Only a few publications considered PCMs in furniture. Rodriguez-Ubinas, Ruiz-Valero, Vega, & Neila [21] proposed this concept in the 2007 American Solar Decathlon. Their system consists of an air heat exchanger with macro-encapsulated PCM, and it is placed underneath box-type living-room or bedroom furniture. However, system performance has not been documented. The performance of furniture integrated PCMs was investigated by Johra, Heiselberg, & Dréau [22] in the Danish climate. This study explored the influence of thermal mass from PCMs and furniture elements on the space heating energy flexibility of buildings. The simulation results demonstrated that the integration of PCMs in inner surface wallboards and in furniture elements are good solutions to increase the effective thermal inertia of lightweight structure dwellings (effective thermal inertia refers to “areal heat capacity” in ISO 13786 [23], which is defined as heat capacity divided by area of element). The PCM wallboards could increase energy flexibility index (capacity to shift in time energy use from high-price periods to low-price periods while maintaining indoor thermal comfort) by 111% and 35% in the cases of low-insulation and high-insulation light-structure houses, respectively. Furniture with integrated PCM could increase the energy flexibility index by up to 87% and 30% in the cases of low-insulation and high-insulation light-structure houses, respectively. Energy flexibility index is defined in Eq. (1).

HVAC components/heat exchanger. The integration of ventilation and air conditioning systems with latent heat storage was documented by some studies. It can be further divided into air-based systems and water-based systems. The air-based system is usually connected with ventilation, where the PCM's discharging process (melting) is activated by warm air passing through the PCM unit and the supply air is cooled to comfort temperature. A night ventilation system using heat pipes embedded in PCM was developed and tested by Turnpenny, Etheridge, & Reay [24]. Measurement results showed that a large temperature difference between air and PCM (more than 15 °C) was needed to cause the phase change within a practical time span (7 - 10 h). If the temperature difference dropped to 5 °C (more realistic in practice), the heat transfer between air and PCM would drop, extending the charging and discharging time to 19 h and reducing heat transfer below 40 W. The maximum temperature reduction of ventilated air is 4.5 °C in Turnpenny's study. In that case, the number of units able to cover heat gains in the ordinary office room would be large and difficult to install in practice. Yang, Shi, Wei, Du, & Wang [25] developed a cylindrical PCM-to-air heat exchanger (PAHE) that uses a cylindrical annulus composed of PCM to regulate temperature of the supply air temperature before it enters the space. The PAHE system can be installed independent of building elements, and the forced convection in the tube enhances the heat exchange between PCM and air. By simulating the system performance under the climate of Chongqing, China (hot summer and cold winter climate zone), the authors found out the PAHE could stabilize the supply air temperature and the maximum temperature reduction could reach 5.4 °C.

The water-based system uses water as the heat carrier to remove sensible heat. A tube-in-tank PCM energy storage system was developed by Tay, Belusko, & Bruno [26], and this storage system was coupled to a low energy night cooling system using a cooling tower. This study optimized the tube parameters to increase storage effectiveness based on the validated numerical model. The energy storage effectiveness of the PCM system could reach 68% to 75%, holding more than 18 times the heat that could be stored by a sensible storage system with the same volume. The energy storage effectiveness represents the useful stored energy of a PCM system, and depends on the freezing effectiveness, melting effectiveness, and tube diameter.

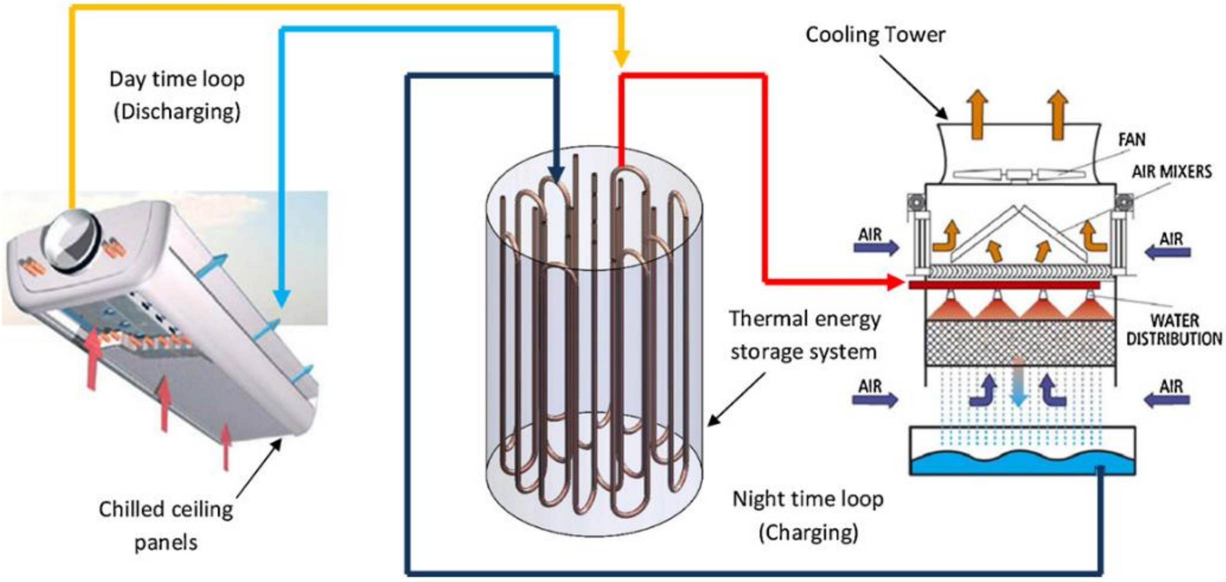


Figure 2-13 Night-time cooling using a tube-in-tank PCM energy storage system [26]

The cooling performance of a PCM system is affected by many parameters, such as the airflow rate, the inlet and exhaust air temperature of the storage unit, the thermos-physical properties and encapsulation thickness of the PCM, and the PCM's melting temperature Souayfane, Fardoun, & Biwole [14]. When PCM is coupled with passive systems, the free cooling performance strongly depends on the outdoor temperature and the temperature variation during the day. If the night temperature does not decrease below the PCM's phase-change temperature, the PCM cannot fully solidify, and the latent heat storage cannot be activated. Active systems are more efficient than passive systems. Because the charge/discharge process is fully controlled and its execution does not fully depend on the outdoor temperature, the thermal energy storage can be obtained when it is required.

2.5.2.3 Ice storage

Most common ice storage systems can be classified as ice harvesting, ice-on-coil external melt, ice-on-coil internal melt, or encapsulated ice [27]. In ice harvesting systems, ice formed on an evaporator surface is periodically released into a tank filled with return water to be cooled by ice. In an ice-on-coil external melt system, the ice is melted from the outside by circulating the warm return water over the pipes discharging storage and built from the inside by circulating negative temperature coolant through pipes; in an ice-on-coil internal melt system, ice is melted from the inside by circulating warm coolant through pipes and built from the inside. Encapsulated ice systems consist of a tank containing many capsules filled with water; during both ice building and ice melting, coolant flows around the capsules. The most common commercial technology for different applications is the internal melt system [27].

Ice storage systems can be designed and operated in full or partial storage. Full storage systems are designed to utilize the stored cooling to shift all building cooling loads from the on-peak period to the off-peak period of the design day. In a partial storage system, the chiller and storage together meet the on-peak building cooling load, allowing the chiller to run continuously at its full capacity [28].

2.5.3 Benefits and limitations

Hu et al. [18] discuss the limitation of PCMs. The main drawback of PCM is its low thermal conductivity. The heat is absorbed by the surface layer of PCM, but heat flow is impeded by low thermal conductivity, slowing melting. This limits the useful thickness of a PCM layer. Another drawback of PCM is its thermal expansion. The PCM thermal expansion could cause leakage in liquid phases [16].

2.5.3.1 Thermal mass

Thermal mass can help naturally in temperature balancing when days are warm, but nights are still cool in spring and fall; this increases the thermal comfort and reduces the need for heating and cooling. While the "greenhouse" effect can trap large amounts of heat during the day, this heat can also be quickly and easily lost unless thermal mass is also used to store the heat. Higher thermal mass is very beneficial in reducing the peak internal temperatures. On the other hand, higher thermal mass slows down both heating and cooling of the building. Also, elevated internal temperatures can be extended when the outdoor temperature decreases. It is on account of that the stored heat might be re-radiated to the indoor environment.

2.5.3.2 PCM

The main advantages of PCMs can be categorized into: (a) environmental benefits such as the potential to be recycled, (b) thermal benefits, such as high specific heat capacity and thermal conductivity, and (c) economic benefits, as they are cost effective materials. One issue with the use of PCMs integrated with building materials is that there is little to no way to perform non-intrusive maintenance on the PCM system. Thus, once the PCM stops being effective, the replacement of PCM without performing any destructive methods to access it is very difficult. Many of the issues associated with PCMs lead to the material degrading over time, rendering it useless after thousands of freeze/melt cycles [29]. Another disadvantage is supercooling which is defined as the state where a liquid solidifies below its normal freezing point, delaying solidification. For example, salt hydrates tend to supercool before freezing during the extraction of stored heat. This reduces the service life of the material and can prevent heat recovery [29].

2.5.3.3 Ice storage

Ice thermal storage shows several advantages: the heat capacity of melting ice is high, the cost of water is negligible compared to that of other technologies [30], and this technology is mature in office buildings. There are some limitations for the two aforementioned strategies/designs in ice storage systems. Full ice storage requires a large storage volume and a large chiller, while partial ice storage insufficiently shifts demand from peak to off-peak as chiller capacity is less than design load. The chiller meets part of the on-peak cooling load and storage. Ice storage consists of two modes of operation, charging mode (ice making) during the off-peak period to freeze the water inside the tank and discharging mode (ice melting) during the peak periods [31]. Ice storage systems are mainly used to offer flexibility in the electricity consumption (allowing for electricity peak shaving and electricity load shifting, therefore decreasing the operating cost of the cooling plant), as a back-up cooling solutions system in case of power outages or breakdown of the chiller [32].

2.5.4 Performance

2.5.4.1 Performance indicators

The performance of a thermal storage system is characterized by its storage capacity (in thermal kWh) and its ability to provide cooling or heating power (in thermal kW) as a function of the state of charge of the storage. Having still some available cooling capacity in the storage but with a too low available rate of heat transfer can prevent the storage from fully meeting the building cooling demand. For instance, with internal melting ice-on-coils systems, the delivered cooling power is greatest at the beginning of the discharge process. Then, as the ice melts, the liquid water layer introduces an additional thermal resistance between the heat transfer fluid (glycol water) and the ice, yielding a decrease of the overall heat transfer coefficient. The delivered thermal power can be controlled by varying the glycol water flow rate [33]. A similar penalty occurs during ice building because of the additional thermal resistance introduced by the ice layer. However, the penalty is lower during charging than discharging since the ice conductivity is higher than the liquid water conductivity [33].

To get large thermal power throughout charging and discharging processes, the convective heat transfer coefficient on the heat transfer fluid side must be maximized by appropriate design (shape and size of PCM container). The thermal conductivity of PCMs other than water can be increased by doping the PCM with particles of metal or graphite. Another solution lies in developing ice-phobic heat exchangers that prevent the built ice to stick on the freezing surface (AES 2020). Finally, with external melting ice-on-coils systems, during discharging, the heat transfer fluid (pure water) enters in direct contact with the ice. Such configurations limit the heat transfer resistance between the heat transfer fluid and the ice.

Also, an appropriate control strategy should prevent the storage such as ice storage and TABS from being depleted too early during the day. Early depletion could cause overheating in the building or additional use of the vapor compression chiller.

Using an ice storage system permits decreasing the size of the cooling plant (chillers, cooling towers, etc.). Also, ice storage systems can meet the building's cooling load in case of breakdown of the chiller.

Key performance indicators collected by Cabeza et al. [34] for thermal energy storage (TES) can be divided into those for (1) sensible heat storage, (2) latent heat storage, (3) thermochemical material (TCM) energy storage technology, and (4) system. All KPIs related to TES are shown in Table 2-5

Table 2-5 KPIs defined for TES in buildings [34]

Description	Metric		BASELINE	TARGETS	
			2012	2016	2020
1. Sensible heat storage	KPI-1	Cost of containment of 1000 L tank (excl. insulation and VAT)	400-900 €	350-800 €	300-700 €
	KPI-2	Heat loss related to storage vessel with capacity of 1000 L	150–200 W	76 W	56 W
	KPI-3	Cost to customer (excl. VAT) of high-performance insulation with thermal resistance (Rc) = 7 $m^2 \cdot K/W$	300 €/m^2	230 €/m^2	<100 €/m^2
	KPI-4	Underground Thermal Energy Storage (UTES) energy efficiency, defined as the (heat out)/ (heat in)	60%	65%	75%
	KPI-5	Lifetime of the UTES at elevated temperature (years)	10-25	15-30	20-30
	KPI-6	UTES maintenance cost as share of operational costs	4-8%	3-6%	2-4%
	KPI-7	Heat transfer and storage fluids: viscosity of the fluid (related to the energy required for pumping)	Water: 1.002 mPa·s Slurries: > 1 mPa·s Mineral oil (Therminol VP-01 at 400 °C): 0.39049 µPa·s Silicone (Syltherm 800 at 400 °C): 0.25 mPa·s Molten salts: 31–543.5 µPa·s	25% reduction	30% reduction
	KPI-8	Annual electricity consumption for pumping in DHW (1) systems	75 kW·h	60 kW·h	50 kW·h
	KPI-9	Energy density (inversely related with the storage volume)	Water at 20 °C: 1000 kg/m^3 Slurries: n.a. Mineral Oil at 400 °C: 694 kg/m^3 Silicone at 400 °C: 547 kg/m^3 Molten salts at 400 °C: 1787 kg/m^3	20% reduction of storage volume through increase of energy density	30% reduction of storage volume through increase of energy density

Description	Metric		BASELINE	TARGETS	
			2012	2016	2020
2. Latent heat storage	KPI-10	Stable, micro-encapsulated salt hydrate PCM	Only paraffin PCM available; price over 8 €/kg	Novel materials in pilot applications	Production technology optimized; material available at < 2 €/kg
	KPI-11	Micro-encapsulated PCM for medium and high temperature	Some pilot plants with bulk PCM for high temperature	Several materials developed, pilot applications	Production technology developed; materials available on a large scale at < 2 €/kg
	KPI-12	Novel heat exchangers including PCM	Few concepts	Proof of concept for at least 5 concepts; typical peak power 25 kW	Several applications commercialized
	KPI-13	New sensors for PCM state of charge	First concepts (TRL 1) (2)	Industrial prototypes (TRL 5)	State of the art (TRL 9)
3. TCM	KPI-14	Level of maturity TC (3) solar collector concepts	First concepts (TRL 1)	Industrial prototypes (TRL 5)	State of the art (TRL 9)
	KPI-15	New sensors for TCM state of charge	First concepts (TRL 1)	Industrial prototypes (TRL 5)	State of the art (TRL 9)
	KPI-16	Improved seasonal solar TCM	60 kW·h/m^{3}system	160 kW·h/m^{3}system	250 kW·h/m^{3}system
4. System	KPI-17	Installation time reduction	–	30%	–
	KPI-18	Material cost reduction for the end-user	–	20%	–
	KPI-19	Human interventions for maintenance/reparation reduction	–	20%	–
	KPI-20	Reference heat cost of DHC (4) systems	200-50 €/MW·h	90-40 €/MW·h	70-35 €/MW·h
	KPI-21	Reference energy efficiency of DHC systems	Baseline index: 100	110	120

(1) (DHW): Domestic Hot Water, (2) (TRL): Technology Readiness Level, (3) (TC): Thermal Collector, (4) (DHC): Domestic Heating and Cooling

The energy flexibility index assesses the capacity to shift in time energy use from high-price periods to low-price periods whilst ensuring good indoor thermal comfort. The index is calculated from the following equation [22,35]:

$$F = \left[\left(1 - \frac{\%High}{\%High_{\mathrm{ref}}}\right) + \left(1 - \frac{\%Medium}{\%Medium_{\mathrm{ref}}}\right)\right] \times \frac{100}{2} \quad (1)$$

where %High and %Medium are the percentages of annual cooling energy (relatively to the total annual cooling needs) used during high and medium price periods respectively when the heat storage strategy is operational. Equivalently, %Highref and %Mediumref are the percentages of annual cooling energy for the reference scenario (no heat storage strategy).

From an economic perspective, both the capital cost of the PCM and the electricity tariff are important to assess the potential application of PCMs in buildings. The economic evaluation was done by using the Static Payback period (SPP) and is given by Eq. (2) [36].

$$\mathrm{SPP} = \frac{C_{\mathrm{PCM}}}{S} \quad (2)$$

where CPCM is the extra initial investment for PCM application and S is the income generated from energy savings.

The thermal performance was evaluated by Kenzhekhanov et al. [36] using the concepts of average temperature fluctuation reduction (ATFR), maximum temperature reduction (MTR), and discomfort hours. ATFR was used to estimate the monthly PCM performance and determine the periods in which it worked best. MTR was used to estimate the effect of PCM on maximum air temperature reduction during different seasons (swing and summer), while the concept of discomfort hours was used to investigate the effect of PCM on human thermal comfort.

2.5.4.2 Thermal and energy performance

PCM can reduce the HVAC cooling load in a building if an appropriate phase-change temperature and high storage density is chosen [37]. Many studies showed that the ice-storage cooling provides a cost-effective solution for traditional air-conditioning systems by shifting the peak period daytime (10 am to 8 pm local time) power demand to the off-peak nighttime (8 pm to 10 am) [38–42]. On the other hand, it may consume more natural resources than the conventional cooling systems for two reasons: (1) coefficient of performance is lower than that of conventional conditioning systems, and (2) the natural resource consumption to generate same amount of electricity in off-peak hours is more than in the peak hours [41]. But also, it reduces the natural resource consumption for generating a kWh of electricity by increasing the load of peak generating unit during off-peak hours. It is due to the fact during the off-peak periods, peak unit is operated at a load that is far lower than the design value. Although the peak regulating unit has good operating characteristics under different loads, it has low efficiency when it is not operated under design load and its coal consumption for generating a kW h electricity will increase as load decreases [41]. From this perspective, applying ITS air conditioning system will decrease the natural resource consumption of the system which consumes the electricity supplied by the peak regulating unit. As a result, an evaluation is needed to assess the impact of ice-storage implementation in natural resource consumption prior to application [41]. Moreover, ice-storage systems allow for self-consuming electricity from photovoltaic panels [43]. In ice-storage conditioners, the air does not contact the water or ice, so the inflow air quality is not altered before entering the cooling space [44].

Thermal mass cooling has practically constant lifetime performance. On the other hand, the performance of a PCM may decrease over time, depending on the material and its compatibility with its container. For instance, non-organic PCM materials such as salt hydrates corrode metals and metal oxides [37]. Also, they may experience volumetric changes after each phase transition. As for organic materials, such as fatty acids and paraffin, may dissolve with some organic capsule materials and some are flammable. The repeated heating and cooling processes during practical cold storage systems needs higher standard of stability eliminating corrosiveness and dissolubility [37]. Therefore, one should select a PCM that can sustain many freezing/melting cycles without degradation. The range of efficient service life for ice-storage system is estimated to be 7 to 20 years depending upon the type of system [45].

A summary of PCM application in building environment and their performance is presented in Table 2-6.

