

Feng, Wei

Working Paper

Passive solutions to reduce the need for cooling in buildings

ADB Working Paper, No. 1387

Provided in Cooperation with:

Asian Development Bank Institute (ADBI), Tokyo

Suggested Citation: Feng, Wei (2023) : Passive solutions to reduce the need for cooling in buildings, ADB Working Paper, No. 1387, Asian Development Bank Institute (ADBI), Tokyo, <https://doi.org/10.56506/ABDS1960>

This Version is available at:

<https://hdl.handle.net/10419/296781>

Standard-Nutzungsbedingungen:

Die Dokumente auf EconStor dürfen zu eigenen wissenschaftlichen Zwecken und zum Privatgebrauch gespeichert und kopiert werden.

Sie dürfen die Dokumente nicht für öffentliche oder kommerzielle Zwecke vervielfältigen, öffentlich ausstellen, öffentlich zugänglich machen, vertreiben oder anderweitig nutzen.

Sofern die Verfasser die Dokumente unter Open-Content-Lizenzen (insbesondere CC-Lizenzen) zur Verfügung gestellt haben sollten, gelten abweichend von diesen Nutzungsbedingungen die in der dort genannten Lizenz gewährten Nutzungsrechte.

Terms of use:

Documents in EconStor may be saved and copied for your personal and scholarly purposes.

You are not to copy documents for public or commercial purposes, to exhibit the documents publicly, to make them publicly available on the internet, or to distribute or otherwise use the documents in public.

If the documents have been made available under an Open Content Licence (especially Creative Commons Licences), you may exercise further usage rights as specified in the indicated licence.



<https://creativecommons.org/licenses/by-nc-nd/3.0/igo/>



ADB Working Paper Series

**PASSIVE SOLUTIONS TO REDUCE THE
NEED FOR COOLING IN BUILDINGS**

Wei Feng

No. 1387
May 2023

Asian Development Bank Institute

Wei Feng is a research scientist at the Chinese Academy of Science of Shenzhen Institute of Advanced Technology, Shenzhen, Guangdong Province, People's Republic of China and an affiliate scientist at the Lawrence Berkeley National Laboratory, Berkeley CA, United States.

The views expressed in this paper are the views of the author and do not necessarily reflect the views or policies of ADBI, ADB, its Board of Directors, or the governments they represent. ADBI does not guarantee the accuracy of the data included in this paper and accepts no responsibility for any consequences of their use. Terminology used may not necessarily be consistent with ADB official terms.

Discussion papers are subject to formal revision and correction before they are finalized and considered published.

The Working Paper series is a continuation of the formerly named Discussion Paper series; the numbering of the papers continued without interruption or change. ADBI's working papers reflect initial ideas on a topic and are posted online for discussion. Some working papers may develop into other forms of publication.

The Asian Development Bank refers to "China" as the People's Republic of China.

Suggested citation:

Feng, W. 2023. Passive Solutions to Reduce the Need for Cooling in Buildings. ADBI Working Paper 1387. Tokyo: Asian Development Bank Institute. Available: <https://doi.org/10.56506/ABDS1960>

Please contact the authors for information about this paper.

Email: w.feng@siat.ac.cn, weifeng@lbn.gov

Asian Development Bank Institute
Kasumigaseki Building, 8th Floor
3-2-5 Kasumigaseki, Chiyoda-ku
Tokyo 100-6008, Japan

Tel: +81-3-3593-5500
Fax: +81-3-3593-5571
URL: www.adbi.org
E-mail: info@adbi.org

© 2023 Asian Development Bank Institute

Abstract

This paper introduces designs, technologies, and best practices aimed at reducing the cooling energy demand in buildings. It covers the basic principles of why occupants need cooling to meet thermal comfort requirements and how heat is transferred into buildings from the outdoor environment. Passive designs help buildings make use of natural cooling resources and maximize free cooling opportunities such as natural ventilation. The paper summarizes best practices for each passive strategy used in buildings. As a result, architects and engineers will also be able to better orient functional spaces and design cooling operation strategies to provide cooling for spaces where and when needed. The building envelope provides the necessary insulation to stop heat transfer from a hot outdoor environment to an indoor one. Criteria for designing a high-performance building envelope are introduced. For fenestration systems, this paper covers energy-efficient technologies for glazing and shades to reduce solar heat gain. Cool roofs can effectively reflect sunlight back to the atmosphere and also significantly reduce buildings' solar heat gain. Also, to create a cooler outdoor environment in cities, strategies are introduced to mitigate the urban heat island effect. Finally, policy recommendations are suggested, such as improving building codes and standards; creating labels and certifications for passive cooling technologies; establishing incentive programs to promote passive green buildings; educating architects, builders, and occupants; and developing sustainable city policies.