Table 2-6 Summary of recent studies of PCMs application and performance

Type of PCM	Climate	Building typologies	HVAC solution	Evaluation method	Performance	Ref
PCM plasterboard (Knauf comfort board) Melting point: 25 °C	25 cities in different climatic zones	Lightweight relocatable residential building	A packaged terminal heat pump with additional heating coil	EnergyPlus	Annual overall electricity energy savings (heating + cooling) range 1% to 53% depending on climate Annual cooling energy saving (electricity) range from 6 kWh to 133 kWh depending on climate Significant potential in arid and warm temperature climate Select proper PCM melting point is critical	[46]
PCM integrated in furnishing; PCM wallboards (Energain®) Melting point: 22 °C	Denmark (design reference year weather)	Light, medium, heavy (30, 50, 100 Wh/K·m²) Light passive, medium passive, heavy passive (30, 50, or 100 Wh/K·m², but high insulation)	Heating: radiator, floor heating (only heating demand is discussed)	Simulink	PCM wallboard increased the energy flexibility index by 111% in low-insulation lightweight houses and by 35% in high-insulation lightweight houses Furniture with PCM increased the energy flexibility index by 87% in low-insulation lightweight houses and by 30% in high-insulation lightweight houses	[22]
PCM cool roof Melting point: 25 °C, 30 °C, 34 °C, 44 °C	Gangdong-gu district, Seoul, Korea	Lab with dimension of 2.5 m × 2.5 m × 2.5 m		Experiment and CFD Simulation	Measurement indicated PCM with 44 °C melting point is most appropriate in Seoul Reduction on roof surface temperature 2.5 °C in winter, 4.7 °C in transition season, 5.5 °C in summer	[47]
PCM-air heat exchanger coupled with ventilated window paraffin wax 22, Melting point: 22 °C	Copenhagen, Denmark	Component level	Ventilated window, night ventilation	Experiment and COMSOL	10 mm plate: energy savings in precooling mode is 3.19 MJ/day, discharge efficiency of heat exchanger is 89% 5 mm plate: energy saving 2.5 MJ/day, discharge efficiency 90%	[18]

Type of PCM	Climate	Building typologies	HVAC solution	Evaluation method	Performance	Ref
PCM–air heat exchanger incorporating “OP25E” PCM Melting point: 25 °C	Chongqing, China (hot summer and cold winter)	Component level	Ventilation cooling	Experiment and numerical	Simulation from May to Oct, average air temperature reduction 2.5 °C, max air temperature reduction 5.4 °C	[25]
PCM in inner layer of building envelope 9 types of PCMs with temperature spectrum 19 -27 °C	Eight cities located in subarctic climates: Anchorage (USA), Fort McMurray (Canada), Val-d’Or (Canada), Arkhangelsk (Russia), Bratsk (Russia), Oulu (Finland), Surgut (Russia), and Umea (Sweden)	Four-story multi-family residential apartment	PTHP (Packaged terminal heat pump) HVAC system was used	DesignBuilder	In warm period (Sep to Apr), average temperature fluctuation reduction indicator (ATFR) ranged 1.6-2.7 °C. Discomfort hour reduction in summer 110-430 h. ATFR shows that in summer PCMs with higher melting temperatures work efficiently, while in the transient season PCMs with lower melting temperatures work efficiently Discomfort hour reduction indicated PCM21 is the best in transient season, PCM23 the best in summer PCM in range of 23-24 °C has the highest energy saving (4 – 10 MWh/y per city) Economic analysis shows payback period of 16 - 32 y Environment analysis shows using PCM could reduce CO_2 emissions 0.089 - 4.8 t/y per city	[36]

2.5.5 Application

2.5.5.1 Building typology

Lightweight buildings tend to experience frequent indoor air temperature fluctuations in the heating and cooling seasons due to lack of sufficient thermal mass in the construction; this results in discomfort and high energy consumption. The application of PCM has been suggested to be a promising solution to control the indoor thermal condition [22,46,48]. Johra et al. [22] found out the application of PCM wallboards could increase the energy flexibility index by 111%, 18%, and 4% in lightweight, medium weight, and heavyweight buildings (thermal inertias 30, 50, and 100 $Wh/K \cdot m^2$), respectively.

The traditional thermal mass materials, such as brick and concrete are not appropriate choices for the renovation of lightweight buildings because they are heavy. Their bulkiness also diminishes the space that can be occupied. Therefore, PCMs integrated with indoor content such as indoor items/furniture, PCM integrated with furnitures, and PCM wallboards are good options for building renovation.

It is possible to implement thermal mass cooling technology either passively (combined with natural ventilation) or actively (within a thermally activated building system (TABS) [49]. Thermal mass alone may not yield acceptable thermal comfort in the buildings. Passive usage of thermal mass is usually combined with night ventilation [49]. Night ventilation in thermally massive buildings is very effective in lowering the indoor maximum temperatures below the outdoor temperature maxima, especially during the heatwave periods [50]. If the heating or cooling loads fluctuate quickly, fast-reacting HVAC systems (e.g., fan coil units) may be needed to compensate for the slow reactions of thermal mass cooling technology.

Thermal diffusivity is the rate of temperature spread through a material [51] between the cold and hot ends which can be calculated by dividing conductivity by density and specific heat [52]. For a known material or wall thickness, thermal diffusivity captures both the thermal mass of the wall and the heat flow rate through the wall for a given temperature difference between internal and external faces [53]. Thus, it is one of the main tools to quantify the thermal mass benefit of the building envelope in different climates [53]. In a cold climate, conductivity plays the main role. In a mild or marine climate, there is a trade-off between using material with low diffusivity at higher conductivity instead of the material with lower conductivity at higher diffusivity [53]. Generally, at the same conductivity using material with low diffusivity (higher thermal mass) has energy-saving impacts. Thermal mass incorporated with natural ventilation can reduce overheating effects without compromising energy efficiency efforts regardless of the building type [54]. However, there should be a way to appropriately integrate natural ventilation and building thermal mass utilization.

PCMs can be installed in the building through passive (building envelope) or active (HVAC) systems. It means that both free-running and mechanically cooled buildings can be equipped with PCMs to reducing energy consumption. Low-mass buildings can be converted to the heavy-mass buildings by using PCM in the building envelope. PCM material can be used in both new and existing buildings to save energy. It can be incorporated in the building via either addition or substitution. PCM can be integrated into building materials and the building envelope in several ways [55]:

It can be directly applied to building materials in the form of liquid or powder.

In the immersion method the building material is dipped into the PCM absorbing it into its holes.

It can be implemented through macro-encapsulation/micro-encapsulation processes, wherein the PCM material is encapsulated in a container or enclosed in a thin, sealed, and high molecular weight polymetric film.

In shape stabilized PCMs, PCM (e.g., paraffin) is dispersed in supporting material (e.g., high-density polyethylene) which is in a different phase from the PCM to form a stable form of composite material.

Conventional construction materials can be used as containers for PCM materials.

2.5.5.2 Climate

Climatic is one of the major factors influencing the efficient application of PCMs, especially for the passive application of PCM. It is important to choose PCM with a suitable melting temperature based on the surrounding climate (Souayfane et al., 2016). If the melting temperature is too low, it is difficult to maintain the indoor air temperature at a comfortable level during the night; if the melting temperature is too high, the quantity of solar radiation heat stored by the PCM will be reduced in the daytime [56]. In addition, it is important to consider the outdoor temperature variation during the year. A low melting point might lead to insufficient use of PCM in the hottest month or heat waves, while a too-high melting point will result in marginal feasibility in the transition seasons.

In addition, choice of PCM depends on the application—to save heating or cooling energy, or both. A database has been developed by Cabeza, Castell, Barreneche, Gracia, & Fernández, (2011) to guide PCM selection by application. For cooling applications in buildings, the melting point is up to 21 °C. If the aim is to control indoor comfort temperature, the melting point ranges between 20 °C to 30 °C is commonly used in passive systems. The melting point of 1-3 °C above the average room temperature is optimal for diurnal heat storage. For free cooling system design, a PCM melting point between 19 °C and 24 °C is suitable to apply in the spaces with indoor environment of 23-27 °C in summer conditions [57]. Souayfane et al. (2016) and Kenzhekhanov et al. (2020) concluded that PCM with a higher melting point is more suited to environments with high outdoor temperatures, while PCM with a lower melting point is more suited to environments with low outdoor temperatures.

The efficiency of the PCM cooling depends on the PCM layer thickness, location of application in the building, thermostat range, and surface area [58]. PCM efficiency depends on the climatic zone. It has been found to save energy in regions with cold temperate, mild temperate, and warm temperate climates, but has less effect in hot and humid climatic zones [58]. Thermal mass utilization reduces annual HVAC source energy consumption by 22%, 4.9%, 3,9% and 1.5% in mild marine, hot/dry, hot/humid, and cold climates respectively [53].

Climate change might influence the efficiency of PCM cooling technologies designed for the current climate [59]. Impacts of climate change on PCM effectiveness vary depending on the region [58].

The energy saving benefit of a PCM varies significantly on its melting point and the time of the year [59]. A PCM melting point outside the comfort range is not effective in reducing the energy consumption [58].

Off-peak cool storage systems can save energy in both existing and new buildings. Cool storage systems can be applied in most buildings with the space cooling system [60]. In climatic zones with high temperature and humidity in summer, the cooling potential of condenser is deteriorated resulting in high chiller energy consumption.

In hot and humid climates, the chiller cannot beneficiate from lower outdoor air temperature, thus have higher energy consumption with respect to the regions with low summer temperatures [61]. According to Brown [60], off-peak cool storage technology originally designed for the integration with chiller in larger buildings, and the initial usage of off-peak cool storage was for the applications with relatively high ratios of peak to average cooling demand, as in churches, dairies, arenas, and theaters. Integration of cool storages with roof-mounted, direct-expansion cooling systems made it possible to be utilized in smaller residential buildings.

Ice storage systems are currently used mainly in large buildings (commercial buildings, hospitals, schools, etc.). However, some research projects are currently investigating their use in residential buildings [43].

2.5.6 Technology readiness level

Common materials for thermal mass utilization are concrete or filled concrete block, stone or masonry, bricks, and tiles. These materials are available all around the world as they do not necessarily require special technology to be produced.

TES systems based on sensible heat such as water tank or underground storage methods are widely available, but devices based on latent heat such as PCM or TCM are mostly under development and study. The higher costs of PCMs compared to sensible TES technologies is another barrier to widely enter the markets. The cost difference between sensible TES and PCM is even higher in active applications. Other issues are related to the stability of the PCM materials. Further research and development are needed in PCM and TCM to adopt these technologies in more cost-effective manner.

Pomianowski et al. [4] mentioned that while many studies have published, the competitiveness of PCM application in buildings to other available passive and energy-saving solutions is still doubtful. Even though some of the conceptual investigations have evolved into the first available commercialized products, most of the concepts are still in the prototype stage, and PCM applications are not “broadly” used in the buildings.

Vigna, Bianco, Goia, & Serra [62] concluded that the Technology Readiness Level (TRL) of PCM in building envelopes can be assessed as being between L4 to L6, which means the technologies are in the validation phase in laboratories and prototype are tested in a relevant environment.

Using off-peak ice storage technology goes back to 400 BC when Iranian engineers first invented the “Yakhchal” evaporative coolers [63]. Advances in technology integrated the off-peak ice storage into the air-conditioning systems. Nowadays, in most countries the air-conditioning manufacturers are implementing this technique in their products if there is a demand for it in the market. As a result, it can be counted as an available technology around the world even in the remote areas.

2.5.7 References

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3 Remove sensible heat from indoor environments

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3.1 Introduction

To reduce indoor temperatures, dissipative techniques may be adopted to remove sensible heat from the indoor environment. In accordance with the objectives of this work, this section focuses on low-energy cooling solutions and high-performance systems for sensible heat dissipation. Among them, natural and hybrid cooling dissipative techniques mainly refer to the exploitation of natural heat sink potential to reduce the temperature of fluid instead of activating a mechanical heat-transfer system. The main difference between a natural and a hybrid solution concerns how the circulation fluid is driven being natural or mechanical circulated. Nevertheless, hybrid solutions, such as hybrid ventilation, are generally used to define two-mode systems, in which a smart control allows to automatically choose between natural and mechanical driving forces [1] minimizing energy consumptions but maintaining indoor comfort conditions. Concerning natural heat sinks it is possible to mention air (e.g., night ventilation of thermal masses), water (e.g., passive downdraught Evaporative cooling), ground (e.g., heat-to-fluid heat exchangers), and sky (e.g., radiative exchange to the sky) [2,3]. For each sink, a specific series of cooling techniques have been developed concerning respectively ventilative cooling, Evaporative cooling, ground cooling and radiative cooling, even if combinations of heat sinks are often adopted [4]. For example, all the first three natural sinks may be adopted to dissipate the heat from a primary air flow increasing the potential and the number of activation hours of ventilative cooling techniques. In addition, a focus on night sky radiative cooling is also included considering both passive and active technologies. In addition to natural dissipative solutions, the cooling sensible heat dissipation toolbox includes additional active cooling solutions such as high-temperature cooling systems – i.e., radiant cooling and chill beam –, desiccant cooling systems and solar cooling solutions, and refrigerators.

3.2 Ventilative cooling

3.2.1 Physical Principles

Ventilative Cooling (VC) is defined as the application of the cooling capacity of the outdoor air to reduce or eliminate the cooling energy demands of buildings while guaranteeing a comfortable indoor thermal environment.

3.2.2 Typologies and Design Parameters

Different strategies and solutions may be selected when designing ventilative cooling. Ventilative Cooling can be achieved by natural or mechanical ventilation systems or a combination of both. To identify the most appropriate system for a particular application, a multidimensional approach to the design of the ventilative cooling should be adopted by considering all variables influencing the performance of the system.

The most common techniques in ventilative cooling are based on the optimization of the potential of daytime and nighttime ventilation (Heiselberg, 2018). Some studies [5,6] group ventilative cooling into daytime comfort ventilation (or direct cooling) and night cooling (indirect cooling). Daytime comfort ventilation (daytime ventilative cooling) introduces outdoor airflow through the building during the day to directly remove heat gains. It aims to improve the occupant's thermal comfort via convective and evaporative heat transfer and by decreasing indoor air temperature. While night cooling utilizes the building's thermal mass during the night, thermal mass works as a heat sink during the occupied period. The type of installed ventilation system and ventilation control strategy depends mainly on regulation requirements, climatic conditions, installation, and operational cost, building and site characteristics, thermal loads, and design preferences [7].

The effectiveness of ventilative cooling strategies mainly depends on the available heat sinks (external thermal mass) with pronounced temperature gradients between the indoor and outdoor and coupling between the thermal mass and sink [8,9]. Ventilative cooling can be provided through active and passive methods.

The potential of thermal energy storage in reducing heating and cooling energy demands of buildings and improving the comfort of building users has received increased interest among the research community in recent years [10]. Latent thermal energy storage (LTES) utilizes the heat exchanged in materials phase change [11]. LTES can provide more energy per volume compared to sensible energy storages, thus it is one of the promising solutions in buildings either integrated into the building envelope (passive solution) or in ventilation systems to reduce cooling or heating demand [12,13]. Active LTES integrated in ventilation system has received considerable attention during the last two decades [11]. as it is capable overcoming some of the limitations of passive systems because of the increased heat transfer [11].

Phase Changing Materials (PCM) through storing and discharging thermal energy can reduce peak power load for heating and cooling, shift peak heating and cooling loads to the low tariff hours, shift temperature peaks to non-working hours and improve the indoor environment [14]. Depending on the approaches adopted to activate the latent heat storage of PCMs, Pomianowski et al. [14] divide PCM into passive and active activations. The passive activation represents that thermal mass is heated up or cooled down only by indoor temperature fluctuations and does not rely on any mechanical facility or additional energy. Active approaches include in the construction elements embedded water-carrying pipes and air heat exchangers [15] to remove absorbed heat from thermal mass. Johra et al. [16] have pointed out the furnishing elements and other internal content can have a significant impact on the indoor thermal dynamic and that the large exposed surface area of furniture offers a good potential for the integration of PCMs. Johra et al. [17] invested the effect of PCM integrated with furnishing in the Danish climate. The simulation results demonstrated the integration of PCMs in inner surface wallboards and in furniture elements are good solutions to increase the effective thermal inertia of lightweight structure dwellings.

Furthermore, the latent heat storage systems may be divided into the air-based system and water-based systems. In the air-based system, the discharging process is activated by passing warm air through the PCM unit to cool the supply air to comfort temperature. Turnpenny et al. [18] in an experiment in which they imbedded heat pipes in PCM in a system for nighttime ventilation concluded that there should be a temperature difference between air and PCM of more than 15 K to make the system work effectively. In contrast, the water-based system uses water as as the heat carrier to remove sensible heat. In a system developed by Tay et al [19] in which the water is passed through a pipe in PCM tank they estimated that the energy storage is more than 18 times than sensible storage system with the same volume.

Sensitivity analysis is an important tool to identify the critical parameters for the building design and energy analysis. This method has been widely applied to investigate the most important design parameters for ventilative cooling. Corgnati et al. [20] examined the design and operational parameters in a night ventilated library building located in a maritime type of climate. The result showed the building mass is the most significant parameter, followed by the internal heat gains and night air flow rates. Breesch et al. [21] analyzed the input parameters causing the uncertainty on the thermal comfort for a single-sided night natural ventilation in an office located in the moderate climate. The results showed that the top three important design parameters were the internal heat gains, the solar heat gain coefficient of the sun blinds, and the internal convective heat transfer coefficient. Encinas et al. [22] found that for night cooling of a real estate market in a warm climate region, the most important input parameter for summer comfort is solar and light transmittance of the solar protection devices, followed by the night ventilation flow rate. Ran et al. [23] adopted the local sensitivity analysis method to investigate the influence of external wall insulation level, night ventilation airflow rate on the indoor air temperature reduction in hot and humid regions, showing that the increase of the insulation level and night airflow rate will enhance the night cooling performance. Guo et al. [24] implemented a holistic approach integrated sensitivity analysis and parametric simulation analysis to investigate the key design parameters for nigh cooling. The sensitivity analysis indicated that the window-wall ratio, internal thermal mass level, internal convective heat transfer coefficient, and night mechanical air change rate are the most important design parameters.

3.2.3 Benefits and limitation

Among the main benefits of VC is the employment of natural ventilation being among the most energy efficient measures in buildings also capable of improve air quality while enhancing thermal comfort and wellbeing of users. However, implementing the natural ventilation is challenging due to the lack of precise information in predicting cooling load needed, integration of ventilative cooling in energy performance calculations, indicators, and control strategies [25]. In addition, operation of windows to provide natural ventilation depends on the occupant's behavior which is related to lifestyle, psychological, physiological and ease of access to openings and hence it is rather difficult predict how well it may be managed in practice [26–29].

Although the application of Phase Changing Materials (PCM) has been suggested to be a promising solution to control the indoor thermal condition and especially in lightweight buildings [17,30,31], have outlined the limitations and drawbacks of PCM. For example, Hu and Heiselberg [32] claim that due to the low thermal conductivity of PCM, the heat absorbed by the surface layer of PCM is blocked, which results in a long time for the melting procedure.

3.2.4 Performance

Ventilative cooling can reduce the energy demands of buildings while enhancing thermal comfort and wellbeing of their users. The performance of ventilative cooling is affected by a range of parameters including climatic conditions, building characteristics and user's behaviors. Occupants' behavior is identified as a major factor influencing the performance of ventilative cooling. The impact becomes more critical in passive low energy buildings. User behavior is related to psychological, cultural, educational, social and lifestyle factors [33,34]. It has been demonstrated that the passive houses can effectively provide high indoor air quality and thermal comfort even in summer periods when they have proper combination of shading devices and natural ventilation strategies [35]. Natural ventilation as most convenient passive ventilation strategy can improve indoor thermal and air quality in summer and transitional seasons [36]. Although, in some cases auxiliary mechanical ventilation systems cannot be avoided in winter to use low temperature outdoor air with low draught risk [36]. There is a considerable body of evidence that occupants in naturally ventilated buildings do not experience the 'sick-building' symptom compared to those in conditioned environments controlled by active systems [37,38].

Computer simulation analyses and actual monitoring are used to investigate the potential of different ventilative cooling strategies and solutions in reducing energy demands of buildings and improving indoor thermal conditions. For example, Yu et al. [36] aiming to overcome the likelihood of draught risk caused by natural ventilation developed a technology combining natural ventilation, building thermal mass and diffuse ceiling forming a thermally activated building system (TABS). Santos et al. [11] studied the potential of Phase Change Materials (PCM) in regulating the internal environment of buildings. Schrade and Erhorn [39] analyzed the effect of passive night ventilation on the energy performance and thermal comfort. Grosso et al. [40] demonstrated the effect of window opening areas on the cooling demands of office buildings. Plesner and Dupin [41] studied the performance of a hybrid system using both natural ventilation and mechanical ventilation in maintaining the thermal comfort of a house throughout the year.

Psomas, et al. [42] through simulations analyzed the effects of ventilative cooling through automated window opening on users' thermal comfort. Zone operative temperature was used as the main criteria for assessing comfort. The simulations showed that for Copenhagen's climate static set points performed better (best results with 22℃ and 23℃) compared with low and medium natural indoor ventilation cooling set points (22℃-24℃).

A climatic cooling potential (CCP) indicator was developed by Artmann et al. [43] to evaluate the indirect night ventilative cooling potential by analyzing only the climatic data, without considering any building-related parameters. The CCP is defined as a summation of products between the building internal and external air temperatures difference and the time interval. Similarly, Ghaaus and Allard [44] used indoor-outdoor temperature difference as an indicator to analyze the potential of ventilative cooling in free-running buildings. Based on Artmann et al. work [43], IEA Annex 62 utilized authors' method to calculate the cooling potential of ventilative cooling considering envelope thermal properties, occupancy patterns, internal gains, and ventilation needs [45].

Yao et al. [6] proposed the natural ventilative cooling potential (NVCP) as an indicator for ventilative cooling. NVCP is defined as the ratio of the number of hours within the comfort zone to the total occupied hours. Brambilla et al. [46] proposed a new indicator to evaluate the life cycle efficiency of passive cooling strategies. The life cycle efficiency ratio (LCER) compares the operational savings of a given scenario with the reference case weighted on the difference between the embodied impacts of the two scenarios. The greater the LCER, the higher the life cycle benefits.

Phase Changing Materials (PCM) can be evaluated by using the concept of average temperature fluctuation reduction (ATFR), maximum temperature reduction (MTR) and discomfort hours. ATFR allows estimating the monthly PCM performance and determining the periods where it works the best. MTR can be used to quantitatively estimate the effect of PCM on maximum air temperature reduction during different seasons (swing and summer) while the concept of discomfort hours is used to investigate the effect of PCM on human thermal comfort [47].

Rui G. et al. [48] have compiled a list on indicators for night-time ventilation through literature review. The family of indices they have suggested including heat removal effectiveness, energy efficiency, reduction in cooling energy, and thermal comfort improvement in daytime. Each family of indices contains a range of indicators. In addition to similar energy performance-based indicators suggested by Guo et al. [48], Annex 62 [49] suggest some KPIs using thermal comfort as a criterion for assessing the effectiveness of ventilative cooling. These include Percentage Outside of Range (POR) the percentage of occupied hours when the PMV or the operative temperature is outside a specified range; Degree-hours criterion (DhC) a measure of operative temperatures exceeding the specified range weighted by a factor which is a function of how many degrees the range has been exceeded; Long-term percentage of Dissatisfied (LPD) an index to evaluate comfort conditions of buildings against each other expressed in percentages.

Yoon et. al. [50] developed a set of two metrics to help predict building's ventilative cooling during an early design procedure. One of the two metrics, natural ventilation cooling effectiveness (NVCE), measures the proportion of cooling potential obtainable by natural ventilation to an actual cooling capacity of a mechanical system. It directly indicates whether ventilative cooling would be effective for a given building design under various conditions, including opening size, solar gain, and thermal mass. The other metric, climate potential utilization ratio (CPUR), informs how much a building utilizes climate's cooling potential. CPUR is useful to estimate the limit of NVCE under a given climate. For example, under a hot climate, NVCE may still be low even if a building was designed to have high natural ventilation rates. In this case, a high CPUR indicates that the building has well utilized climate's cooling potential, but it is hard to improve NVCE with additional efforts.

3.2.5 Application

Graca [5] summarizes the climatic characteristics of a region which can influence the performance of ventilative cooling. These include for example the number of days with air temperature above 30 °C, temperature variation between day and night, wind speed, and humidity variations. Artmann et al. [51] suggests that in addition to fluctuations in the air temperatures, the most important factor for nighttime ventilative cooling is the minimum temperature at night. They demonstrated that the night cooling potential is high in Northern Europe, including the British Isles, during most of the year. In Central, Eastern, and even in some southern Europe, the cooling potential is still significant, but a series of warmer nights might occur and could not guarantee indoor thermal comfort. In Mediterranean countries, night-time ventilation is promising to be part of the hybrid ventilation strategies.

Graca et al. [5] evaluated the ventilative cooling potential in apartment buildings in Beijing and Shanghai. Beijing represents a climate with cold winters and low humidity, while Shanghai is hot and humid in summer. Their findings suggest that night ventilative cooling can replace air-conditioning about 90% of the cooling season in Beijing. Graca et al. [5] suggested that daytime ventilation or night ventilation do not function well in Shanghai because of its hot and humid climate.

The natural ventilative cooling potential (daytime ventilation, night-time ventilation, and combined strategies) of office buildings was also assessed by Yao et al. [6] in five recognized climate zones in China. Five cities, Harbin, Beijing, Shanghai, Guangzhou, and Kunming were selected to represent the climate zone of very cold, cold, hot summer and cold winter, mild, hot summer and warm winter, respectively. The results demonstrated that strategies for ventilative cooling should consider multiple influencing factors such as thermal characteristics of buildings, ventilation type, occupancy profile and internal gains in conjunction with climatic conditions.

Brambilla et al. [46] through a multidimensional approach investigated combined effects of different levels of building thermal mass and different ventilative cooling strategies in a continental climate as in Fribourg. The results showed that temperature-controlled mechanical ventilation system was more efficient in reducing cooling loads than time-controlled strategies. Additionally, taking the whole environmental burdens of a building by considering both annually repeating operational impact as well as materials impacts through Life Cycle Assessment (LCA), a medium thermal mass will have less impact as compared with a thermally heavy building.

Ventilative cooling is also sensitive to climate change. Artman et al. [52] quantify the impact of global warming on the night-time ventilative cooling potential in Europe using a degree- hours, site-specific regression models. The climatic cooling potential index (CCP) was calculated and compared between current (1961-1990, ECA data) and possible future (2071-2100, IPCC scenarios A2 and B2) climatic conditions. The results indicated that future warming would have a significant impact on the night-time ventilative cooling potential across Europe. The CCP was expected to decrease by 20-50% in Central and Northern Europe by the end of 21 century. For Southern Europe, CCP was found to become negligible in summer and decrease by 20-55% during the transient season.

The impact of the climate change on the uncertainty of thermal comfort in a naturally ventilated office was investigated by H. Breesch and Janssens [21]. The probability of discomfort increases significantly when a warm weather data sets, e.g., with recurrence time of 10 years was applied. To reduce the risk of overheating in a warming climate, natural night ventilation should be combined with additional measures e.g., by considering mechanical ventilation coupled with cooling coil or passive cooling strategies (earth-air heat exchanger, indirect Evaporative cooling) or increasing thermal storage of the building.

The resilience of different natural ventilation strategies to future climate was assessed by Lomas and Ji [53]. By adopting a multidimensional approach considering different opening areas and internal load gains, they found that buildings using advanced natural ventilation strategies are more resilient to future climate change compared with buildings which use single side natural ventilation.

Climatic conditions have also been found to be among the major factors influencing the efficient application of Phase changing materials (PCMs), especially for the passive application of PCM. Souayfane et al. [54] suggest when considering the application of PCM, materials with right thermal properties, e.g., having a suitable melting temperature, should be specified to satisfy the prevailing climatic conditions.

Hiyama and Glicksman [55] compared the target ACHs and cooling energy saving intensity in various regions across the United States of America. They found that the potential of natural ventilation in reducing cooling demand depends on climate, building properties, internal heat gain, and airflow rates. They found a strong correlation between the level of internal heat gains and the required ventilation rates. They found that in warmer parts of the USA the building need much higher ACH target for higher internal gains. For different climatic regions of the USA, they suggested a range of ventilative cooling strategies.

In addition to local climate, building materials, internal heat gains, and opening area, opening positions of a building can also influence the potential of ventilative cooling, as pressure distribution on building facades is a key factor of wind-driven natural ventilation. Yoon et. al. [56] proposed a framework for identifying optimal opening positions for seasonal performance of natural ventilation. The optimization utilized computational fluid dynamics (CFD) results via a parametric design platform and weighted the cooling and ventilation potentials by the frequency of seasonal wind directions and average wind speeds.

Established ventilative cooling strategies and their effectiveness are influenced by local climatic conditions and required to be re-evaluated due to changing climates. Maintaining the right balance between the key parameters: installation cost, operating cost, energy consumption, indoor climate and comfort, user satisfaction, and robustness should remain as deciding factors in designing control systems for ventilative cooling [49].

3.2.6 Technology Readiness level

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

3.3 Evaporative cooling

3.3.1 Physical Principles

Evaporative cooling is an adiabatic process, where the sensible air temperature is reduced and compensated by latent heat gain. Evaporative cooling systems allow reducing dry bulb temperatures with a general high efficiency being the latent heat absorption by water evaporation a high value if compared to other heat transfer strategies used in the building sector.

3.3.2 Typologies and Design Parameters

Evaporative cooling includes several solutions, with special regards to the integration of Evaporative chillers in mechanical treatment units, even if those systems may be classified into two main approaches: direct coolers (e.g., desert coolers) and indirect coolers (e.g., Evaporative chiller units for fan coil).

Direct Evaporative cooling (DEC) systems are well known since ancient times, thanks to their ability in cooling an airflow by increasing its absolute humidity. Several historical buildings in hot (and dry) climates show DEC solutions, such as the Ziza Palace in Palermo, Italy, or Ford Red in Delhi, India, with special regards to large space treatments in combination to natural airflows. DEC bases on an adiabatic process, by increasing the absolute humidity of an airstream following isenthalpic line on a psychrometric chart. Without additional treatments, such as dehumidification pre-treatment, the air dry-bulb temperature can be theoretically cooled since its wet-bulb temperature covering the wet-bulb depression. Nevertheless, this theoretical limit is generally not reached, being the treated air temperature commonly about 2 °C higher than the wet bulb temperature [57]. Even if DEC applications mainly refer to desert coolers, this review focuses on direct natural Evaporative technologies treating an airflow, such as passive downdraught Evaporative cooling towers (PDEC). In these systems the air is naturally moved using wind forces and especially negative buoyancy (downdraught) forces [58–60], with special regards to the effects of i) wind pressure at the tower inlet, ii) increase in air-stream weight due to the increase in air absolute humidity thanks to water evaporation, and iii) the transfer between not evaporated water drops and the airflow (momentum transfer) – see in particular [57].

Focusing on PDEC systems, it is possible to divide these solutions according to the adopted water-evaporation technology into four main typologies [57,59]: cool tower (or wetted pad); shower towers (or coarse sprayers); misting towers (or atomized nozzles); porous media (or wet internal surfaces). In the first, a wet pad is adopted at the entrance of the tower and is maintained humid thanks to devoted nozzles. The airflow passing through the wet pad (e.g., cellulose matrix) reduces its temperature by increasing the absolute humidity. Shower and misting towers are characterizing by directly spraying water in the airflow, even if the second adopt nebulization, while in the first larger water drops are used. For this reason, at the bottom of shower towers residual water is expected, while a well-designed misting tower allows for full evaporation in the airstream if the water supply is adjusted according to environmental conditions [58]. The first type generally reaches higher effectiveness, but the presence of unevaporated water may increase the risk for legionella. Finally, porous media includes several solutions in which porous surfaces are maintained humid to allow water evaporation when exposed to inlet airflows.

The porous media solution was adopted in several historical examples, e.g., the Botijo, a porous ceramic jar typical of southern Spain locations [59], but it is also at the base of numerous recent studies related to the development of innovative ceramic materials. For example, Panchabikesan et al. [61] studied the effect on a real time experiment of a combination between PCM and DEC systems in an Indian location favorable for Evaporative cooling (hot and dry). PCM phase change temperatures in the range 27-29 °C were adopted and experimental results show how without DEC, PCM remains liquid without activating due to unfavorable conditions, while when DEC is integrated, in all experimental cases the energy storage tank reached a solid-state even under unfavorable environmental temperatures. The study underlines how by integrating DEC and PCM the storing of useful energy may be increased in hot dry locations even when environmental temperatures are not suitable for PCM activation. Another research compares the adoption of different new DEC organic materials as an alternative to cellulose pads to reduce embodied energy and operating costs [62]. In this study, Dogramaci and Aydin analyze five porous media derived by natural materials (eucalyptus fibers, ceramic pipes, dry bulrush basket, yellow stone, Cyprus marble). Wind tunnel tests were performed simulating very dry conditions and testing different air velocity. Particularly, eucalyptus fibers and ceramic pipes were demonstrated to be very effective, reaching effectiveness in the range 72-33% and 68-26% respectively, followed by the yellow stone. As expected, with higher velocities the effectiveness reduces, but the cooling capacity increases, nevertheless a suggested optimum mass flow rate of 0.063 kg/s for Turkish Cyprus cases is calculated to optimize DEC systems. Furthermore, a new mathematical model to analyze DEC effects by porous media is introduced by Sellami et al. [63]. The model considers heat and mass transfers in airflows and water flow by adopting the finite volume method and SIMPLE algorithm for velocity-pressure coupling. Results allow to define the high potential of DEC by porous layers in dry climates, while higher performances are reached with lower inlet air velocities, high porosity, and thick, porous layers.

3.3.3 Benefit and Limitation

Evaporative cooling systems, e.g., PDEC, may allow to considerably reduce dry bulb temperatures in a space helping in reaching comfort conditions without additional cooling sources. PDEC systems are generally low cost and, when local WBT is sufficiently high, allow to cool and airflow with a limited amount of energy. Nevertheless, they need a high maintenance to avoid microorganisms and connected diseases (e.g., legionella). Being the process adiabatic, an increase in humidity (absolute and relative) is evident. For this reason, direct Evaporative cooling systems need to be controlled to avoid too high space relative humidity values. DEC may be a valid dissipative system for open or semi-open spaces, in where the growth of air absolute humidity is mitigated by natural air movements. In enclosed spaces, DEC systems can be controlled to prevent too high humidity values by adopting a control system. Furthermore, such as discussed in the below section, these systems are dependent by the local wet bulb depression, and they are more suitable for hot and dry locations. Another potential limitation of Evaporative cooling systems is the water consumption, which in desert or semi-desert areas may limit their applicability, even if recent projects (e.g., the Sahara Forest Project or research in water harvesting) focus on developing integrated solutions able to condensate water from the air.

3.3.4 Performance

A general indicator used to define the ability of a specific DEC system in cooling airflow by evaporation is the calculation of the effectiveness of the system, which is a function of the ratio between the difference among inlet and outlet dry bulb temperatures and the wet-bulb depression [4,64]. The effectiveness is at the base of several empirical expressions able in calculating PDEC tower outlet temperatures [4,65]. Four of these expressions together with the PHDC Air flow software [59] were compared with experimental databases in a recent paper showing good correlations in different climatic and typological conditions [66].

Considering the DEC design methodologies for building integration, a complete guide on PDECs is included in the Ford et al. sourcebook [59], which is part of a funded EU project (6th framework). This study includes case study descriptions, a life cycle cost analysis, and a review on components and control solutions with the addition of a performance assessment tool. It was demonstrated that PDEC may cover between 25 to 85% of the non-domestic building cooling loads in Europe and can reduce well below 15 kWh/m^2 y the cooling consumptions in residential buildings. Furthermore, PDEC installation costs are about 50% lower than full AC ones, showing consistent life cycle cost benefits, suggesting a payback time of 5-15 years in China and Europe and 2-5 years in India. Another study focuses on the prediction of thermal office building performances when DEC systems are used for space cooling in Indian climates [67]. This analysis, based on experimental validated models in EnergyPlus shows the positive effect of DEC in covering about 42-52% of original discomfort hours in two different typical office building types: a single floor building and a larger multi-story (3) building. Differently, Schiano-Phan [68] analyses PDEC implications focusing not only on climate aspects but especially on the correlation between PDEC performances and users' perception plus architectural integration. This study is based on four buildings using PDEC in U.S. characterized to follow different integration schemes. Two buildings use a misting tower, while the other two a wet pad tower. The paper underlines how PDEC good performances are correlated to the correct design of buildings, which is correlated to the ability of architects in anticipating users' implications and to the quality of the overall definition of passive and natural strategies. User perceptions are demonstrated to be correlated to user expectations and user ability in controlling surrounding spaces. Focusing on building integration and simplified approaches to dimension PDEC systems in combination with spaces, a simple design methodology is described for different residential building typologies and integration schemes in [69]. This paper support early-design steps to integrate PDEC towers in buildings by: i) analyzing tower performances in specific climatic contexts, e.g. by adopting short-term PDEC tube monitoring to characterize the effectiveness or assuming this value in the range 0.75-0.8 for shower tower; ii) defining a simple method to correlated required airflows for ventilative space cooling considering air-temperatures and DEC pre-treated airflow conditions to define PDEC tower minimum dimensions, and iii) analyzing for selected representative environmental conditions the effect of PDEC activation on indoor temperatures and humidity assuming well-known air mixing expressions. Differently, other studies analyzed the effect of different PDEC tower characteristics on the cooling effectiveness. In particular, the aerodynamic performances of a PDEC tower (multi-stage) before installing the nozzle system is analyzed in [70], showing the effect between inlet and outlet geometries on airflows, aiming at reducing the aerodynamic resistance of towers by adding an outlet water permeable deflector. A correlated study [71] analyses the water spraying performance of the same system. The specific shape and the adoption of a multi-stage system with a higher area of contact between water and air allow reaching equal or superior cooling effects in comparison to traditional DEC while lower amount of water is consumed. The study shows the importance in reducing the dimension of drops to obtain fully evaporation when required (e.g., people usage of spaces under or very close to tower outlet) but suggests adopting larger volume of water with shower tower systems and water recirculation when this specific requirement is not present to reduce the pumping power and limit clogging risks with the consequent amount of water drift near the tower bottom part. This last phenomenon increases the risk for creating DEC correlated microorganisms and diseases [72].

3.3.5 Application

On the climatic point of view, the wet-bulb depression is at the base of different analyses, from the cumulative hour map reported in [57] for Europe, to the mapping studies of Salmeron et al. [73] and Ford et al. [59], including further variations [74]. Other studies analyze DEC applicability in Australia [75] showing high applicability in all main cities (excluding Darwin, which is too humid) adopting psychrometric charts; in the Mediterranean Basin, combining climatic indexes, empirical effectiveness expressions, and dynamic energy simulations [76]; and in China [77], in which Evaporative cooling and radiative cooling potential are compared. Furthermore, the DEC applicability in the U.S. was investigated by Aparicio-Ruiz et al. [78] adopting the method described in [73] combining WBD and theoretical cooling requirements (26 °C-WBT). A series of maps were reported showing these indexes for all counties and county-equivalents administrative units. DEC potential is scaled from null to very high, showing very high potentials especially in western and central-western areas of U.S., with the exclusion of some western coastal zones. Overlapping DEC potential with climatic cooling needs (CDD), higher applicability classes are reached in south-western areas (California, Arizona, Nevada, Utah, New Mexico). Finally, a shortly recent review on DEC topics is included in [79].