Keywords: buildings, building envelope, cool roofs, thermal comfort, passive cooling, policies

JEL Classification: R0

Contents

1.	INTRODUCTION	1
2.	ADEQUATE BUILDING DESIGNS	3
2.1	Building Orientation and Massing.....	3
2.2	Window-to-Wall Ratio	4
2.3	Developing Energy-Efficient Space Conditioning Strategies	4
2.4	Summary of Best Practices in Building Design to Reduce Cooling Energy Demand.....	5
3.	FREE COOLING SOLUTIONS	6
3.1	Natural Ventilation and Free Cooling.....	6
3.2	Other Free Cooling Solutions.....	8
4.	HIGH-PERFORMANCE BUILDING ENVELOPE	8
4.1	Opaque Building Envelope.....	9
4.2	Building Fenestration Systems.....	10
4.3	Examples of Advanced Envelope Design to Reduce Cooling Load.....	13
4.4	Summary of Best Practices in Building Envelope Design to Reduce Cooling Load.....	13
5.	COOL ROOFS AND SURFACES	14
5.1	Cool Roofs.....	14
5.2	Cool Walls.....	17
5.3	Summary of Best Practices on Cool Roofs.....	17
6.	URBAN PLANNING TO REDUCE THE URBAN HEAT ISLAND EFFECT	18
7.	POLICY INSTRUMENTS TO REDUCE COOLING DEMAND.....	20
7.1	Building Codes and Standards.....	21
7.2	Labels and Certifications.....	22
7.3	Incentive Policies	22
7.4	Capacity Building and Cultivating Passive Cooling Behaviors	22
7.5	Sustainable Urban Planning Policies.....	23
7.6	Million Cool Roof Challenge.....	23
8.	PASSIVE COOLING BUILDING DESIGN AND CASE STUDY	23
8.1	School of Design and Environment 4 Net-Zero Energy Building.....	23
8.2	Passive Design of the Shenzhen Institute of Building Research.....	24
9.	CONCLUSION AND POLICY RECOMMENDATIONS.....	25
	REFERENCES	27

1. INTRODUCTION

Space cooling is needed when building occupants feel uncomfortable because of a rise in room air temperature and/or relative humidity. When occupants feel uncomfortable, they often turn on fans or air-conditioning, which consumes energy. Identifying how to make occupants feel comfortable without using mechanical cooling is critical to reduce cooling energy demand.

Each of us may have a different ambient temperature we feel comfortable with, and there are a number of standards that attempt to define a common range of comfortable temperature and humidity levels. For instance, the American Society of Heating Refrigeration and Air-Conditioning Engineers' (ASHRAE) Standard 55 defines the temperature and humidity ranges for occupant thermal comfort zones, as shown in Figure 1. Air-conditioning tends to be used outside of such comfort zones, cooling when the temperature is higher than the range.

Figure 1: Thermal Comfort Zones with Temperature and Relative Humidity Ranges

Cloth rate	Operative temperature (°C)	Wet bulb temperature (°C)	Humidity ratio (kg H ₂ O/kg dry air)	Relative humidity (%)
1.0	20.7–25.3	7.5–19.0	0.000–0.012	5%–79%
0.5	23.5–28.2	9.2–20.1	0.000–0.012	4%–68%

Source: ASHRAE Standard 55.

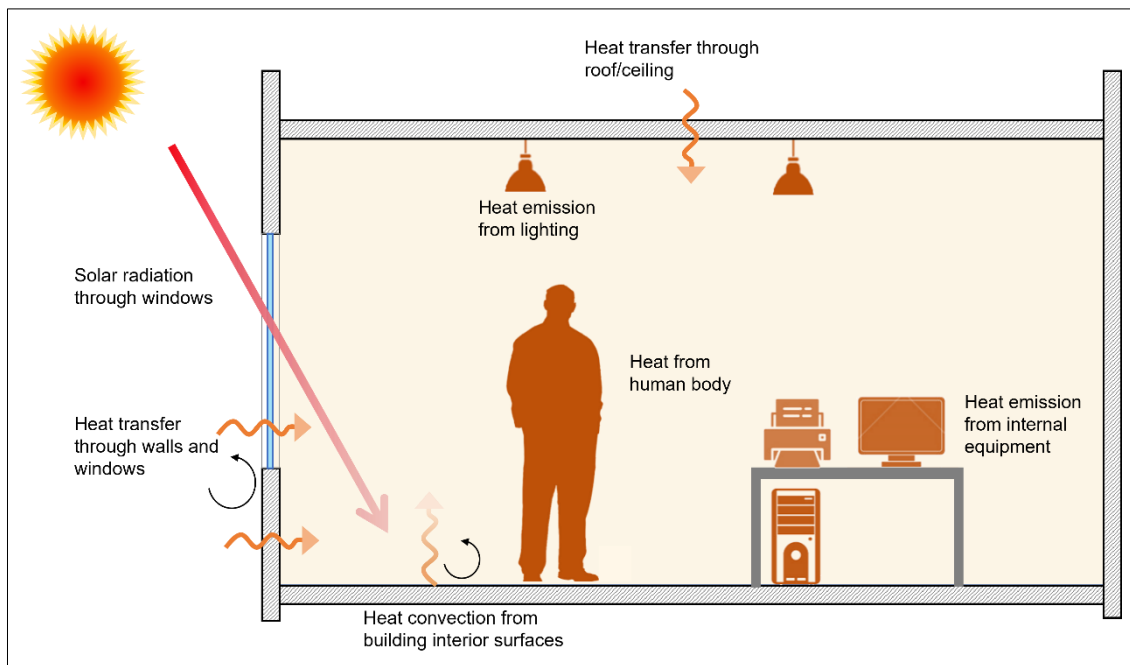
Rises in indoor temperature are often caused by heat transfer from the exterior environment to buildings as well as by internal heat gain. The occupants' metabolic rate and clothing choices can also affect their thermal comfort and use of space cooling. The amount of cooling energy needed to cool a space to meet the occupants' thermal comfort criteria is called the "cooling load". Figure 2 illustrates building heat gains from different sources. In cooling seasons, solar radiation passing through a building's windows and skylights is one of the major sources of indoor heat gain (radiation heat gain). Heat can also be transferred through the building envelope into the indoor space when the outdoor temperature is high. Heat transfer conduction can also happen when solar radiation is received on an opaque building surface, and the rise in a building's external surface temperature causes heat flux into its interior space (conduction and convection heat gain).

Interior heat gain can also cause the indoor temperature to rise and the cooling load to increase. Interior heat can be emitted from human bodies, as well as indoor electrical devices such as lighting, computers, cooking devices, and appliances. Moisture changes in an indoor environment can also cause discomfort. To reduce the amount of moisture in the indoor environment (such as moisture generated from a shower), cooling energy is often needed to absorb it or condense the moisture into water. The amount of energy used to remove moisture from the air is often called "latent heat," while the energy expended to condition the indoor air temperature is called "sensible heat." In hot and humid climates or buildings that generate a lot of indoor moisture, properly managing moisture and removing it from indoors is as important as conditioning the indoor space temperature. It is worth mentioning that in developing regions and low-income communities, residents may not be able to afford space conditioning. Passive cooling solutions (Peters and Sayin 2022a,b) are preferable

low-cost solutions. This paper will also cover passive design strategies for buildings such as natural ventilation, cool roofs and surfaces, and using fans to provide good thermal comfort.

Cooling is also needed for refrigeration purposes to keep food fresh and to keep medicine effective (e.g., vaccines). Storing food in a refrigerator is a common way to keep food fresh. In addition to home refrigerators and commercial refrigeration cabinets, refrigeration is also commonly found in cold chains to ship food or medical products from one place to another, often around the world. Refrigeration systems are often installed in trucks and shipping containers, as well as in warehouses.

Figure 2: Building Space Heat Gains



Source: Author's own.

As passive cooling can effectively cut energy demand for mechanical cooling, the passive cooling design and technologies introduced in this paper are especially suitable to promote cost-effective cooling methods focusing on low-income communities. To identify methods for reducing the cooling load in built environments, this paper discusses many basic principles, including better building designs, high-performance building envelope systems, the use of cool roofs and reflective surfaces, and sustainable urban planning.

Besides technological solutions, financing solutions are needed to scale green and energy-efficient cooling systems. Various financing tools are available to facilitate the purchase, installation, and energy-efficient operation of cooling technologies. Commercial financial instruments often include loans, equity investments, and risk mitigants. With financing institutes paying more attention to climate change, certain financing opportunities can be leveraged for cooling solutions, such as the utilization of climate funds, funding for refrigerant replacement, and improvements in energy efficiency. Due to the low-cost features of passive measures, when promoting energy-efficient, green, and net-zero carbon buildings, policy priorities should be given to passive cooling solutions.