3.3.6 Technology Readiness Level

On the TRL point of view, several PDEC systems have been installed in different building typologies. This technology is already at the market level, nevertheless, new research are under development for new porous materials, and to develop specific systems connected to ventilative cooling solutions. In these cases, lower TRL may be found. Finally, movable simpler evaporation solutions (e.g., personal evaporator fan systems) independent by building system integration are commercialized in every-day shops.

3.4 Compression refrigeration

3.4.1 Physical principles

Vapor compression refrigeration is certainly the most used “active” technology to produce a cooling effect. Alternative commercialized technologies are, among others, the sorption machines (absorption and adsorption) and Peltier coolers (only used for small cooling capacities and hence for local cooling).

The Vapor compression refrigeration system mainly comprises an evaporator, a compressor, a condenser, and an expansion device. A working fluid, called “refrigerant” successively flows through these components and describes a thermodynamic cycle, as illustrated in Figure 3-1.

The low-pressure refrigerant in slightly superheated Vapor state is compressed by the compressor to a high-pressure superheated Vapor. The compressor is usually driven by an electric motor, yielding an electric consumption $\dot{W}_{el}$. In less usual configurations, the compressor can also be driven mechanically by an internal combustion engine fed, for instance by natural gas.

The Vapor is then routed to the condenser where it is successively cooled-down to saturated Vapor state, condensed to saturated liquid state and slightly subcooled. The heat released by the condenser is evacuated by a secondary fluid, which is commonly air or water. In the latter case, the water loop is connected to a heat sink, such as a dry cooler, a wet cooling tower or a geothermal boreholes field.

The subcooled high-pressure liquid at the condenser outlet is throttled to the low pressure, by means of an expansion valve yielding a mixture of saturated liquid and saturated Vapor.

This two-phase flow enters the evaporator, where it is Vaporized and eventually slightly superheated. In the evaporator, the thermal power $\dot{Q}_{ev}$ transferred to the refrigerant represents the cooling effect. The evaporator can be heated by air or water (possibly, glycol water). This secondary fluid, which is cooled down in the evaporator, is then routed to the building for cooling purpose. Cold air is directly pulsed in the building zones to cool down. Chilled (glycol) water feeds, among examples, cooling coils in air handling units, fan coil units, radiant panels, ejecto-convectors, or chilled beams. Note that in the case of air-heated evaporators, for low enough evaporating temperatures, the evaporator can both cool down and dehumidify the air.

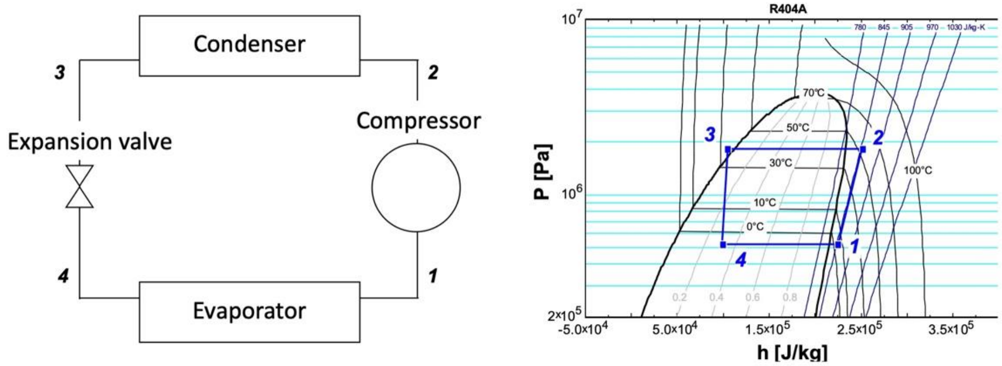

Figure 3-1. The Vapour compression refrigeration machine (left) and the thermodynamic cycle described by the refrigerant (right)

The indicator of the performance of a Vapor compression refrigeration unit is named Coefficient of Performance (COP) defined as the ratio of the cooling power to the electrical consumption. For cooling production, the COP is sometimes called the Energy Efficiency Ratio (EER). The acronyms COP and EER will be used in the rest of the report to clearly distinguish performance in heating mode and performance in cooling mode. Hence:

$$EER = \frac{\dot{Q}_{ev}}{\dot{W}_{el}} \quad (3)$$

$$COP = \frac{\dot{Q}_{cd}}{\dot{W}_{el}} \quad (4)$$

The value of the COP largely depends on the temperature of the heat source (the secondary fluid at the evaporator) and the heat sink (the secondary fluid at the condenser), but a typical order of magnitude is around 3, which means that for 1 unit of electricity “consumed”, 3 units of cooling energy are “produced”.

When assessing the energy performance of a Vapor compression refrigeration system, it also important to account for the electric consumption of all the auxiliaries, namely the fans and the pumps. A more relevant performance indicator would be the system COP, defined as

$$EER_{system} = \frac{\dot{Q}_{ev}}{\dot{W}_{el} + \dot{W}_{aux}} < COP \tag{5}$$

Finally, to have a better assessment of the energy performance of the Vapor compression system, a seasonal efficiency should be computed or measured rather than looking to the performance on one nominal operating point. That is, a seasonal COP or seasonal EER can be defined by integrating the powers on one cooling or heating season:

3.4.2 Typologies and design parameters

Vapor compression systems can be classified according to the nature of the heat source and the heat sink (usually air, (glycol) water, soil…), the type of thermal power that is produced (cooling, heating, simultaneous cooling, and heating), the overall technology, the technology of compressor, the type of refrigerant (natural versus synthetic fluids), the size (i.e., the cooling capacity) or the reversibility and heat recovery of the systems as shown latter.

3.4.2.1 Classification according to the technology

Vapor compression refrigeration systems encompass many different technologies including

- Chillers
- Reversible air-source heat pumps
- Reversible geothermal heat pumps
- Heat pumps for simultaneous heating and cooling
- Exhaust air heat pump system
- Split systems
- Room air-conditioners
- Variable Refrigerant Flow (VRF) systems

Chillers are aimed at producing chilled water to feed cooling emitters, such as fan coil units, radiant ceilings, chilled beams, ejecto-convectors, etc. Chillers are either air-cooled or water-called. Water-cooled chillers usually show larger cooling capacities than air-cooled chillers. Water cooled chillers have their condenser usually connected to a dry-cooler or a wet cooling tower. Chillers provide cooling only.

Reversible heat pumps (or reversible chillers) are most of the type a variation of a chiller but equipped with a 4-way valve that allows to switch the operation of the condenser and evaporator and make the chiller working as a heat pump.

Reversible geothermal heat pump is a reversible water-to-water unit connected from one side to the distribution system of the building and to the water loop connected to the geothermal heat source on the other side. The system can be operated in free-chilling mode (also called geo-cooling) if the geothermal source temperature is in the range of the building distribution temperature. In cooling mode, the geothermal-side exchanger acts as a condenser and the water exchanger acts as an evaporator while in heating mode the geothermal-side exchanger works as an evaporator and the water exchanger works as a condenser.

Some machines, which are not equipped with reversing valves, are both a chiller and a heat pump. They are categorized as heat pumps for simultaneously cooling and heating. The cooling effect produced at the evaporator and the heating effect produced at the condenser can be both valorized, simultaneously, or not, to cool or heat a building. The simultaneity of cooling and heating can be increased by using thermal energy storages.

Exhaust air heat pump system where exhaust air is used as a heat source in heating mode and as heat sink in cooling mode. There is a changeover made on the water circuit for allowing heat pumping or heat rejection. The exhaust ventilation air is an excellent heat source and a fair heat sink for heat rejection. In both modes the ventilation exhaust air is not sufficient to cover all the energy demand of the building, an additional heat source should have to be added. The heat recovery on ventilation exhaust air requires the use of air-water coils which can be supplied by glycol water to prevent freezing, the coil must be designed to allow condensation and to work at different temperatures. In cooling mode, the supply air coil is an evaporator, and the exhaust air coil is a condenser, the production of chilled water is ensured by the water-heated evaporator. The air-cooled condenser is used to reject heat while the water-cooled condenser is not used in cooling mode.

Split systems comprise an outdoor unit and one or several indoor units. In cooling operation, the heat exchanger inside the outdoor unit acts as a condenser, while the heat exchangers inside the indoor units act as evaporator. In split systems, the secondary fluids in both the indoor units and outdoor unit is air. Hence, the cooling power produced in the indoor units can be split into a sensible contribution and a latent contribution (dehumidification).

Variable Refrigerant Flow (VRF) systems can be seen as a variant of split systems where the indoor units can simultaneously work as evaporators (cooling mode), condenser (heating mode) or a mix of evaporators and condensers (for buildings showing simultaneous cooling and heating demands). Depending on the mode of operation of the indoor units, the outdoor unit works as an evaporator or condenser. The interest in the mix cooling/heating mode lays in the fact that some heat transfer is achieved from building zones requiring heating to zones requiring cooling, which reduces the overall energy consumption for heating/cooling the building.

3.4.2.2 Other classifications of vapor compression systems

The other classifications that are of interest when considering resilient technologies are the cooling capacity and the nature of the refrigerant.

Vapor compression refrigerant technology covers a large range of cooling capacities going from a few hundreds of Watts (household refrigerators), and even lower, to tens of MegaWatts (industrial chillers and large-scale heat pumps). The size impacts the choice of technology of components (heat exchangers, compressor) and the refrigerant.

Sustainable Vapor compression systems must also use refrigerants that are environmentally friendly. That means, that must be characterized by Ozone Depletion Potential (ODP) equal to zero and Global Warming Potential (GWP) as low as possible (and ideally close to 1, which is the GWP of CO_2 considered as a reference). Since Montreal Protocol, fluids characterized by non-null ODP are banned off. Regarding the GWP, regulation is progressively lowering the authorized threshold, depending also on the activity sector (building HVAC, mobile air-conditioning…). The European Union is aiming to reduce the environmental impact of Fluorinated gases via regulation. The most common f-gases in use within Europe are HFCs, such as R134a, R404A and R410A. These gases have a few applications, the largest being as a refrigerant. F-gas emissions to be cut by two-thirds by 2030 in the EU compared with 2014 levels [80]. F-gases have a relatively high GWP, and thus contribute to global warming when released to the atmosphere. As a response, chemical industry has been developing synthetic refrigerants with very low GWP (such as R1234yf and other HFO fluids), which often show the advantage to be drop-in solutions. In parallel, natural fluids are more and more largely investigated. However, they show some drawbacks such as high operating pressure (CO_2), flammability (hydrocarbons) or toxicity (ammonia).

Table 3-1: Vapor compression refrigeration systems classification according to the reversibility and heat recovery [81]

Type	Reversibility	Heat Recovery
Air-to-water heat pump system	Yes	No
Geothermal heat pump system	Yes	No
Exhaust air heat pump system	Yes	No
Air-to-air dual duct heat pump system	Yes	No
Mono-split / Multi-split	Yes	No
Water-cooled chiller	No	Yes

Water-to-water heat pump	Yes	No
Air-to-water heat pump	Yes	No
Water loop heat pump system	Yes	No
Variable Refrigerant Flow (VRF) systems	Yes	No

3.4.3 Benefits and limitations

3.4.3.1 Benefits

Vapor compression refrigeration systems are among the active cooling technologies. As such, they can be operated with large flexibility if electricity is available. Also, their cooling capacity is more constrained by the design and size of the machine than the cooling capacity (i.e., the temperature) of the heat sink. In contrary passive systems, such as free-ventilative cooling (cooling by means of ventilation with cold outdoor air), free Evaporative chilling (cooling with water cooled down by cold outdoor air in a dry cooler or cooling tower) or ground cooling – geo-cooling - (cooling using the coldness of the ground) are limited by the temperature of the heat sink (respectively, the air and the ground). Essentially, the heat sink temperature (or wet-bulb temperature in free chilling with a wet cooling tower) must be lower than the building indoor temperature. Vapor compression systems, as thermal machines, allow for the heat transfer from a low temperature heat source to a higher temperature heat sink. Hence, they can transfer the heat from the building to the higher temperature outdoor air.

3.4.3.2 Limitations

Energy consumptions. As a thermal machine obeying the Second Law of Thermodynamics, an external work is necessary to drive the heat against the temperature gradient. Practically, that means that a Vapor compression system consumes electricity. As mentioned before, the electricity consumption (to which we also add consumptions of fans and pumps) is related to the cooling power by the COP. Passive systems, which take benefit of a heat sink at a lower temperature than the building, do not need a refrigeration cycle to transfer the heat from the building to the heat sink. Consequently, their only electrical consumption is due to pumps and fans yielding to much larger system COP than those achieved with Vapor compression systems (to give an order of magnitude, 12 versus 3).

It must be stressed that Vapor compression chillers can be connected with a passive system to cope with the cooling capacity content of the sinks (outdoor air, ground, lakes, etc.,) while maximizing the energy efficiency of the overall cooling plant.

Some residential heat pumps are also equipped with a system to by-pass the refrigerant circuit and use the cold ground as a heat sink for geo-cooling operation to prevent overheating in the buildings. Among those systems, some only provide passive cooling operation (no possibility to use the Vapor compression heat pump as a chiller).

Thermal regeneration of the heat sink acting as seasonal energy storage. In the case of a reversible heat pump connected to a heat sink that can store the heat released from the building, seasonal energy storage can be achieved. This is the case of geothermal heat pumps connected to a borehole field or to an aquifer thermal energy storage (ATES). In such a case, during the cooling season, the heat released from the building is injected in the ground or in the ATES. This heat can be rejected from the chiller condenser (in active cooling mode) or directly from the building chilled water loop (in passive cooling mode). During the heating season, part of this heat can be recovered and serve as the heat source of the heat pump. Design and operation of the system must ensure that the amount of heat injected into the ground during cooling season balances the amount of heat extracted during the heating season. This process is named thermal regeneration.

Impact of high outdoor temperature (heat sink) on the cooling capacity. During a heatwave episode, the condensing temperature of the chiller is increased leading to a decrease of the cooling capacity of the chiller. Unfortunately, the cooling demand of the building increases with the outdoor temperature. These opposite trends could lead to chiller oversizing and more recurrent part-load (and possibly) less efficient operation. To cope with this limitation, thermal energy storage can be used.

Hazardous refrigerant. Split and VRF systems (which could comprise a few hundred meters of refrigerant pipes) do not allow for the use of flammable refrigerants, that are limited to compact systems.

3.4.4 Performance

Defining resilient cooling as "passive or low-energy cooling that benefits people, HVAC equipment, and/or the power grid, especially during hot weather", the following conditions fulfilled to classify Vapor compression refrigeration as part of the resilient cooling solution.

3.4.4.1 High energy efficiency

As mentioned before, the energy performance of a Vapor compression cooling plant is usually characterized by its COP. The latter can also include, in a system COP, other electricity consumptions than that of the compressor. The Second Law of thermodynamics teaches us that the COP of the Vapor compression system is a fraction of the COP of totally reversible heat pump (heat pump describing a thermodynamic cycle with evolutions that are both internally and externally reversible). The COP of such an ideal heat pump is given by the Carnot COP, which depends only on the temperatures of the heat source (T_L) and heat sink (T_H). The aforementioned fraction is called second law efficiency η_{II}. That is,

$$COP = \frac{\dot{Q}_{ev}}{\dot{W}_{el}} = \eta_{II} \cdot COP_{Carnot} = \eta_{II} \cdot \frac{T_L}{T_H - T_L} \tag{6}$$

Examining this equation, it can be observed that there are two ways to improve the COP of a Vapor compression system:

By increasing the second law efficiency, whose order of magnitude is around 50%. This efficiency is highly dependent on components performances: compressor isentropic efficiency (and performance variation following modulation), heat exchangers pressure drop and thermal efficiencies, etc.

By increasing the Carnot COP. Even though the formula cannot be modified, HVAC systems designers can select the heat source and heat sink in such a way to increase $T_L$and decrease T_H. Increasing T_L (named high temperature cooling) can be achieved by using radiant emitters and by limiting all temperature differences ("pinch points") between the emitter and the secondary fluid leaving the evaporator (by limiting the number of heat exchangers and mixing points). One way to decrease T_H is to use heat sink at a temperature lower than outdoor air (ground, aquifer, lake, river, sea) or to operate chillers during the night (when the outdoor temperature is lower) and to store the coldness in a thermal energy storage unit or in the building envelope.

The system COP can also be maximized by limiting the electricity consumption of auxiliaries. This can be ensured by using variable speed fans and pumps with efficient electric motors.

As mentioned before, if part of the time, the temperature of the heat sink T_H allows for passive cooling operation, this latter operating mode must be used, since it yields a large system COP.

$$COP_{system,passive} = \frac{\dot{Q}_{ev}}{(\dot{W}_{el} = 0) + \dot{W}_{aux}} \tag{7}$$

The condition to satisfy to operate passive cooling is that the temperature of the heat sink (or wet-bulb temperature in the case of a wet cooling tower) is lower than the temperature at the inlet of the emitter (radiant panel, chilled beam…) minus a temperature pinch point (of a few Kelvins) lumping the cumulative temperature differences associated to all thermal barriers between the heat sink and the coolant at the emitter inlet.

$$T_H < T_{emitter} - \Delta T \tag{8}$$

Using a wet cooling tower increases the fraction of time when passive cooling (free chilling) is used, since the wet-bulb temperature is lower than the dry-bulb temperature. Increasing the operating temperature regime of the emitter is also a way to increase the fraction of time when passive cooling is used.

3.4.4.2 Use of electricity produced from the conversion of renewable energy sources

Vapor compression systems have most of the time their compressor driven by an electric motor. It should however be mentioned that the compressor can be driven by an internal combustion engine fed by fossil fuels of biofuels. This is more common for very large chillers. Coming back to chillers driven by electricity, as the primary energy factor (PEF) decreases, the primary energy efficiency of the chiller increases.

3.4.4.3 Contribute to limit the impact on the grid of local electricity consumption

Vapor compression chillers can also largely contribute to self-consume the electricity produced by PV panels in a building. Self-consumption of local production is more and more encouraged through the shift from net-metering billing mechanisms to a billing mechanism where the resale tariff (or buy-back) is lower than the retail tariff. This is an incentive to shift the building electricity consumption in time to match the PV production. As mentioned by [82], “with the increase in the number of prosumers, electricity grid congestion and PV curtailment become more frequent, which restricts the amount of distributed power supplied to the grid and tends to modify the economics of surplus electricity sale to the grid”.

In contrary to heat pumps, chillers are more likely to operate simultaneously to PV electricity production. There is hence good candidate to improve building self-consumption.

The impact of the grid of on-site generation can be quantified by the grid impact indicators defined by [83]: the supply cover factor (the fraction of local electricity production that is consumed on-site) and the demand cover factor (the fraction of the local electricity demand that is covered by on-site production). Connecting the PV-chiller to electric batteries and/or cold thermal storage improves the load matching and reduces the operating cost when electricity buy-back tariff is lower than retail tariff [82]. A better load matching is characterized by higher values of the supply and demand cover factors.

In the limiting case of an isolated grid, the chiller would only be run with the electricity produced (and possibly stored) locally.

Chillers connected to energy storage (batteries, thermal storage units of building thermal mass) can also contribute to the management of electrical grids by the flexibility provided by such combinations. This flexibility is activated by a Time of Use (ToU) tariff as a Demand Side Management (DSM) mechanism. It should be stressed that heatwaves lead to electricity peak demands on the grid and DSM mechanisms become of paramount importance.

3.4.4.4 Back-up cooling solution during grid failure

A chiller connected to either a cold storage (sensible or latent) or batteries can constitute a back-up solution in case of grid failure.

3.4.5 Application

To cool a building using heat pumps requires having both heat source and heat sink. Outdoor air is the most widely used as heat source/sink. Water is also used as heat source/sink and it comes from different origins like ground water, wastewater, and condensing water, in some applications The ground itself is used as a heat source/sink, its performance depends on the soil properties.