The objective of this paper is to introduce the technical opportunities for implementing passive cooling measures and provide policy instruments for governments to advance the adoption of passive solutions. This paper introduces several passive cooling approaches, such as adequate building designs (Section 2), free cooling and natural ventilation (Section 3), high-performance building envelopes (Section 4), cool roofs and surfaces (Section 5), and urban planning methods to reduce urban heat island effects (Section 6). It then provides policy instruments to help countries and regions implement passive cooling measures in buildings (Section 7). Comprehensive case studies provide examples of implementation of these passive measures.

2. ADEQUATE BUILDING DESIGNS

Building design is the first and foremost approach that can be used to help reduce cooling load without the installation of expensive building technologies. To reduce cooling load, the key building design aims are to avoid building solar heat gain and to make use of its natural cooling environment to enhance energy-free cooling.

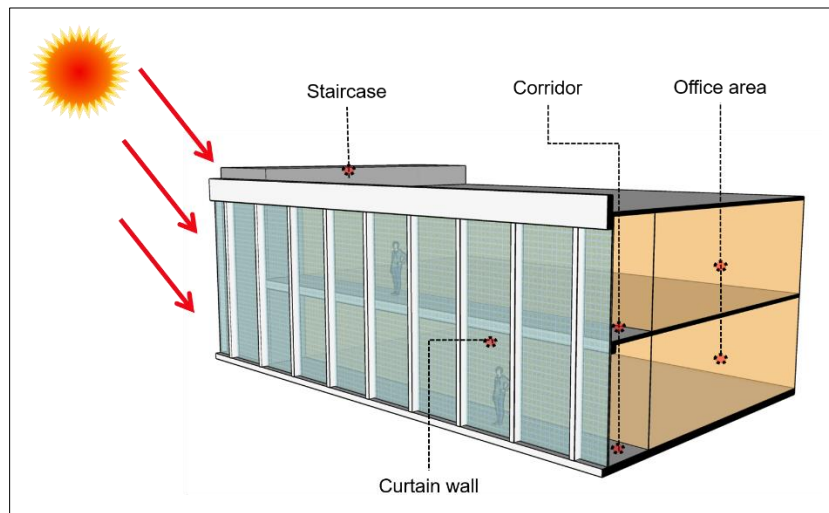
2.1 Building Orientation and Massing

Properly orienting a building to reduce solar heat gain can effectively reduce the cooling energy demand. The shape of a building and building envelope material types also have a strong influence on cooling energy use. During the design stage, energy simulation analysis is often needed to calculate the cooling energy demand under different design strategies, given the constraints of the site, landscape, and shade analysis from the exterior environment. The general principles of orientation and massing design are used to ensure buildings receive as little heat transfer from the outdoor environment (including solar radiation) as possible. Most green building designs require buildings to utilize daylight. Finding a balance between energy savings, daylight utilization, and cooling load reductions needs to be considered in the design stage.

Another design strategy is to have buildings close to natural cooling resources, such as a river, pond, lake, or green vegetation. The adjacent cool resources can provide natural breezes that are useful for building ventilation. Understanding the local wind profile and optimizing the building's orientation can maximize its free cooling opportunities.

It is also important to analyze the building's interior functional space, as not all functional spaces need mechanical cooling all the time. Assigning some zones (e.g., corridors, staircases) that do not need much air-conditioning to locations that receive large amounts of solar gain is also a good design strategy (Figure 3).

Figure 3: Orientation and Massing Strategies to Reduce Unoccupied Space Conditioning Energy



Source: Author's own.

2.2 Window-to-Wall Ratio

The window-to-wall ratio (WWR) is the ratio of the window areas to the total facade area. The WWR value ranges between 0 and 1. Properly designing a building's window areas is important to reduce cooling energy demand, as well as to utilize daylight. Nowadays, architects often like to design large window area facades, as windows tend to cost less and are easy to build compared with opaque walls. However, large window areas often mean more solar radiation will be received by the building and may increase its cooling demand. Several countries' building energy codes and standards have developed regulations to limit the WWR in new building designs. For example, the US ASHRAE Standard 90.1 limits the WWR to 40%. Should a building need to build a WWR value larger than 40%, the design team needs to consider more aggressive energy conservation measures to prove that increasing the WWR will not significantly increase the building's cooling energy use. Often, advanced shading methods and daylighting utilization strategies are adopted when designers choose a large WWR. Section 5.2 introduces methods for designing a building fenestration system to achieve good cooling energy savings.

2.3 Developing Energy-Efficient Space Conditioning Strategies

Deciding which kind of cooling service needs to be deployed for each building zone, and at what time it must be deployed, are very important design issues. The design of cooling strategies should be developed at the same time as zoning and WWR design strategies are decided upon. Overall, not all the zones in a building need the same quality of cooling throughout an entire cooling season. Some zones, such as a data center, may need mechanical cooling 24/7 to maintain a constant indoor air temperature, while zones like corridors may not need such a high quality of cooling as office spaces. The general principle for providing mechanical cooling is to develop a "partial-time partial-space" strategy that only provides mechanical cooling for a space at the time when it is needed, and to maximize the natural ventilation and free cooling opportunities.

Some functional spaces do not need cooling or a full cooling service. Corridors, staircases, and storage rooms where occupants will not spend a lot of time in the space may not need to be cooled or do not need to be cooled at the same temperature as other occupied spaces. It is also not necessary to condition the entire open office space with the same room temperature setpoint, as the occupants' thermal comfort criteria vary. Providing individual personal cooling at each occupant's workstation delivers cooling directly to the occupants instead of conditioning the entire open office, which significantly cuts cooling energy demand.

Selecting an appropriate period of time for mechanical cooling requires designers to analyze local weather data and understand each building's natural ventilation potential. It is optimal to turn on mechanical cooling only when natural ventilation cannot meet the occupants' adaptive thermal comfort requirement. Even in the same room, mechanical cooling does not need to operate in the same condition all the time. Changing the room setpoint or turning off cooling when the room is not occupied can save significant cooling energy demand. Using modern control technologies and building management systems (BMSs) to control the cooling setpoint and schedule the cooling on and off is an effective way to reduce cooling energy use. To avoid overcooling and unnecessary energy waste, control algorithms can adjust a cooling system's operation based on a building's occupancy level and outdoor weather conditions.

2.4 Summary of Best Practices in Building Design to Reduce Cooling Energy Demand

A few best practices in designing a building to reduce cooling energy demand are summarized below:

- Optimize building massing and orientation to reduce heat gain from the outdoor environment.
- Utilize natural cooling resources (e.g., pond, river, vegetation) from the outdoor environment to enhance natural ventilation.
- Properly design a building's window area and window-to-wall ratio value to minimize solar heat gain and utilize daylight.
- Optimize a building's shape and orientation to facilitate natural ventilation.
- Select operable windows for natural ventilation.
- Use fans (including ceiling fans) to enhance natural ventilation.
- Use an air-side economizer with centralized ventilation systems to supply cool outdoor air without conditioning it.
- Develop and apply adaptive thermal comfort criteria for natural ventilation needs.
- Use computational flow dynamics (CFD) to analyze the effectiveness of natural ventilation to optimize building design.
- Use the "partial-space, partial-time" rule to design a building's cooling operation strategy.
- Employ smart control of cooling using a building management system with the proper setpoint and schedule.

3. FREE COOLING SOLUTIONS

Several design features can lead to cooling an indoor space without the use of active cooling technologies and with little cooling energy consumption. This section introduces the common strategies for natural building ventilation and other indoor and outdoor free cooling solutions.