Reversible air-to-water heat pumps can be used in new buildings and particularly their use is common in existing air-conditioned buildings where an air-cooled chiller is installed. They can be installed in renovated buildings depending on the availability of air/water distribution systems. Geothermal heat pumps without heat recovery are suitable for new buildings and difficult to be installed in renovated buildings, the building shouldn't have simultaneous heating and cooling demand if there is no backup system installed as there is no heat recovery allowed with this system. While if the heating and cooling demand are simultaneous, geothermal heat pumps with heat recovery are very beneficial in this case and can generally reduce the plant complexity. In case of building retrofit, split systems and VRF Systems are typically used because of the small diameter of the refrigerant pipeline compared to the water pipeline, split systems are installed in small buildings and VRF systems are installed in medium buildings.

When installing an active Vapor compression chiller for a building, several aspects should be considered.

- What are the available chiller heat sinks: ground, ground water (Aquifer Thermal Energy Storage), ambient air, etc.
- Could passive cooling be used in yearly association with active cooling?
- What is the peak cooling demand? Could a cold storage be used to limit the size of the cooling plant (size of the chiller, but also size of the cooling tower)?
- Could the same machine cover (part of) cooling and (part of) heating demand? In the latter case, should a reversible machine have been used or a machine with heat recovery? This is related to the simultaneity of the cooling and heating demands and to the comparison of the peak heating and cooling demands. Essentially, replacing a boiler by a reversible chiller or by a chiller with heat recovery allows for primary energy savings.
- Is it a new building or a retrofitted one? For instance, VRF systems are suitable for retrofitting, because of the reduced diameter of refrigerant piping.

3.4.6 Technology Readiness Level

The heat pump market was, till now, concentrated on residential buildings. Now, attention is given to (new and existing) non-residential buildings, where heating and cooling demands co-exist [84]. All technologies described in this report can be purchased today. Building contractors and engineering offices define the most appropriate cooling/heating plants depending on the availabilities of heat sink/heat source, on the building characteristics, on the cost of energy (and the presence of a local electricity production), on local regulation/incentives, but also on the customer's expectations. While there are many solutions on the market, geothermal solutions are the most efficient solutions, but the investment costs are high, so they are not applicable everywhere in the different applications.

3.5 Desiccant cooling system

3.5.1 Physical principles

The desiccant cooling systems were developed to handle sensible and latent heat loads independently [85]. According to Figure 3-2, the dehumidifier absorbs the moisture of the supplied air and afterward will pass to the regeneration unit to recover its initial moisture absorption capability [86]. The dry supplied air stream passes the cooling unit for sensible cooling and then routed to the conditioned space. Additional heat exchangers could be added on different points such as economizers to increase the system efficiency.

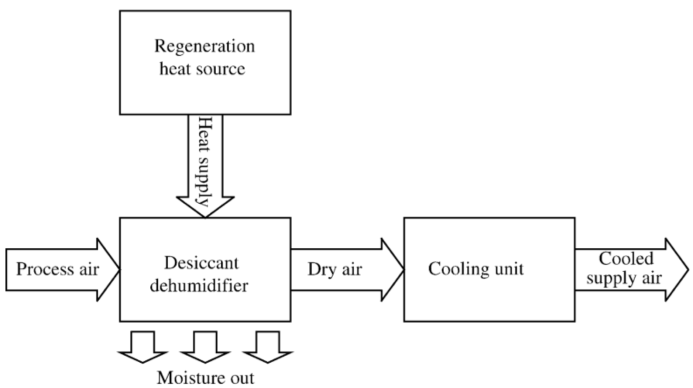

Figure 3-2 Basis of desiccant cooling system (Daou et al., 2006)

In wet areas which the latent heat load is more than the sensible load, the desiccant cooling systems work optimally and perform latent cooling by removing moisture [87,88]. Desiccant materials extract moisture due to the difference of water Vapor pressure between the surrounding air and the desiccant surface [86]; therefore, there is not any condensate water in this system and consequently, the system could work continuously even below the freezing temperature of the water. The total energy for system operation including the energy required for running fans and the possible renewable energy sources for the regeneration section is quite low and easily accessible.

3.5.2 Typologies and design parameters

Desiccant systems are classified to solid (adsorbent) and liquid (absorbent) desiccators. The first step to design a desiccator is to select a suitable desiccant material [89]. The rotary wheel with solid dehumidifiers are compact systems made from matrix-shaped parallel channels coated with desiccant material, e.g., SiO_2, $TiSiO_4$ and Al_2O_3, that operate continuously with low corrosion probability, are more well-known [85]. Other parameters such as surface roughness, rotation speed and Reynolds number also affect heat and mass transfer [86,90–93]. The liquid desiccant materials such as ClLi, LiBr, $CaCl_2$, TEG HCOONa, HCOOK, CH_3COONa, CH_3COOK, or a combination of these solutions, ideally should be stable, odorless, non-toxic, non-flammable, inexpensive, non-crystalized in the operating temperature range, non-corrosive and non-volatile with good heat transfer characteristics and low surface Vapor pressure at the contacting temperature [92]. Low capacity of solid desiccants and corrosivity of liquid desiccants are important limitations. Therefore, new desiccants including bio-desiccants, composite desiccants, and polymer desiccants are introduced. According to new research, some of the new introduced desiccants increase the absorption capacity 2-3 times of traditional absorbers [94].

3.5.3 Benefits and limitations

The major benefits of the desiccant cooling are as below [85,87,95]:

- Utilizing echo-friendly fluids including air and water, no negative impact to the environment, like fluorocarbons, on the ozone layer.
- Using diverse thermal energy sources, even low-grades resources, in the regenerators. Furthermore, the required electrical energy can be less than 25 percent of conventional refrigeration systems and this technique acts as an energy-efficient method, especially for hot dry and hot humid areas.
- Using desiccants leads to increased process air quality by removing the airborne pollutions and contaminants from airstreams.
- Working in a low pressure, near atmospheric pressure, makes it easy to construct, install, preserve, and maintain of desiccant cooling systems. Furthermore, their energy consumption is very low in comparison with traditional cooling systems.
- In cold seasons, it is possible to use desiccant cooling system as a heat source

The major limitation of desiccant cooling is that it needs an additional energy source for regenerating the desiccant for stable operation. [86]

3.5.4 Performance

The dehumidifier's performance depends on its geometry and desiccant material. The geometry has effects on pressure drop, size, cost, and cooling performance [87]. [96] estimated numerically the efficiency of a desiccant cooling system combined with a Combined Heat and Power (CHP) unit. The maximum efficiency of an ideal desiccant dehumidifier (second law efficiency) is about 0.85 while it decreases to 0.6-0.7 for actual systems [97]. [98] found that their liquid desiccant heat recovery devices (LDHR) can work in ambient air to -30 °C. Furthermore, they proved that the preheating of the inlet air has a higher performance rather preheating the desiccant. According to their research, the heat recovery efficiency is 70%, 62.5%, 58.3%, and 54.6% at -15, -20, -25, and -30 °C respectively.

3.5.5 Application

Using desiccant cooling systems because of their specific capabilities for controlling the humidity level of streams or closed areas have been studied several times in hot and humid areas in recent decades. Based on a summary of experimental and numerical research that has been performed from 2002 up to now, most of the investigation has focused on the application of desiccant cooling systems in buildings located in hot and humid climates. However, some publications have investigated the application of desiccant cooling in moderate or even cold climates.

Solid dehumidifiers could be used for new construction and revamping projects in buildings. A simple configuration of these systems with a rotary desiccant wheel is made by some factories as a package and could be installed in every location. Their utilization bottleneck is to provide the required energy for regenerating desiccants and running the fans. Combining the basic desiccant cooling technology with renewable sources, for example, tidal energy in marine facilities, solar radiation, or geothermal might be also possible and should be considered. In addition to the previous studies, desiccators could be utilized in industrial dehumidifiers for example to extract humidity from treated sweet natural gas, air driers, electronics, fixed and portable marine facilities and pharmaceutical applications.

3.5.6 Technology readiness level

Desiccator wheels are used for residential and industrial purposes. For instance, those are utilized in product storages and warehouses, for preservation of equipment, in skating rinks, for pharmaceutical production, in the food industry etc. Some factories produce desiccator packages with various capacities. However, they usually use a simple system with basic equipment and developed systems are not used widely in the market.

This technology could be categorized in TRL 9 according to the Technology Readiness Assessment Guide issued by the U.S. Department of Energy [99]. TRL 9 signifies that the technology operates and can achieve all its defined missions. Liquid desiccators could be categorized in TRL5 that represent that the system is tested on a laboratory scale and need to be validated on the pilot scale.

3.6 Ground Source Cooling

Geo-cooling or ground-source cooling is among the most sustainable and resilient technologies used for providing cooling to buildings. The working principle of the technology is based on the fact that the ground temperature below approximately 10 m remains constant all year round at about mean annual ambient air temperature [100] and is not influenced by ambient air. In summer, the underground temperature is significantly lower than the ambient air temperature. Thus, a ground-source cooling system benefits from lower and more stable ground temperature over the cooling period, regardless of outside air temperature. The lower the ground temperature is, the greater is the potential for utilizing the ground as a cooling source.

Ground-source cooling is provided through ground heat exchangers. A ground heat exchanger is an array of pipes inserted vertically or horizontally into the ground. Cooling is performed by rejecting heat to the ground by circulating a working fluid through the ground heat exchangers. Based on the heat transfer medium (liquid or air), the ground source cooling can be further categorized into earth-to-air heat exchanger EAHE and Borehole heat exchanger BHE. The following sections will describe these two systems separately.

3.6.1 Earth-to-air heat exchanger

3.6.1.1 Physical Principles

EAHE allows exchanging of sensible heat between airflow and the ground taking advantage of the high inertia of the soil in which external temperature variations are attenuated and shifted according to depth and thermal soil properties with the possibility to absorb daily and short-/mid-term variations.

In respect to other ground cooling systems, such as Borehole heat exchangers, EAHEs adopt air as thermo-vector and are based on horizontal low-depth pipes. Installation and operational costs are limited in comparison to liquid-based systems and air movements can be easily controlled by fans. EAHE can work alone to treat inlet air (e.g., as a pre-heater of exchanging air in winter and cooling system for ventilative cooling in summer) or as pre-treatment components of a mechanical HVAC system.

3.6.1.2 Typologies and design parameters

Roughly speaking it is possible to correlate the effect of an EAHE system to its ability in covering the difference between inlet air and pipe surrounding earth temperature. This correlation can be expressed as a EAHE efficacy comparing the difference between the inlet and outlet temperatures with inlet and soil ones [4]. This value, also named temperature ratio [101], is a function of several parameters, including pipe diameter, length, airflow rate, soil, and tube thermal characteristics [102]. A parametric study to define this parameter in accordance with different configurations is reported in [103], while analysis on the effect of pipe distances was recently reported in [104], based on a validated CFD model considering also pipe diameters, operating modes, and air velocities. The study concludes that, for the traditional considered velocities and diameters, distances between tubes may be reduced from the previously suggested 1 m till 0.5 m without affecting the general EAHE performance, supporting the possibility to reduce the amount of required site-area to install buried pipes. Focusing on soil properties, a recent study analyses the effect of soil compaction level on

EAHE effectiveness by using an experimental lab facility reproducing hot and arid environmental conditions [105]. Results demonstrate that soil properties may induce large effectiveness variations (between 0.3 and 0.7 in the considered cases). Another factor to be considered for efficiency is related to EAHE operational mode, being correlated to the potential alteration of pipe surrounding earth temperature due to continuous EAHE operation. This issue is generally named the soil derating factor and is more evident when the earth thermal conductivity is low [106,107]. Different solutions were analyzed for reducing this effect, including alternative operation modes [108].

3.6.1.3 Benefit and Limitation

EAHEs were demonstrated to have a very high COP levels in both heating and cooling modes [109]. Nevertheless, in thermally neutral periods it is important to include a bypass control mode to avoid unwanted heat exchanges, requiring additional post thermal treatments by building HVAC systems. Furthermore, the removable of potential condensation water during cooling mode need to be considered since the design stage – i.e., by defining a minimal slope during pipes' installation and a drainage system. Furthermore, the presence of underground water levels near to the soil surface may reduce the applicability of this technology, even if recent studies are investigating EAHE effects under wet soils and in coastal sites. Finally, in specific climate characterized by an unfavorable yearly soil variation range in temperatures, this technology may not be fully effective. E.g., in hot-climates the EAHE potential may be limited by temperature summer variations of low-deep soil layers in a range higher than the assumed comfort threshold.

3.6.1.4 Performance

The EAHE effectiveness is at the base of monitoring comparisons [109] and climatic mapping of EAHE applicability. One climate-related simplified approach to define EAHE applicability is introduced in [110] and further validated on experimental data in [102]. The approach was applied to North American climates [111] including climate changes [112]. Further monitoring and simulation analyses of EAHE are performed by different authors considering large varieties of climates and showing a very large applicability potential for EAHE in different environmental conditions. For example, a study on EAHE effects on different Iranian climates is described in [113] analyzing the energy conservation effect on a sample residential building by using FLUENT 3D modeling. The study shows high variations in EAHE performances according to different climate and soils, suggesting that silt city soil is performing better than loam and clay soil in Iranian conditions. Furthermore, when EAHEs are correctly activated, a reduction in energy need is evident in all conditions, with special regards to desert areas. Similarly, another study on Iran climates was performed comparing hot-arid and cold conditions adopting a steady-state model [114]. This study shows a cooling potential of EAHE in reducing inlet air temperatures in summer in the range of 1.3-11.4 °C in hot-arid climate and between 5.7-11.1 °C in a cold climate. Differently, in winter, EAHE allows to increase the inlet temperature in the range 0.2-11.2 °C and 0.1-17.2 °C respectively for hot-dry and cold climate conditions. In line with the above-mentioned Iranian analysis, EAHE is more efficient in hot-dry climates even in term of potential number of activation hours and in energy saving percentage, i.e., a reduction by about 50 to 63% in energy needs in the desert site compared to a reduction by about 24-48% in the cold site. For hot and arid Algerian climates, a study analyses the effect of different design configurations of an EAHE assisted by a wind tower facility for space passive cooling [115]. The analysis demonstrates the higher importance that pipe dimensions have on the whole system performances in respect to wind tower dimensions. The best obtained result for the consider site in the south-west of Algeria reports a wind-tower generated airflow of about 590 m^3/h (tower height = 5.1 m and tower section = 0.57 m^2) and cooling potential of 30.7 kWh (EAHE pipe length = 70 m). The combination of wind-tower and EAHE performs better than the traditional combination of wind-tower and Evaporative porous surfaces. Another paper analyses the EAHE thermal performances in coastal Brazilian city locations [116]. The study bases on simulation results adopting the Simplified Computational Model described in [117] and adopting three different soil thermal properties by elaborating standard penetration test results. The considered climate is the one of the Rio Grande cities in the south of Brazil. Results show how water penetration in soil coastal sites, especially when coupled with high quantities of clayey soil layers, may reduce EAHE performances even by 60%, although, in these conditions, EAHE performances show very low variations when the installation depth is below 2 m. EAHE performances under warm humid climatic conditions were studied for a Mexican site adopting experimental results [118]. A pipe of 6 meter in length was buried at 2.5 meter in depth and monitored for 6 months showing a good performance both in winter and in summer suggesting that this technique is able in cooling an airflow in humid-warm climate conditions. Soil temperatures were also monitored showing a slight variation in the range 26-28 °C with higher temperatures in August and September. Cooling arrives during daytime (operation time 9.00 – 18.00), while in some winter night EAHE may also be used for air heating, even if the environmental air never goes below 20 °C. Another research focuses on different Mexican climate conditions adopting a pseudo-transient numerical model [119]. The warmest and coldest days for an extreme, a mild and a hot location were assumed for this analysis. In all the three locations EAHE allows to reduce heating needs in winter and cooling ones in summer, reaching respectively for extreme, mild, and hot conditions the following maximum differences in temperature in winter 6.3 °C, 12.5 °C and 3.2 °C, and in summer 17.4 °C, 10.2 °C, 10 °C. A study analyses the potential benefit of EAHE when coupled with traditional window air-conditioner units in the central Indian climate (hot and humid conditions) [120]. The paper analyses the effect of different hybrid mechanical cooling system configurations on an experimental test room. Results demonstrate the positive effect of EAHE when coupled with traditional window air-conditioners for space cooling. A reduction in electricity needs by 6.7-10.9% was reached according to specific configurations adopting a typical window AC airflow of 11 m/s. Nevertheless, higher energy reductions may be reached by this hybrid configuration due to the fact that EAHE allows reducing the airflow without losing comfort, especially under specific soil wetness conditions. Furthermore, EAHE coupled solutions are more suitable also on the economic point of view (between about 5 to 10% more positive) considering payback analyses. Another analysis of EAHE performance evaluation, including life cycle analysis and CO_2 emission payback periods, is reported in [121] focusing on developing country applications. The paper underlines the great potential of EAHE in bringing extreme conditions to comfort ones in both winter and summer for typical environmental conditions of Bangladesh climates.

3.6.1.5 Application

Concerning EAHE applications, a recent study focuses on the definition of a EAHE design methodology based on quantitative analysis (CFD) with the aim to inverse calculate buried pipes parameters able in maximizing the indoor comfort [122]. Starting by the required indoor temperature fluctuations, the approach inversely defines EAHE characteristics to fit requirements. The method allows to reduce over dimensioning of EAHE and including building characteristics as new EAHE design parameters. A sample application is also included for the Chongqing climate (China) showing the soundness of the approach. Other advancements regarding EAHE applications concern the integration of EAHE with additional technologies. On the one hand, several studies focused on coupling EAHE with passive airflow activation systems, such as solar chimney [123,124]. In [124] the integration of EAHE with a solar chimney is investigated for ventilation and cooling purposes in solar house spaces without activating fans during the daytime. Results show very interesting results, suggesting that with the correct dimensioning of both coupled systems, it is possible to guarantee indoor comfort conditions in buildings especially in favorable climatic conditions. The presented simulation model shows that this system may work even with limited solar radiation intensity (e.g., 100 W/m^2) and high environmental temperatures (e.g., 50 °C). The study reported in [123] demonstrates that EAHEs coupled with solar chimney allows to considerably reduce the electricity needs for space cooling and also have a positive effect in balancing peak electrical demand during the summer season. The research adopts a test facility (Allwine Praire Preserve) to analyze the system behavior showing that, during the monitored period, the solar chimney may allow to activate an airflow of 1000 m^3/h and a consequent maximum whole system cooling capacity of about 2580 W, which is higher than the expected building cooling needs. Maximal effectiveness is reached during the daytime, while results demonstrate that the coupled system may assure indoor comfort thermal conditions during the monitored periods. In addition to solar-chimney assisted ventilation, other studies focus on the potential airflow inducted in the building-EAHE system by the sole buoyancy ventilation forces. In [125], the potential of a buoyancy ventilation system in activating natural ventilation through the EAHE system is analyzed. A simulation model is applied to a sample building adopting the climate of Chongquing, China, characterized by hot summer and cold winter conditions. Results show that with a correct design of a buoyancy ventilation system –see for example the complete work on buoyancy ventilation dimensioning in Ref. [126] –, it is possible to reach a good cooling and heating capacity, higher than the one due to the sole ventilation, extending the applicability of ventilative cooling and IAQ ventilation.