3.1 Natural Ventilation and Free Cooling

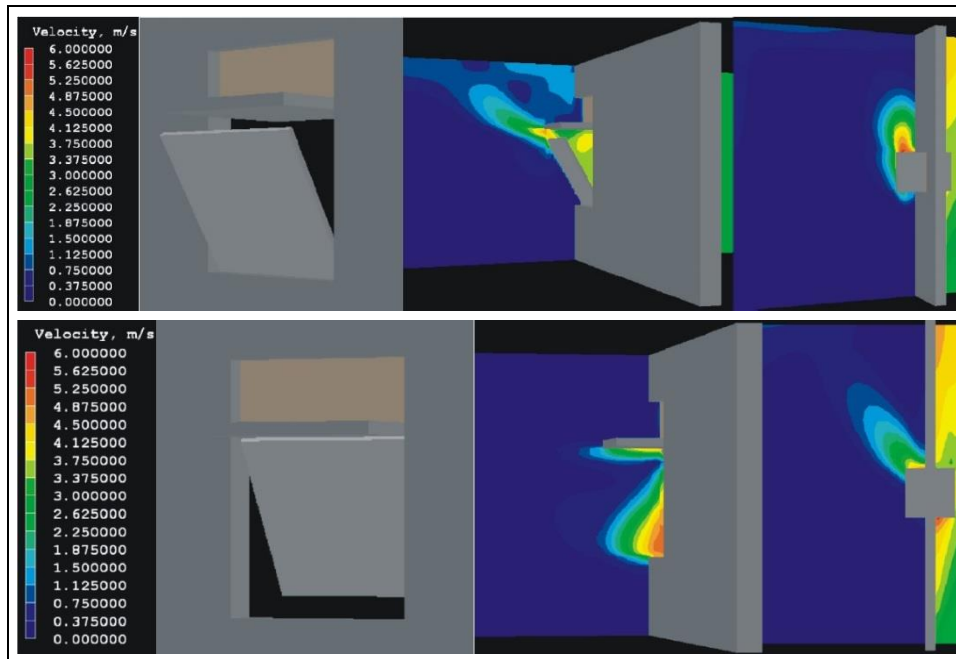
Naturally conditioning a building is one of the most effective ways to reduce mechanical cooling energy demand. To design a building that is naturally ventilated, architects should study the local wind patterns so they can best orient the building to utilize the location's breezes. As natural ventilation is often used in early summer and shoulder seasons, it is important to design a building that is oriented towards its dominant wind directions during these seasons. The building's shape and size are also important for natural ventilation. A good design for natural ventilation is to enable wind crossflow from one side of a building to another. However, cross ventilation in a large building is difficult, as the wind velocity tends to drop when blowing through a building's indoor space. Therefore, a thin building better facilitates a natural ventilation design.

Windows are the basic elements that enable natural ventilation. To ensure the best thermal comfort, they need to be opened during natural ventilation seasons and fully closed during air-conditioning seasons. It is not desirable to open windows while room air-conditioning is on, as hot and humid air can then pass through the windows and add to the building's cooling load. The selection of window types is also important. The general principle for window selection is for the opening area to be as big as possible and to be able to adjust the open area to utilize natural ventilation and manage ventilated airflow velocity. The selection of operable windows should take into consideration the different window openings that lead to different airflow patterns. Figure 4 shows images from a study done by the Shenzhen Institute of Building Research (IBR) in the People's Republic of China (PRC) on window openings and natural ventilation flow patterns.

Natural ventilation is not only driven by cross-building wind pressure differences, it can also be caused by the stack effect. Designing a building with a ventilation chimney or atrium can generate the stack effect and enable natural ventilation.

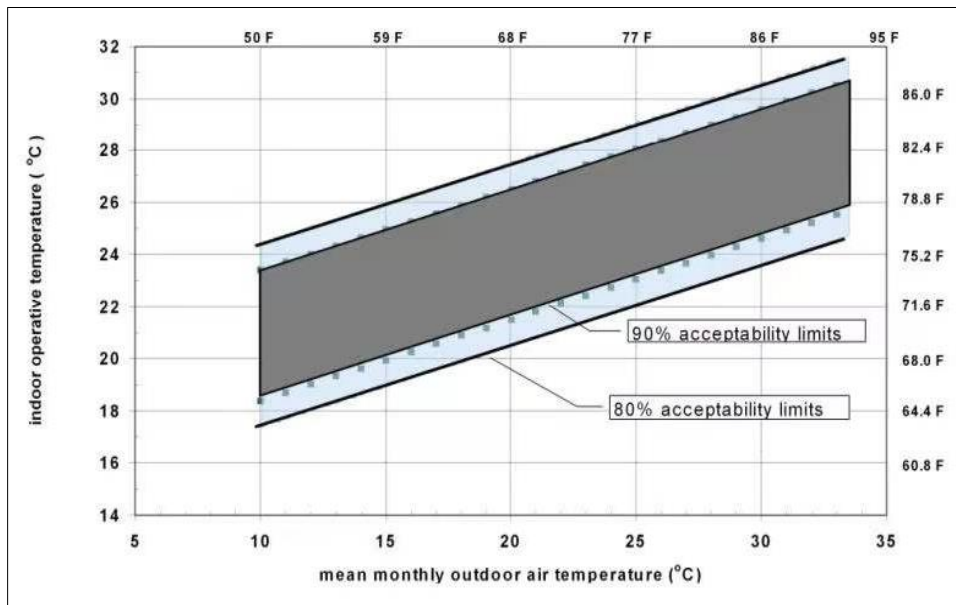
When a building is naturally ventilated, its occupants' thermal comfort criteria may be different from those of occupants with room air-conditioning. Overall, the occupants' thermal comfort with natural ventilation is influenced by room air temperature, relative humidity, and wind speed. Instead of using room conditioning thermal comfort criteria as shown in Figure 1, Figure 5 below shows the "adaptive thermal comfort" criteria under the natural ventilation mode, provided by ASHRAE Standard 55. Thermal comfort satisfaction boundary lines are drawn to indicate the percentage of occupants who feel comfortable within a certain indoor temperature and relative humidity range. Natural ventilation can also occur when the building is not occupied in the evening, due to a pleasant nighttime ambient air temperature and air quality. Natural ventilation during off-work hours is also called "night purge," which refers to flushing out the polluted indoor air and replacing it with cool, fresh outdoor air. Especially during the COVID-19 period, night purge can reduce a building's demand for energy use in ventilation and greatly improve indoor air quality.

Figure 4: Airflow Pattern under Two Different Window Opening Strategies



Source: Diamond and Feng (2014).

Figure 5: Adaptive Thermal Comfort Criteria from ASHRAE Standard 55



Source: ASHRAE Standard 55 (2017).

Using mechanical fans for natural ventilation can also provide good adaptive thermal comfort. Fans tend to use much less energy than mechanical compressor-based cooling systems and are favored in many countries, especially developing Asian countries. There are many ways to use a fan for cooling. A personal desk fan is one of the most common and cost-effective solutions. When using fans, it is important to properly manage the air speed caused by them, as high-speed air movement tends to cause discomfort and distraction in a work environment. Advancements in ceiling fan

technologies now enable them to spin at low speed, resulting in comfortable, low-velocity air movement that can meet occupants' comfort needs. More recently, combining fans with mechanical cooling systems for hybrid cooling has been studied, and it has proven to provide plausible thermal comfort and save cooling energy.

For a centralized ventilation system, natural ventilation can also be achieved using a centralized duct air supply. Smart control of the ventilation system with an air-side economizer can determine when to introduce outdoor air to the indoor space without conditioning, based on the temperature and humidity (enthalpy) of outdoor air conditions. In some countries, the local building codes and standards encourage buildings to use air-side economizers, and allowing the use of economizers can be traded off against their cooling system efficiency. That is, if air-side economizers are not used in a building, its cooling system efficiency needs to be more stringent compared to a building in the same climate using air-side economizers.

To analyze the effectiveness of natural ventilation, computational flow dynamics (CFD) is often needed during a building's design stage. Two- or three-dimensional flow patterns can help designers understand the building's air velocity and temperature distribution profile. Should any space be overventilated or not receive enough natural ventilation, designers can adjust the fan's location and operable window design strategy to optimize the indoor airflow.

3.2 Other Free Cooling Solutions

In an outdoor environment without mechanical cooling technologies, cooling is often provided through natural solutions. A shaded environment is a good option to provide free cooling, as people can avoid direct solar heat gain. Buildings can provide outdoor shades, and human activities can be hosted around buildings during the right seasons and times. Trees and other outdoor infrastructure can also create a pleasant outdoor shade environment.

Outdoor water features can also create a good natural cooling environment. Water evaporation tends to absorb heat and can lower the air temperature of the micro-environment around a river or a pond. A wind blowing above a water feature can also accelerate water evaporation and create a comfortable natural cooling environment. Water spray and mist are another way to increase water evaporation and provide enhanced cooling. Some cities have installed water mist sprayers in outdoor facilities such as bus stations and outdoor dining places.