Another EAHE research frontier concerns the development of solutions to reduce the amount of land required to install EAHE systems to install this technology also in dense areas such as cities. A recent approach is characterized by the development of vertical earth-to-air heat exchangers allowing to reduce the required land to only 1 m^2. Nevertheless, these solutions are more subject to large daily variations in the outlet air correlated to environmental conditions. A recent approach to increase the applicability of vertical EAHE by reducing outlet air fluctuations is presented in [127]. This study adopts annular PCM around the buried pipe. Thanks to an experimentally validated model the analysis shows that PCMs are able in reducing EAHE outlet air fluctuations by about 30% (31% for an air velocity of 1 m/s and 29% for an air velocity of 2 m/s). Furthermore, results show that PCM effectiveness may be increased by acting on its thickness, more than changing its thermal conductivity, even if small changes arrive after 5 mm. The proposed results early-illustrate that this solution may increase the applicability of EAHE even to dense urban areas where installation free land is very limited. Another innovative approach to reduce the amount of additional land required by EAHE is presented in [128]. In this research, a EAHE system integrated in foundations named FONDATHERM is analyzed. This system consists of a specific component installed in the foundation footing, subdividing this technological component into a first footing, the new EAHE element and a final blinding concrete layer. The paper presents this approach together with experimental validations. After one year of measurements, energy and economic analyses were carried out showing that the proposed system is very efficient during the cooling season even in respect to tradition EAHE solutions. During wintertime, the proposed technology is also effective, even if an on/off control system is suggested to allow an airflow control. Also, in this case EAHE can be installed in dense areas, being directly included in the foundations. A similar approach was presented in [129] by integrating EAHE in the water-filled raft foundation. This solution allows to take advantages of the almost stable temperature reached in building raft foundations and to install EAHE even in dense city areas. A residential application is analyzed thanks to monitoring data. The case study is in Yilan, Taiwan. Results show that this approach reach results similar to those of a traditional soil buried EAHE system at a depth of 2 m or more. Monitored data were also used to validate a simulation model to suggest design strategies. The paper clearly shows the energy and economic benefit of this EAHE system, being its installation done during foundation construction without considerable additional costs.

EAHE is a valid technology to support space cooling and pre-heating in different climatic conditions. Additional studies on the topic are summarized in [130] for what concern analyses on different configurations, in [131], concerning EAHE design, characteristics and HVAC system coupling, and in [132], focusing on latest research trends with special regards to EAHE combination with other technologies.

3.6.1.6 Technology Readiness level

In recent years, a growing number of EAHE systems is installed in buildings characterized by different dimensions and typologies. The reached TRL is hence 9, being fully commercial. Nevertheless, only few companies (e.g., Rehau, see Ground-air Heat Exchanger) support the design and installation of these systems limiting the commercial applications of this technology. Differently, other EAHEs' installations are independently designed by green architects and engineers requiring specific knowledge to define the system and its components (e.g., by adapting sewer tubes), due to the limitation on the market of specific commercial solutions. Several dynamic energy simulation tools allow to include EAHE, helping in dimensioning these solutions (e.g., TRNSYS; EnergyPlus including some of its commercial interfaces, i.e., DesignBuilder, – even if earth tubes are only allowed with scheduled natural ventilation mode). Research on the topic are characterized by a growing trend supporting the spread of innovative solutions characterized by different integration levels with building HVAC systems.

3.6.2 Borehole heat exchangers

3.6.2.1 Physical principle

The ground heat exchangers are classified as open- or closed-loop [133]. Borehole heat exchangers (BHEs) are the most common type of ground heat exchangers. BHEs are typically 50- 400 m deep and have a diameter of 10-15 cm [134]. The most common heat exchanger types used in BHEs are U-pipes and coaxial pipes, Figure 3-3. A U-pipe BHE consists of two straight plastic pipes connected at the bottom through a U-bend. A coaxial BHE consists of two concentric or eccentric pipes for working fluid circulation.

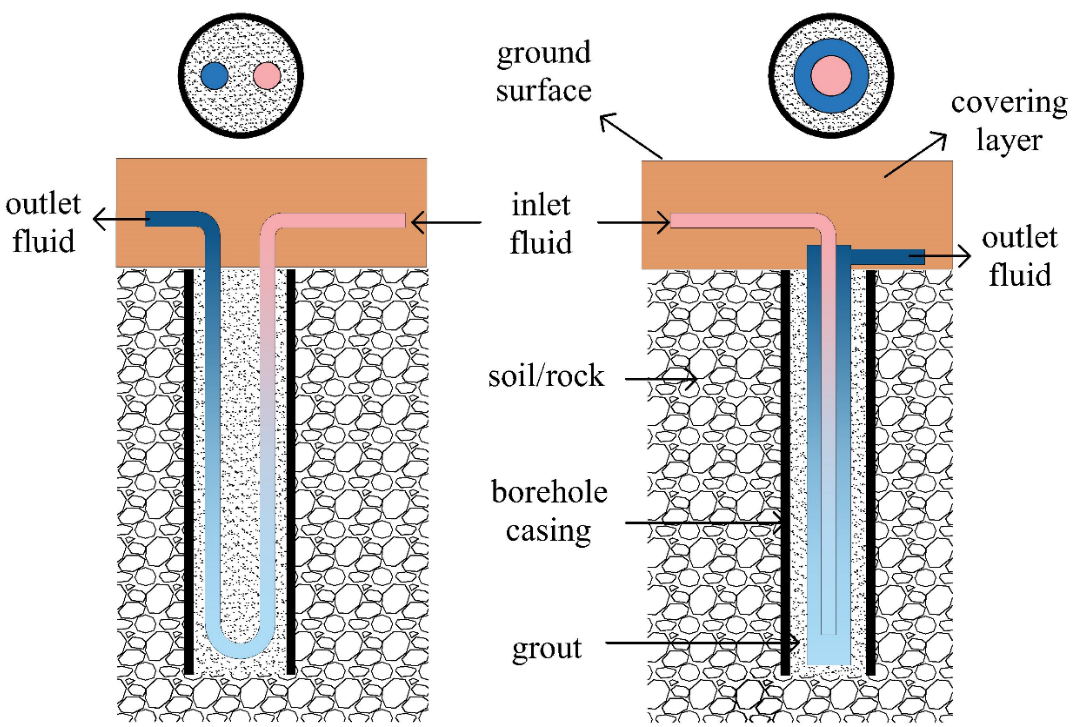

Figure 3-3 Schematic diagram of a A) single U-tube BHE and B) coaxial BHE

3.6.2.2 Classifications and design parameters

The classification of BHEs for comfort cooling in buildings falls into two main categories: direct-ground cooling (passive method) and ground-source heat pumps (active method), Figure 3-4. In a direct-ground cooling system, cooling is provided by supplying the cold water from the borehole system directly to the building cooling system. The direct-ground cooling system utilizes ground as the only source for cooling the working fluid without any mechanical refrigeration. In a ground-source heat pump system, the cooling is provided through a mechanical refrigeration system using the ground as a sink for dissipating the heat [135].

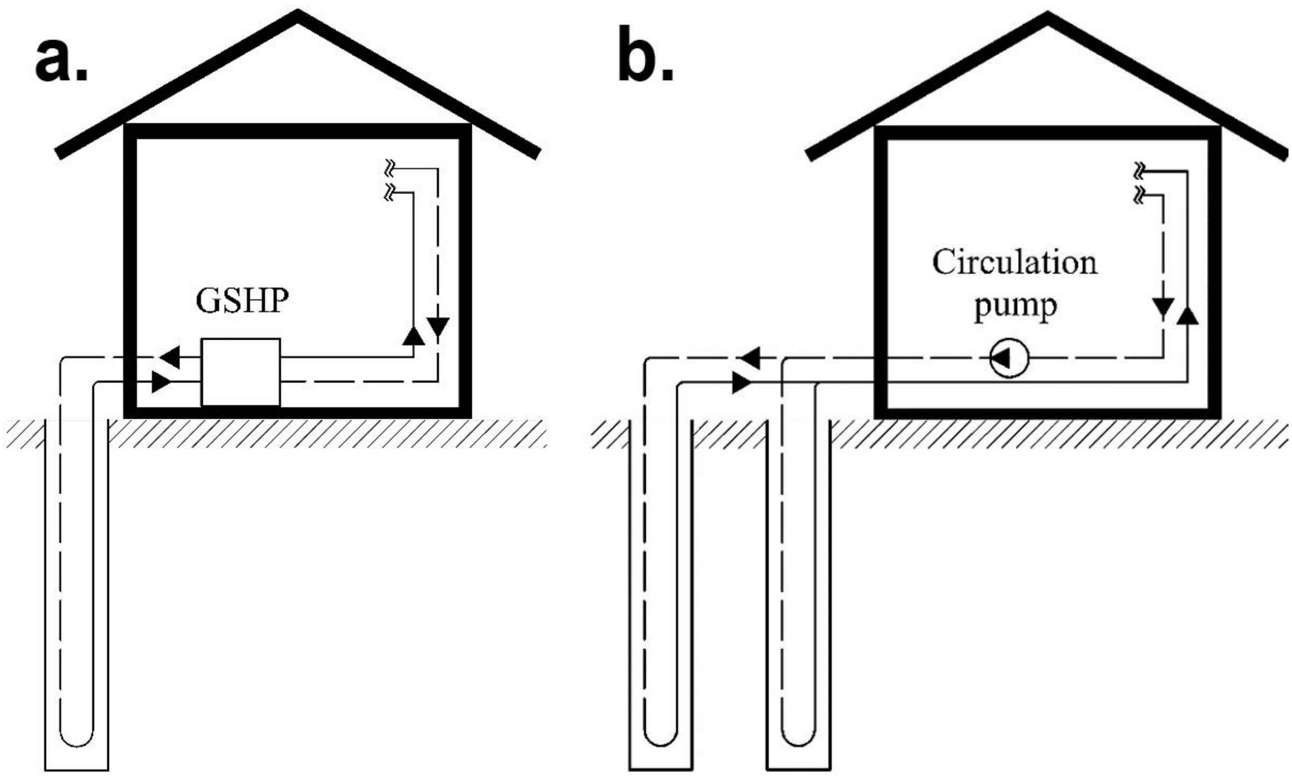

Figure 3-4 Schematic diagram of a A) ground-source heat pump GSHP and B) direct-ground cooling system

Sizing and dimensioning of is one of the principal tasks of designing a ground-source cooling system. BHEs are generally the most expensive part of a ground-source cooling system, and their appropriate dimensioning can help reduce drilling and installation costs, while simultaneously improving the thermal performance of the overall system. The key design parameters of BHEs include undisturbed ground temperature, ground thermal conductivity, borehole thermal resistance, ground heat transfer rates, and pumping rate of the working fluid [136,137]. Each of these parameters not only has its design requirements but each parameter also influences the choice of the other parameters.

Undisturbed ground temperature refers to the natural temperature of the ground before any thermal interaction takes place. The difference between the undisturbed ground temperature and the working fluid temperature in the building cooling system characterizes the feasibility of using the ground as the cooling source. The undisturbed ground temperature also influences the required depth of the BHE. The undisturbed ground temperature is usually determined by performing in-situ measurements in large projects and by applying estimation methods in small projects [138,139]. More information on the measurement methods and the estimation of undisturbed ground temperature can be found in [140–143].

Ground thermal conductivity characterizes the ability of the ground to conduct heat. It is mainly affected by environmental and compositional factors of the underground. The compositional factors are usually intrinsic properties of the ground, and include among others mineralogy, particle size, shape, and gradation of the underground. The environmental properties of the ground include the moisture content and the temperature of the ground. For larger systems, ground thermal conductivity is often determined by performing an in-situ thermal response test [139]. For smaller systems, conservative estimation of ground thermal conductivity based on the underground structure are used instead [144]. Generally, ground thermal conductivity values range from 0.5 W/m-K for clay to 3.7 W/m-K for carbonate rocks [145].

The thermal resistance of a BHE is the effective thermal resistance between the ground loop and the surrounding ground. It characterizes how well the working fluid in the BHE exchanges heat with the surrounding ground. Borehole thermal resistance is negatively correlated to the borehole heat transfer rates and its value depends upon several design parameters including the type and the circulation rate of the working fluid, BHE thermal properties and diameter, configuration of the BHE and thermal properties of filling material.

The influence of borehole fluid mass flow is generally accounted for in the borehole thermal resistance values [146,147]. While the low flow rate reduces the exchange rates of the borehole, excessive flow rates increase the pumping energy and thereby electricity consumption. Therefore, various studies have recommended setting the flow rate to ensure having a turbulent flow in the BHE [137,148,149].

Both the intensity and duration of the heat transfer rates to the ground influence the BHE dimensioning. Current borehole sizing tools use two different approaches for representing the ground loads to dimension BHEs. In the first method, presented by Eskilson [137] and later further developed by Hellström and Sanner [135,150], ground heat rejection rates are provided as monthly values. In this approach, monthly peak loads are used for determining the peak working fluid temperatures. The long-term thermal behavior of the borehole is defined by the total heat rejection and extraction to the ground. Another approach originally developed by Kavanaugh and Rafferty [151] is described in the ASHRAE Handbook- HVAC Applications [152]. This approach utilizes annual loads, average monthly load during the design month, and the maximum load for a period of 4-6 h during the design day.

3.6.2.3 Performance

Ground-source cooling has several potential advantages over other conventional methods. Firstly, and most importantly, the cooling performance of a ground-source cooling system does not deteriorate with rising ambient temperatures. This, as discussed earlier, is because the subsurface temperature below a certain depth is insensitive to seasonal and diurnal variations. Several measurement studies [138,153] have shown that ground-source systems have better performance at peak load conditions than at part load conditions. This is because the percentage share of the parasitic energy consumption of circulation pumps and other auxiliary equipment is lower under peak load conditions. Another noteworthy advantage of the ground-source cooling system is that the heat rejected to the ground in summer can be extracted back in winter to provide heating. If the net injection and extraction rates to the ground are balanced, the size of the BHE is reduced significantly. In case of a cooling dominant situation, the BHE must be sized accordingly to handle the future heat buildups in the ground. Another, positive aspect of the ground-source cooling is that it can be delivered to the conditioned space in convective or radiant forms and using water or air systems. Thus, it is possible to utilize the inherent advantages of the standard room cooling methods to provide the desired IEQ and occupant comfort, and/or to peak shave the cooling demand.

The performance of ground-source systems is typically measured as a ratio of the cooling energy provided to the electricity consumed by the system and is expressed as seasonal performance factors (SPFs). The SPFs of BHEs depend upon the method of their application. The direct-ground cooling applications with passive cooling have very high SPFs as the only energy input to the system is the work required to drive the circulation pumps. The typical SPFs reported in the literature for the direct-ground cooling systems are between 13-25 [154,155]. The ground-source heat pump systems with active cooling have comparatively lower SPFs than the direct-ground cooling systems due to the use of electrical or thermal energy to operate the heat pump. The SPFs of the ground-source heat pump systems for non-residential building cooling applications are reported in the literature to be between 2.1 and 3.1 [156,157]. Nevertheless, compared to the more commonly used air-source heat pumps, the ground-source heat pumps have superior performance and considerably higher SPFs. This is because the ground temperature during the cooling period is lower than the ambient air temperature, and because the heat is transferred through a working fluid (liquid) which, compared to air, has higher heat capacity and heat transfer coefficient [158].

The higher SPFs of ground-source systems suggest that their electrical energy consumption is lower. Moreover, the high performance of these systems also leads to smaller system sizes and lesser space occupation.

3.6.2.4 Application

In direct-ground cooling applications, the BHEs provide high-temperature cooling and supply water temperature to the building at higher temperatures than the traditional refrigeration-based cooling systems. The typical supply water temperatures from a direct ground cooling system are between 12 and 16 °C. The high-temperature cooling terminal units are very well suited for the direct ground-cooling applications. Evaluation studies of direct-ground cooling systems have indicated high thermal and energy performance of the system with various types of high-temperature terminal units, including pipe-embedded wall systems [144,155,159], radiant floor heating and cooling systems [160], thermally activated building systems [161–163], ceiling cooling panels [154], active chilled beams [156,164] and fan-coil units [164]. The direct-ground cooling systems can also be used to provide cooling through the ventilation air from the air handling unit [153].

In ground-source heat pump applications, the BHEs are used together with a mechanical refrigeration system. BHEs allow the heat pump to exchange heat with the ground. The heat pump uses the refrigeration cycle to further decrease the working fluid temperature to the level suitable for space comfort cooling. Since any desired supply temperature can be achieved, all types of room terminal units are compatible with this system in non-residential buildings [164]. The size of individual ground source heat pumps ranges from 5.5 kW for residential applications to several MW for commercial applications.

The limitations of the ground-source cooling systems are mostly associated with their first cost. These systems have considerably higher initial costs than traditional cooling systems. However, the payback time of a ground-source cooling system is short [157].

3.6.2.5 Technology readiness level

At the system level, ground cooling using borehole heat exchangers and comprising both direct and indirect applications is a fully mature technology at TRL 9. It has been used worldwide for several decades and there exist hundreds of thousands of actual systems operating over the full range of possible conditions. There also exists a great wealth of information and knowledge concerning design methods, installation procedures, operating practices, and application examples in literature. Moreover, there are several research centers, professional associations, and scientific and professional bodies defining norms and standards, protocols and guidelines, and best practices at local, national, and international levels.

At the subsystem level, a borehole heat exchanger comprises a closed-loop vertical heat exchanger and the grouting material. The most used heat exchanger types, including U-pipes with single or double loops and coaxial, are made from polyethylene. These heat exchangers are widely available commercially and are at TRL 9. The typical grouting materials for borehole heat exchangers are bentonite- or silica sand-based. These grouting materials are also widely available and are at high TRLs. However, research and development on new heat exchanger types and more suitable materials is actively going on both in academic and in industry settings. The focus is on developing innovative designs and materials to enhance the heat transfer and/or to decrease the thermal resistance of the borehole heat exchanger. Several alternate heat exchanger designs, including spiral, multipipe coaxial, coaxial with helical vanes, and coaxial with flexible outer pipes, among others, are at different stages of development and commercialization. Similarly, several new materials and additives, including new cementitious mixes, carbon fibers, and phase change materials, among others, are being investigated and developed for borehole heat exchanger applications. The TRLs of these new developments range from early lab-scale (TRL 1-3) to commercial demonstration (TRL 8).

3.7 Night Sky Radiative Cooling

3.7.1 Physical Principle

Night sky radiative cooling represents the passive process in which a terrestrial surface releases heat to the sky through net loss of long-wave (thermal infrared) radiation [165,166]. The radiative heat exchange with the sky can take place both during night and day. However, incident solar radiation on the body during daytime counters the radiative heat transfer to the sky [165,167,168]. Therefore, this technology is mostly associated with nighttime when the sky can reach temperatures below 0 °C [169,170]. Moreover, the convective heat transfer has a negative impact on the cooling output if the surface temperature of the body is lower than the surrounding air [169,171–175].

The major parameters that influence the radiative cooling directly are related to the environment: air temperature, relative humidity, cloud cover, cloud base height [169,173–175], and the radiative properties of the terrestrial surface, such as thermal emissivity [172,176]. Additionally, the convective heat transfer and evaporative cooling can also enhance the total cooling potential subject to air temperature, relative humidity, and wind velocity [169,173–175,177,178].

3.7.2 Typologies and design parameters

The use of night sky radiative cooling for buildings can be classified as passive or active. Passive sky cooling occurs when a surface radiates heat to the sky without any energy input [165]. Active sky cooling uses energy to circulate a heat transfer medium (e.g., water or air) through a radiator [166] that releases heat to the environment.

The application of night sky radiative cooling can have a wide range of use since any surface can release heat to the sky through long-wave radiation. However, it can be integrated in the building sector through cool envelope materials or through solar heating systems. Thus, night sky radiative cooling can complement solar heat and power production if the required additions (components such as storage tanks, pumps) and alterations to the control are made. Certain innovations with high solar reflective materials can even allow dedicated radiators to cool below ambient air temperature during the day under direct sunlight [168].

In most of the previous studies, night sky radiative cooling was employed actively with a solar thermal collector or a photovoltaic/thermal panel (PV/T) as the radiator and a liquid as the heat transfer medium. The systems were usually comprised out of two loops connected by a storage tank. On one side, the fluid in the tank was cooled by circulating it through the solar panel at night. The second loop, located on the building side, circulated the cold water from the storage tank through an indoor component (e.g., radiant ceiling), conditioning the indoor environment. Since the two loops usually had different working fluids, a heat exchanger was present between them. Such a system was presented by [169] where cooling was provided to a low-energy building by circulating cold water through a system containing a cold-water tank, a radiant floor and an active phase change material (PCM) ceiling construction. The water in the tank was circulated through the floor and the ceiling to extract the heat which was then released to the environment through the PV/Ts. A similar system having a PCM ceiling connected to a PV/T system for electricity, hot, and cold-water production was analyzed by [179] where the PCM ceiling was discharged at night by the cold water produced by the PV/Ts.

Design is an important factor for the optimal performance of both passive and active systems. Regardless of the application, most studies mention properties such as geometry, emissivity [167,176,180], and tilt [166,171] as parameters that influence the radiative heat exchange. When a heat transfer medium is circulated actively through a radiator, its flow rate and supply temperature are also included as design parameters [166,171,172,181]. The radiator area and the thermal mass are also essential design parameters when dimensioning the system.

3.7.3 Benefits and limitations

Energy savings is one of the main benefits of night-sky radiative cooling [165]. By radiating heat to the sky, a share or the entire cooling energy required can be covered depending on environmental conditions [166,171,177,182]. Moreover, as solar thermal collectors and PV/Ts are mainly used for heat and electricity production during the day, generating cold water at night increases their utilization factor [166,171,183]. Since each can use water as a heat transfer medium and provide high-temperature cooling, solar thermal collectors and PV/Ts can be coupled with water-based high-temperature cooling systems [171][184]. Another advantage is the low cost of solar thermal collectors, and PV/Ts, with even lower investment costs when they are already installed for hot water production [166,180,181].

The main limitations to night-sky radiative cooling are its time and climate dependencies, similar to other renewable energy technologies such as solar and wind energy [171]. Due to its fluctuating nature (hourly, daily), it requires some form of thermal storage such as additional thermal mass for direct passive use. Active systems can use storage tanks and enhanced thermal mass such as thermally active building systems (TABS) and PCM panels [169,175,179,183,184] to counter short-term (hours to days) availability issues. Another negative side effect is represented by the increase in the HVAC system complexity, i.e., addition of pumps, piping, and storage tanks. Furthermore, the HVAC system's control will require additional conditions for an efficient use since the system must decide when to prioritize heating over cooling or the other way around if the same radiator is used for both. Since certain substances such as glycol/water mixture are used as the heat transfer medium to reduce the risk of freezing, safety equipment might be required to avoid the pollution of the environment.

3.7.4 Performance

When assessing the performance of night sky radiative systems, most studies reported the specific cooling power in W/m^2 panel area [166,168,169,171–174,177,178,180,181,183,185] and the specific cooling energy in kWh/m^2 panel area [169,174,177,179]. However, due to the effect of other factors such as the convective heat exchange on the total cooling power, at least one of the contributions due to convection and radiation should be presented in order to critically assess the technology's potential [166,169,175].

For active systems, where energy is supplied to a component such as a pump or a fan to circulate the heat transfer medium through a radiator, the cooling power of the radiator can be divided by the energy use of the pumps, i.e., determining the coefficient of performance (COP). Nevertheless, only a few of the previous studies provided COP values. Since auxiliary systems can be employed when the cooling energy provided from night-sky radiative cooling cannot cover the entire cooling load, the amount of energy savings provided can be quantified as the share of renewable energy supplied into the system [166,169,171]. Moreover, in cases where solar collectors or PV/Ts are investigated, the heating energy and electricity should also be reported [169,171,179]. Nevertheless, the indoor thermal environment could also be a KPI in instances where the radiator supplies cooling energy to a system that directly conditions the indoor thermal environment of a building [166,173,177,179,182].

In terms of reliability, the performance of night sky radiative cooling in the future depends mainly on the application e.g., on the life of the solar collectors and PV/Ts, and the way the system maintains its radiative properties such as emissivity. However, their performance will be dependent on the climate and will benefit from high diurnal temperature changes due to the convective heat exchange [169,173,177]. According to [178], cloudiness has a negative effect on the radiative cooling power while low humidity levels enhance it. Furthermore, [175] observed an increase in the specific cooling power in locations with large annual variations in sky temperature. A study by [174] investigating the influence of climate on the potential of night sky radiative cooling showed that air temperature has the biggest influence as it affects both the radiative and the convective heat exchange. Relative humidity and wind speed also influence considerably the cooling performance. According to the same study, although overcast skies reduce the night-sky radiative cooling potential at night, the effect might be offset by the reduced higher solar heat gains during the daytime. More information on the cooling potential of solar collectors and PV/Ts is available in Table 3-2.

Table 3-2. Night radiative cooling powers of radiators.

Author	Type of study & season	Location	Climate	Radiator	Specific Cooling Power [W/m^2]
Meir et al., 2003	Experiment, Spring-Summer	Oslo, Norway	Different conditions	Unglazed solar collector	60
Eicker & Dalibard, 2011	Experiment, Winter	Stuttgart, Germany	-	PV/T	100-120
	Experiment, Summer	Madrid, Spain	Hot/Dry		60-65
	Simulation, Summer-Autumn	Madrid, Spain	Hot/Dry		41
	Simulation, Summer-Autumn	Shanghai, China	Hot/humid		61
Anderson et al., 2011	Experiment	New Zealand	-	Unglazed solar collector	50
Hosseinzadeh & Taherian, 2012	Experiment, Summer-Autumn	Babol, Iran	Humid under clear sky	Flat plate solar collector	45
Zhang & Niu, 2012	Simulation, Whole year	Hong Kong, China	Hot/humid	Unglazed solar collector	30
		Shanghai, China	Present higher annual variation in sky temperature than Hong Kong		42
		Beijing, China			45
		Lanzhou, China	Cool/Dry		46
		Urumqi, China	Cool/Dry		46
Yong et al., 2015	Experiment, Summer	Tianjin, China	Hot	Unglazed solar collectors	87
Péan et al., 2015	Experiment & Simulation, Summer	Lyngby, Denmark	-	Unglazed solar collector and PV/T	20-75
Bourdakis et al., 2015	Experiment & Simulation, Spring	Lyngby, Denmark	-	PV/T	92-119
Xu et al., 2015	Experiment, Autumn	Beijing, China	23.2-29.5 °C, 21%-74% RH	Flat plate solar collector	26

Author	Type of study & season	Location	Climate	Radiator	Specific Cooling Power [W/m^2]
Tevar et al., 2015	Experiment, Summer	Almeria, Spain	-	Radioconvective panel	45-60
Hu et al., 2016	Experiment, Summer	Hefei, China	Clear versus overcast sky	SH-RC	23-50
Bourdakis et al., 2016a	Experiment, Summer-Autumn	Lyngby, Denmark	-	PV/T	56-82
Bourdakis et al., 2016b	Simulation, Spring-Autumn	Lyngby, Denmark	-	PV/T	43
		Milan, Spain	-		36
		Athens, Greece	-		33
Péan et al., 2016	Experiment & Simulation, Summer	Lyngby, Denmark	-	Unglazed solar collector	49-52
				PV/T	42-50
Joubert & Dobson, 2017	Experiment, Spring	Stellenbosch, South Africa	-	Unglazed solar collector	55
Bogatu et al., 2019	Simulation, Spring-Autumn	Oslo, Norway	Warm/humid	PV/T	47-81
		Copenhagen, Denmark	Warm/humid		48-88
		Frankfurt, Germany	Warm/humid		38-73
		Milan, Italy	Hot/humid		29-62
		Bucharest, Romania	Hot/humid		35-67
		Madrid, Spain	Hot/dry		38-71
		Athens, Greece	Hot/dry		17-52

3.7.5 Application

Considering that the environment strongly influences the night sky cooling potential of solar thermal collectors and PV/Ts, some locations present higher specific cooling powers (as seen in Table 3-2). Their cooling performance improves in dry, cold climates with high day-night and annual temperature fluctuations. Thus, several studies document that night radiative cooling was able to cover a share or even the entire building cooling energy use depending on the geographical location. [169] showed that the PV/Ts managed to cover 27% of the cooling energy demand of a low-energy building for Madrid, Spain, while only 11% for Shanghai, China. Another study [166] found that the radiative cooling system covered the cooling demand of a modelled single-family house, however not for high-temperature summer conditions with high relative humidity. Coverage ratios of up to 120% were also registered in a simulation study made by [171], where PV/Ts managed to cover the cooling demand of a two-person office in northern European climates.

Both glazed and unglazed solar thermal collectors were used as radiators in the investigated studies. Nevertheless, [186] found negligible differences in the cooling power between the solar thermal collectors and PV/Ts although the glazing was expected to reduce the heat transfer through infrared radiation. Their orientation was rarely investigated as all solar thermal collectors and PV/Ts were south oriented, thus prioritizing solar heating since the studies were made in the northern hemisphere. However, according to [168] the radiative heat exchange is expected to be optimum at a 0° tilt. Furthermore, in a simulation study presented by [171], the cooling energy per night increased for a south oriented PV/T when positioned vertically as the time window in which the incident solar radiation was present on the cells was reduced.

The use of solar thermal collectors and PV/Ts can be widely spread in different urban spatial structures. However, their implementation becomes more complicated as the density of the built environment increases since surrounding objects (e.g., other buildings) can block the radiative exchange to the sky [166]. Additionally, the heat island effect of dense urban environments and reduced wind velocity might negatively affect their performance through the convective heat exchange. Nevertheless, since this technology can be employed through solar thermal collectors and PV/Ts, it is suited for both new construction and retrofits if there is enough space available.

3.7.6 Technology readiness level

As the sky is a free cooling source, night sky radiative cooling is a renewable technology available for any consumer. Moreover, it is ready for market implementation since it can be employed through existing technologies such as solar thermal collectors and PV/Ts. However, further development and research can improve and optimize both the equipment and the systems employed. Although it can be sold directly to consumers, the involvement of design engineers and building contractors will improve its use leading to an optimum operation of the desired application.

3.8 High-temperature cooling systems: radiant cooling

3.8.1 Physical principles

A hydronic (water-based) radiant cooling system refers to a system in which water is the heat carrier (medium of energy distribution) and more than half of the heat exchange with the conditioned space is by radiation [187,188].

Radiant cooling systems condition large surfaces in indoor spaces, usually floors, ceilings, and walls. Heat transfer from indoor spaces is by a combination of radiation and convection via cooled surfaces. The convection is usually natural, unless the air movement over the conditioned surface has been enhanced—e.g., by supplying air from a ventilation diffuser.

These systems employ high-temperature cooling. This means that the heat-transfer medium (usually water) is near room temperature. The large, conditioned surface areas make it possible to cool indoor spaces with a small temperature difference between the conditioned surfaces and the room.

3.8.2 Typologies and design parameters

Radiant cooling systems can be classified as follows [187]:

- Radiant cooling panels. These are physically and thermally decoupled from the structure of the building, usually as a suspended ceiling (
- Figure 3-5).
- Radiant surface systems. These embed pipes in building surfaces that are usually insulated from the main building structure (Figure 3-6 a-c).

Thermally Active Building Systems (TABS). These embed pipes in the main building structure so that the thermal mass of the building can be activated and controlled, usually by means of water circulation. TABS are used particularly in concrete floor slabs, and walls of multi-story buildings (Figure 3-6).

Figure 3-5 and

Figure 3-6 show the different types of radiant heating and cooling systems.

Figure 3-5 Example of a cooling panel [187].

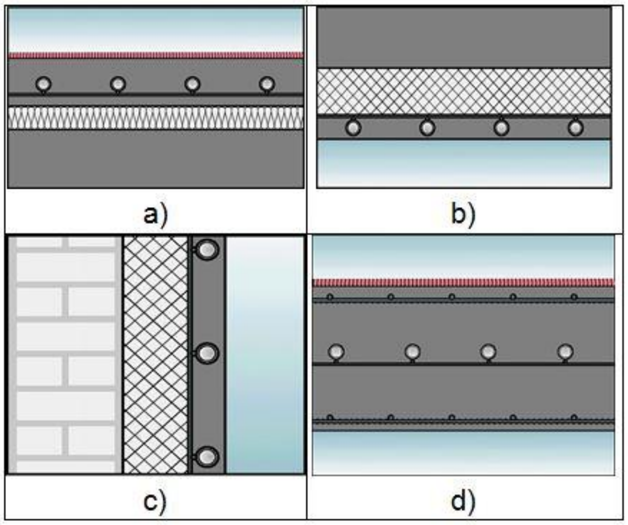

Figure 3-6 Cross sections of embedded radiant systems: (a) Floor, (b) Ceiling, (c) Wall, and (d) TABS [189].

Supply water temperatures in radiant systems are usually 25 – 40 °C for heating and 16 – 23 °C for cooling. When using TABS, the average of 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 all year.

Radiant panel systems and radiant surface systems can be used in both new buildings and renovated buildings. However, TABS need to be installed in the construction phase of the building. This requirement limits the use of TABS in renovation projects, which is particularly relevant in a European context. To address this limitation and to bring the benefits of TABS to renovation projects and to lightweight buildings, a particular type of radiant ceiling panels has been emerging. This technology combines PCMs with radiant ceiling panels to create a similar system to TABS—i.e., PCM radiant ceiling panels. Pipes are embedded in the PCM. Water is circulated in pipes to control the charging (melting) and discharging (freezing) behavior of PCM, which in turn controls the thermal environment in indoor spaces. This is a promising solution and has been proven to perform alike TABS in terms of operation, energy performance, heat removal from rooms, and indoor thermal environment [190–193]. Development is ongoing to characterize the performance of such panels so that they can become one of the common heating and cooling solutions for buildings.

3.8.3 Benefits and limitations

Radiant cooling systems have the following benefits and advantages compared to more conventional (e.g., all-air) cooling systems.

- Use of high-temperature cooling.
- Ability to couple to natural heat sources and sinks, such as ground, lake water, or seawater [195–197].
- Favorable operating conditions for cooling plants (mainly due to operating temperature ranges and return temperatures), increasing the efficiencies of heat pumps, chillers, and boilers [195,197].
- Possibility of transferring peak cooling loads to off-peak hours, reducing peak power demand [196].
- Smaller-capacity cooling plants, and smaller-capacity ventilation systems (i.e., air-handling unit capacity, duct size) [198,199].
- Reduced annual energy use of cooling systems, including auxiliary components such as pumps and fans.
- Lower heat gains during distribution from the cooling plant to indoor spaces [198,200].
- Flexibility in use and design of indoor spaces due to lack of indoor terminal units in occupied zones, no cleaning requirements, and quiet operation [197].
- Uniform temperature distribution in indoor spaces, reduced risk of draft, and reduced vertical air temperature differences.
- Reduced construction costs thanks 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 [199].
- Possible initial and operational (such as maintenance and energy) cost savings [192].

Even though radiant systems have several benefits compared to more traditional systems, the following issues should be considered to optimize system performance:

- Fine-tuning of the system in the first one to two years of operation [201].
- Proper load calculation and system dimensioning [195,198].
- Humidity control (latent loads) [195,197].
- Acoustic environment [199].

- Ventilation - radiant system interaction (e.g., avoiding simultaneous heating and cooling, avoiding condensation, providing the necessary amount of fresh air).

One of the major characteristics of radiant systems is that they address only sensible heating and cooling loads. Therefore, radiant systems need to be coupled with ventilation systems, usually in the form of a dedicated outdoor air system (DOAS). The main function of ventilation systems is to regulate humidity (i.e., to dehumidify the air) and provide fresh air to indoor spaces [187]. There are various combinations according to the location of radiant surfaces and air distribution principles. A summary of the coupled system configurations in the building environment and their performance in terms of thermal comfort and air quality have been systematically discussed [202].

The high-temperature cooling principle of the radiant systems permits coupling to renewable energy sources such as a ground heat exchanger. When coupled to a renewable energy source (e.g., a ground heat exchanger) instead of a refrigeration machine (e.g., a chiller), the only electricity input is to run a circulation pump that circulates the brine in the ground heat exchanger, instead of the electricity input to the compressor of a refrigeration machine. This circulation pump can be powered by on-site and off-grid renewable electricity generation —e.g., solar photovoltaics, or even a generator in case of an emergency. Besides renewable energy sources, radiant systems could also couple with natural or passive cooling resources. A study in Malaysian climate was recently presented in [203], using a pitched roof as heat exchanger to chill the water during the night and as cooling medium to the radiant cooling panels. Another study focused on the adoption of evaporative cooling to reduce the radiative panel fluid temperature in a hot and humid climate [204]. The results show that a cooling tower can be an option to provide cool water for the radiant cooling system and pre-cool the ventilation air to achieve thermal comfort.

Buildings cooled by TABS allow temperatures to drift during the day, rather than maintain a strict temperature setpoint with a certain dead band. The high thermal mass of TABS will even out the room temperatures between day and night. 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., in case of a power failure).

Combining radiant systems with high-efficiency cooling machines means a low power demand so that the system can easily run-on electricity generated by a generator or by batteries (could be critical in cases such as hospitals).

3.8.4 Performance

Usually, a total heat transfer coefficient is used to quickly determine the cooling capacity of a radiant system depending on the conditioned surface (floor, ceiling, or wall). Total heat transfer coefficients (combined convection and radiation) are 7, 8, and 11 $W/m^2{\cdot}K$ for floor cooling, wall cooling, and ceiling cooling, respectively [187] 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 26 °C for cooling under design conditions, the maximum cooling capacities can be estimated. The maximum cooling capacities is 42 W/m^2 at the floor of the occupied zone; 72 W/m^2 at the wall; and 99 W/m^2 at the ceiling. At the floor of perimeter zones, the cooling capacity could also increase remarkably depending on the boundary conditions such as direct solar radiation on the floor. Further details regarding the total heat exchange coefficients, acceptable surface temperatures, and maximum capacities are provided in [187,205].

There is a growing interest in the application of radiant floor cooling systems in buildings with high window-to-wall ratio (such as airports, railway stations, and shopping malls) due to its superior performance compared to more conventional air-conditioning systems. The main reason behind this application is that radiant floor cooling systems remove the heat gains from direct solar radiation immediately (i.e., before it can heat the space) and the cooling capacity of the floor cooling system increases considerably due to the change in boundary conditions on the floor surface [197]. Different studies have shown that the cooling capacity of a floor cooling system exceeds 42 W/m^2 and may even exceed 100 W/m^2, when there is direct solar radiation on the floor surface [187,206–208]. Another reason is that when a floor cooling system is coupled with an appropriate air distribution strategy (e.g., displacement air distribution), this system combination allows conditioning only the occupied zone of the indoor space, in contrast to more traditional all-air systems that condition the entire volume of space.

3.8.5 Application

Radiant cooling systems can be applied in many climates and building types. They have been employed in a variety of indoor spaces such as offices, residential buildings, workshops, laboratories, food storage cellars, and meeting rooms [209]; schools [210]; museums [211]; airports [212]; and sports halls and hangars [187].

The main challenge for using radiant cooling systems is avoiding condensation; therefore, its applications in humid climate zones require careful design and operation considerations. Studies have shown that when properly designed, controlled, and coupled with an appropriate ventilation system, radiant cooling systems can also be applied in hot-humid climate zones without problems [212–215].

3.8.6 Technology readiness level

The previously described radiant heating and cooling systems (i.e., radiant heating and cooling panels, radiant surface systems, and TABS) are available in the market. These systems and components could be bought by private individuals (e.g., for a residential building) or could be bought by building contractors.

There are products in the market that contain PCMs (e.g., gypsum ceiling panels with microencapsulated PCM) or PCM as a raw material can be bought directly from different manufacturers.

The radiant ceiling panels with PCMs described in this study are not yet sold, but all components of these radiant ceiling panels (such as PCMs, piping, and metal panels) are available in the market.

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4 Enhance personal comfort apart from space cooling

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4.1 Physical principles

In contrast to total volume systems which condition entire indoor spaces, personal comfort systems (PCS) condition the immediate surroundings of the occupants, creating micro-environments that can both:

- Extend the range of temperatures that is generally perceived as comfortable, thereby reducing the energy used by mechanical air conditioning, and
- Accommodate the interpersonal thermal differences that are inherent in any occupancy, thereby increasing the percentage of comfort in the space over that possible with uniform environmental control. The improved comfort may also increase occupants' productivity.

Personal comfort systems can use very small amounts of energy, often using DC power, making them inherently suitable for resilience applications and adaptable for use during energy emergencies.

The cooling takes place via two primary mechanisms, cooling the occupant directly by convective heat transfer to nearby airflows or by conduction to cooler contact surfaces. Condensation-proof radiative cooling may become feasible in the future [1].

The human body is continuously losing heat to the environment to stay in comfortable thermal balance. PCS in cooling mode enhance this heat loss, allowing comfort at higher ambient temperatures. The heat is transferred via the body's skin and respiratory tract, through clothed and exposed surfaces with which the PCS interacts. A PCS' total heat extraction depends on the specific body parts that it targets. Human body parts vary significantly in how readily they transfer heat, due to differences in underlying vasculature, sweat production, body geometry, and other factors. In addition, the comfort caused by cooling is sensed by thermal sensors in the skin, whose sensitivities to warmth and coolth vary widely across the surface of the body due to the arrangement of the nervous system. Heat loss rate and cooling sensitivity together determine the effectiveness of PCS designs. These issues are reviewed in [2] and [3].

Cooling the head and upper body is effective in warm and neutral environments. The torso may also be cooled; it has relatively large surface areas for heat transfer from the body's core, but people are sensitive to large cooling temperature gradients in the back. The hands and wrists may also be cooled; when the body is warm, they are vasodilated allowing high heat transfer for their relatively small surface area.

The PCS cooling, in terms of heat loss and in terms of how it extends the subjects' comfort zone, is established during the PCS product design, and is characterized in terms of its *cooling corrective power*. If all occupants have access to PCS, their corrective power can be input directly into a building energy simulation in the form of an elevated cooling temperature setpoint, after which building simulation and design proceeds conventionally.

4.2 Typologies (classifications) and design parameters

4.2.1 Types of cooling PCS

Cooling PCS may involve the following technologies:

- Vertical-axis ceiling fans and horizontal-axis wall fans (such fixed fans differ from pure PCS 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, some including phase change material storage
- Radiantly cooled panels (these are currently less for PCS than for room heat load extraction)
- Conductive wearables
- Fan-ventilated clothing ensembles
- Variable clothing insulation: flexible dress codes, variable porosity fabrics.

Recently completed review articles on PCS give examples of classifications and currently available PCS solutions [4–7].

4.2.2 Design parameters: key performance indicators (KPIs) for cooling PCS technologies

4.2.2.1 Thermal Comfort KPIs

Table 4-1 summarizes thermal (and other) KPIs for fan-powered occupant cooling and for personal comfort systems.

Table 4-1 KPIs for fan-powered occupant cooling and for personal comfort systems (source: Center for the Built Environment, University of California, Berkeley).

Technology	Thermal	Comfort	Efficacy	Energy	Other performance	Experiment and or simulation
Occupant cooling using room fans	Raising the AC cooling setpoint [°C] [8] The setpoint rise can be equal to the fan or PCS CP. Potential to eliminate need for AC	Corrective power (CP) [°C] [7] Fan coverage of occupied floor area (%)	Corrective power energy-efficacy (CP/Pelectrical device); cooling-fan efficiency index (ΔTcooling effect/Pelectrical device) [9]	Energy savings from both fan cooling and PCS can be conservatively estimated from [10] as: 10% of building cooling HVAC energy/1 °C setpoint rise.	Time to comfort; accessibility of controls to individuals or groups	Experimentally determined with human subjects or thermal manikins. Some simulation now feasible.
Personal comfort systems, including thermal wearables and occupancy dress code	Raising the AC cooling setpoint [°C] [8] Potential to eliminate need for AC	Corrective power (CP) [°C] [7] Adequate PCS devices made available to all occupants	Corrective power energy-efficacy (CP/Pelectrical device)	The COP of the PCS itself is determined using an electrical manikin: (Pbody heat loss / Pelectrical device).	Time to comfort; accessibility of controls to individuals or groups	Experimentally determined with human subjects or thermal manikins.

ASHRAE Standard 55-2017 Addendum D [11] provides the following definitions and performance specifications for personal or group cooling.

Definitions related to personally controlled or group-controlled cooling

Corrective power (CP): the ability of a PCS system expressed in degrees (°C, °F) to “correct” thermal conditions toward the comfort zone, measured as the difference between two operative temperatures at which equal thermal sensation is achieved - one a temperature in the comfort zone with no PCS, and one with PCS in use, with all other environmental factors held constant.

- Personal comfort system (PCS): a device to heat and/or cool individual occupants directly or heat and/or cool the immediate thermal environment of an individual occupant, under the control of the occupant without affecting the thermal environment of other occupants.
- Thermal zone: an area of a building designated by the designer such that the comfort zone is maintained within the occupied zone by local controls for its representative occupant(s).
- Readily accessible: capable of being reached quickly for operation without requiring those for whom ready access is required to climb over or remove obstacles or to resort to portable ladders, chairs, or other climbing aids.

Performance specifications needed to qualify as a personal comfort system (Addendum C)

A PCS must satisfy one of the following two conditions:

- A user-adjustable thermostat with ability of user to change setpoint by ±3 °C (±5 °F)
- Capable of changing the thermal environment of the space or individual occupant by the magnitude specified in 15 minutes or less from occupant control initiation, while metabolic rate and clothing insulation values are constant. For control measures that apply to a multi-occupant space, the change must meet the requirements for all representative occupants.

At design cooling condition, the measure shall change PMV by -0.5 or

- Average air temperature by -3 °C (-5 °F)
- Average air speed by +0.3 m/s (60 fpm)
- Mean radiant temperature by -3 °C (-5 °F)
- For personal comfort systems, the measure shall be listed in Table 4-2 or have a minimum corrective power of -2 °C (-4 °F).

Table 4-2 Prescriptive specifications needed to qualify as a personal comfort system (Addendum C)

Description	Requirements
Cooling	
Desk fan aimed at head/face/upper body	Capable of providing air speed at the occupant's head/face/upper body within range of 0.36 – 0.8 m/s (70.9 – 157.5 fpm)
Cooled chair	Capable of extracting 20 W from the body

Similar requirements and specifications exist also in other international standards such as EN 16798-1:2019 [12] and ISO 17772-1:2017 [13].

4.2.2.2 Energy and HVAC KPIs

The bottom-line energy-savings metric is [(HVAC energy required without PCS) minus (HVAC energy required with PCS)], divided by (HVAC without PCS), expressed as a percentage.

Efficient PCS devices used to elevate the setpoint in buildings draw negligible power compared to the HVAC energy savings [14]. One can assume that all PCS are on whenever the interior temperature reaches and exceeds the upper limit of the conventional ASHRAE comfort zone; this will be an overestimate, but the error will be too small to matter.

Energy KPIs related to PCS result from the cooling setpoint elevations enabled by the PCS, fan cooling, and the natural ventilation air movement in the building interior. Numerous studies have found that these setpoint elevations save roughly 10% of total annual cooling HVAC energy per °C elevation, which often amounts to 30-50% of baseline HVAC energy [8]. Elevating the cooling setpoint from a typical 23 °C (73 °F) to 26 °C (79 °F) saves 30% of energy without increasing discomfort percentage.

HVAC KPIs are reductions of annual unmet cooling and heating hours, and the reductions of the cooling and heating energy required during the peak-energy-demand periods. Another KPI is for the HVAC equipment downsizing made possible by widened thermal comfort zone using fan ventilation, personal comfort systems, and natural ventilation.

Effectiveness of PCS in achieving energy savings was reviewed and summarized in [4].

4.3 Benefits and limitations

4.3.1 Benefits

PCS offers both comfort and energy benefits. PCS allows occupants to personally control their thermal microenvironments and thereby satisfy their individual comfort requirements. Such comfort requirements differ due to variation in gender, age, body mass, clothing habits, and metabolic rate, and thermal adaptation [15]. Interpersonal differences among subjects in a typical laboratory study cause a standard deviation of 1 - 2 scale units on the standard ASHRAE seven-point thermal sensation scale [14], even when all are experiencing the same well-controlled conditions. This variation can be larger in field studies due to the non-uniform space conditions found in typical buildings. The 1 - 2 sensation scale units are equivalent to 2 - 5 K difference in ambient temperature. In jointly occupied spaces, it is therefore impossible for everyone's individual requirements to be met by any uniformly distributed temperature. ASHRAE Standard 55's target satisfaction rate among occupants is 80%, but in practice buildings often rate much lower than that. The large dataset of CBE occupant satisfaction surveys shows that 42% of occupants express dissatisfaction with their thermal environment [16]. There is ample room for improvement over the way existing buildings are conditioned. The only published case of a field study of office workers reporting 100% satisfaction involved PCS installed in each workstation [17]. In a large-scale field study, Kroner, and Stark-Martin [18] suggested that it is possible to increase productivity by at least 2% using PCS.

PCS offers an opportunity to save HVAC energy in buildings. HVAC consumes a large portion of the world's energy demand (approaching 20% of total energy use in developed countries and growing everywhere). Much of this energy goes into maintaining narrow indoor temperature ranges that building operators consider necessary for comfort. If it were possible to relax the temperature range in either the hot or cold direction, total HVAC energy is reduced at a rate of 10% per °C [10,19]. Savings of this magnitude exceed those of virtually any energy-conserving technology available in the industry, and they can be obtained through reprogramming controls sequences i.e., without changing the building's HVAC hardware. Saving in real buildings can be even higher due to the prevalence of faulty building HVAC operation, such as simultaneous heating/cooling within zones, whose energy waste is intensified by narrow temperature set points.

Widening the temperature range for energy must continue to ensure occupants' comfort, or at least provide the same level of comfort as in current buildings, which could be improved. Occupants themselves require far less energy to heat and cool than does the entire indoor space that houses them. PCS offers the opportunity to accomplish this. With small amounts of energy, it can provide individual comfort within a broader range of indoor ambient temperatures (varying over both time and space). It would be good to know the ability of different types of PCS and PV systems to correct for ambient conditions that might otherwise be outside the comfort range of individual occupants.

There have been several field studies of PCS cooling including fans [20] and heated and cooled chairs [21]. The most comprehensive study of PCS chairs involved 37 occupants in an office building in California over a six-month period. PCS heated and cooled chairs were distributed to

40 occupants, and thermal comfort was surveyed during the 6-months of the study. The PCS chairs produced much higher comfort satisfaction (96%) than is typically achieved in buildings.

4.3.2 Limitations

Apart from fans, choices for commercially available PCS are limited at present. For example, there are no effective cooled chairs on the U.S. marketplace. The primary objective for research in this area should be to publish performance specifications for effective PCS, for use by prospective manufacturers. These specifications should indicate both the desired corrective power of the devices, as well as targets for electrical energy efficiency levels that have been demonstrated to be possible in the research. Both should be optimal to assure the widespread adoption of PCS in building control, and the commercial viability of PCS products.

4.4 Performance

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

Advantages for resilience are:

- Flexibility in space heating and cooling temperature set points i.e., possibility of extended set points compared to traditional systems such as extending the room temperatures below 20 °C in the heating season and extending the room temperatures above 26 °C in the cooling season; these temperatures are based on the Category 2 of EN 15251:2007 [22] (now replaced by EN 16798-1:2019 [12]). An estimate of possible annual HVAC energy savings is 10% per K set point relaxation [10,19]; this value has been found repeatedly in both commercial office and residential buildings and can be used as a starting point for design.
- Possibility of reduced-size cooling plant or a plant that is run part-time during periods beneficial to electricity grid and supply sources
- Global warming can be better accommodated than at present.

4.5 Application

4.5.1 Building characteristics

For ceiling-fan cooling and PCS, no special building attributes are necessary.

4.5.2 Environmental characteristics

There are no special environmental requirements for PCS and ceiling-fan cooling.

4.6 Technology readiness level

Fans must look beautiful because they are often prominently visible, must generate low- or no audible noise, and be convenient to use. They should be very low power, preferably DC driven, in which the power demand for a middle speed range for a 1.5 m diameter fan is currently as low as 6 W.

In recent years, both ceiling fans and small desk fans have made great strides in their energy efficiency, silence, aesthetics, and acceptance by architects and occupants. Such fans are available and being actively and competitively marketed.

ASHRAE Standard 216 is a recently completed method of test promulgated to encourage the use of ceiling fans in building design. It includes data tables and design tools for fan layout.

The fan controls may be linked to the HVAC system to allow the HVAC system to be downsized or operated less intensively [23]. Also, for closer integration, the terminal ductwork of buildings might be removed with ceiling fans taking over the function of mixing the air-conditioned supply air in rooms. This provides both cost and aesthetic benefits in the most common HVAC air-systems.

The other potential PCS cooling systems, such as heating/cooling chairs and furniture-based systems should be designed to have optimal cooling effect on the human body, and have corrective power of at least 2-3 °C. These operate in the range of 3 to 15 W depending on the technology used. A summary of power use of different PCS was provided by [4].

One of the main barriers related to the application of these systems is the current lack of design and operation specifications, and the lack of performance evaluation guidelines [24].

4.7 References

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5 Remove latent heat from indoor environments

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5.1 Physical principle

Removing 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 the human comfort [1]. In high performance buildings, the percentage of dehumidification energy consumption from the building total energy consumption can be as high as 12.6-22.4% [2]. There are two major physical principles of removing latent heat from indoor environments, depending on the used dehumidification method. Refrigeration dehumidification method dehumidifies the air by lowering the air temperature through cool surfaces that have a temperature lower than the dew point of the humid air. Desiccant dehumidification dehumidifies air by lowering the vapor pressure of desiccant surface that absorb/adsorb the moisture from the passing humid air.

5.2 Typologies and design parameters

There are many dehumidification methods reported in the literature and applied in practice, including mainly desiccant dehumidification, refrigeration dehumidification, ventilation dehumidification, and thermos-electric dehumidification. Compared to ventilation and thermos-electric dehumidification, desiccant and refrigeration dehumidification are more sophisticated in dehumidification capacity and control accuracy, but more complicated in systems and more expensive in initial investment and operational cost.

Desiccant dehumidification is to utilize the humidity-absorbing/adsorbing material to absorb/adsorb the moisture. The driving parameter for the absorption/adsorption of moisture is the difference in vapor pressure between the desiccant surface and the passing humid air. When the desiccant surface vapor pressure is lower than that for the humid air, moisture would transfer from air to desiccant material until saturated or equilibrium conditions are reached. The desiccant can be regenerated by extracting the moisture out by warm air. There are two types of desiccant materials, namely solid or liquid. Solid desiccants [3] work with adsorption processes and liquid desiccants [4] [5] to absorb the moisture through chemical and physical processes. Compared to solid desiccant systems, liquid systems provide higher flexibility and control for moisture removal, as well as lower heating and cooling requirements for the regenerator and absorber [6], which have therefore increased attentions.

Refrigeration dehumidification utilizes conventional vapor compression cycles to dehumidify the humid air through cool-reheat processes. The humid air is dehumidified when it flows over a surface that has a temperature lower than the dew point of the humid air. Refrigeration dehumidification has been widely implemented especially in residential and small office buildings. The latent load of moisture content is reduced by lowering the temperature of the air. 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. It was reported that thermal comfort conditions can be met with refrigeration dehumidification only when the sensible heat ratio is above 0.75 [1]. In addition, the use of refrigerant would make negative effects on global warming and ozone depletion.

Thermos-electric dehumidification is to utilize the thermoelectric effect (Peltier effect) to convert electricity into a temperature difference across a Peltier module. The module includes two heat sinks, namely cold side heat sink and hot side heat sink. Humid air driven by the fan flows over the cold side heat sink and the water is dehumidified. The dehumidified air then passes through the hot side heat sink to be reheated before it is supplied to indoor environments. Compared to refrigeration dehumidification, thermos-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 the desiccant and refrigeration dehumidification.

Ventilation dehumidification utilizes outdoor dry air to replace indoor humid air. This method is widely used in practice, especially in residential buildings and small offices, because of its low initial investment and low maintenance requirement. 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.

The design parameters of a dehumidification system include mainly the characteristics of working medium (for desiccant systems), input air temperature and relative humidity, and output air temperature and relative humidity [7].

5.3 Benefit and limitation

The overall effectiveness of liquid desiccant dehumidification systems compared to refrigeration systems is shown to be more cost effective on the long run due to lower operating costs, better indoor air quality, more accurate humidity levels, more environment friendly, and good energy storage capacities [8]. However, the system installment is more complicated, and the initial investment is higher than refrigeration system.

5.4 Performance

The performance indices of a dehumidification system include moisture removal rate, cooling capacity, performance factor, energy efficiency, and COP, where the first is the mass of moisture exchange between the air and desiccant material per unit time, the second is the total (sensible, latent) energy exchange between the air and desiccant material [7], the third is the relative enthalpy difference between air entering and leaving a dehumidifier, and the fourth is the ratio between latent heat produced by the water evaporation and the net heat input to the system [9] [10].

Desiccant dehumidification systems integrating with renewable and sustainable heat sources such as solar energy [11] [12] [13] [14] [15] and industrial waste heat [16] are widely investigated and rapidly developed in recent decades. The use of low-grade heat from the sun and industry would reduce the heat pollution to the environment and avoid/minimize the consumption of fossil energy to drive the desiccant systems. It was reported that the COP of solar assisted desiccant dehumidification systems is increased largely, although the systems are more complicated and expensive in initial investment. Membrane-based liquid desiccant air dehumidification [17] [18] [19] [20] [21] [22] is another advancement, which uses permeable or semi-permeable membranes to separate the processing air and desiccant liquid so that only water vapor molecules in the air side can transfer through the membrane and be absorbed by the desiccant solution. The use of membrane can avoid the carryover problem of solution droplets in traditional direct-contact systems [23]. The performance of membrane-based liquid desiccant air dehumidification is highly dependent on the membrane technology.

5.5 Application

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 [24]. In addition, as the moisture could come from indoor sources, such as people and humid surfaces, and outdoor sources, namely humid outdoor air. There is a high demand on and thus a potential application of air dehumidification in buildings with high moisture emission and in climates with highly humid outdoor air. For example, temperate marine climate and temperate continental climate including Northern Europe do not need dehumidification for most conditions, whereas subtropical monsoon climate and tropical rainy climate including Southeast Asia require certainly dehumidification for most time of a year.

5.6 Technology Readiness level

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

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6 Conclusions

The outcomes of the present State of the Art Review confirm the initial hypothesis of Annex 80:

Numerous resilient cooling technologies are available for a wide variety of building types, and climates. Many of them are already on a substantially high level of technology readiness.

Nevertheless, significant joint efforts are still needed to really guide the mainstream development of cooling into the direction of sustainability and resilience. The new Annex is motivated to contribute to this challenge and effectively support not only the development but the broad application of resilient cooling:

- Systematical assessment of existing cooling technologies, their potentials, limitations, and qualities of resilience.
- Development and improvement of cooling technologies: robust, efficient, carbon-neutral, affordable.
- Assessment of real performance of cooling solutions, to identify performance gaps and develop solutions to systematically overcome them.
- Identification and communication of policy actions which may support the broad application of sustainable and resilient cooling applications.

Several IEA Annexes have previously dealt with aspects of low energy and low carbon cooling before. They focus on specific technologies. Annex 80 Resilient Cooling of Buildings will build upon the outcomes of these Annexes and will integrate them into its wider approach.