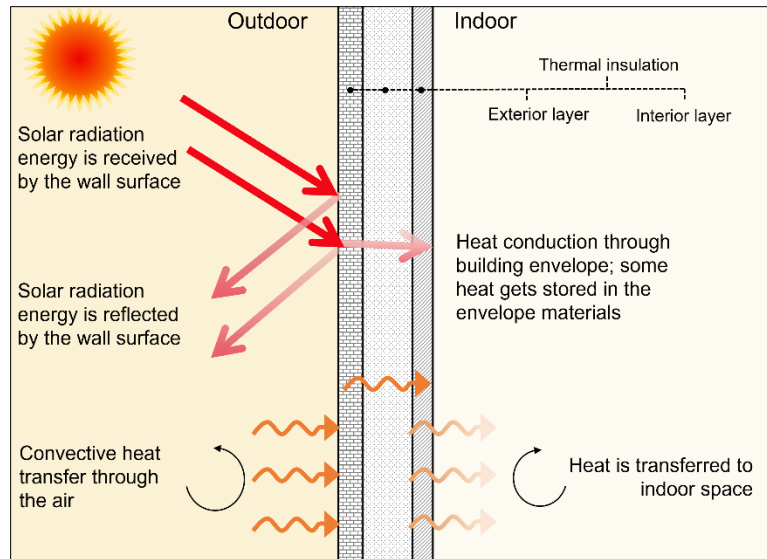
4. HIGH-PERFORMANCE BUILDING ENVELOPE

A building's envelope provides an essential enclosure system and a creative built environment to provide cooling services for occupants. In general, a building's envelope system effectively shades solar radiation from the indoor environment and stops hot and humid outdoor air from directly circulating into buildings. It also provides the necessary insulation to stop or slow heat transfer from the outdoor environment to indoors. Two basic building envelope components are the opaque building external wall and roof and the fenestration system.

4.1 Opaque Building Envelope

In summer, heat is transferred from the hot outdoor environment or hot external building surfaces, due to solar radiation, into the indoor space. The heat transferred from outdoors often adds a cooling load and increases the use of cooling energy. Therefore, properly insulating the opaque building envelope can hamper the heat transfer between the indoor and outdoor environment and reduce the cooling load (Figure 6).

Figure 6: Opaque Building Envelope Heat Transfer Mechanism



Source: Author's own.

The thermal properties of the opaque building envelope determine the rate of heat transfer between the indoor and outdoor environments.

Most countries use either the heat transfer coefficient “U-value” or thermal resistant “R-value” to reflect building envelope thermal performance. A U-value represents the sum of all the building assembly’s material layers’ thermal conductivity, with the same unit as thermal conductivity (C), representing how easily heat can be transferred between the indoor and outdoor spaces. The R-value is usually a reciprocal of the U-value, representing how better building envelopes resist heat flux between indoor and outdoor environments (ASHRAE Handbook Fundamentals 2021). Most countries’ building codes and standards have U-value or R-value requirements for each climate zone. Often, insulation materials must be added into a building’s envelope assembly layers to improve its thermal integrity level, and to reduce the building’s heat gain in the summer and/or heat loss in the winter. For instance, in their building energy standards, both the United States and the PRC specify the U-value or R-value of the opaque envelope. Table 1 below summarizes the commercial building envelope performance requirements based on the US ASHRAE 90.1-2018 Standard Climate Zone 1 and the PRC’s GB50189-2015 Hot Summer Warm Winter (HSWW) climate zone. In hot climate zones, the Chinese standard is less stringent in regulating building envelope thermal insulation than the US ASHRAE Standard 90.1. Both countries have issued their net/nearly zero energy building standard, which requires further improvement of the building envelope thermal integrity.

Table 1: U-value Requirement for Opaque Building Envelope

ASHRAE 90.1 Climate Zone 1 (Miami) and Chinese GB50189-2015 HSWW (Guangzhou)

Max U-value (W/m ² K)	ASHRAE 90.1-2018	GB 50189-2015
Roof	0.27	0.9
Wall	0.51	1.5

Source: ASHRAE 90.1-2018 and PRC GB50189-2015 standards.

Another way to reduce heat conduction into buildings is to place a heat storage layer in a building's envelope system. Phase change materials (PCMs) are a plausible solution for the heat storage layer to store heat transferred from the outdoor environment during the daytime without raising the temperature of the material itself. And during the evening, as the outdoor environment gets cooler, PCMs can release the heat back to the outdoors, significantly reducing the heat transfer into the indoor space. Studies have found that advanced PCMs, when used in building envelopes, can effectively reduce both cooling load and peak cooling energy demand (Lu et al. 2016).

It is also important to make the building envelope airtight, especially during air-conditioning seasons, to stop hot and humid uncontrolled outdoor air transporting to the indoor environment through the building envelope or cool indoor air leakage to the outdoor environment. Building codes and energy standards in different countries tend to regulate the airtightness level of the indoor environment. An airtight building often requires designers and builders to properly seal building envelopes to stop air transport. In the building envelope design, it is common to put an air-barrier layer in the middle of building material assembly to stop air and moisture transport. Leakage also happens at the window and door frame side, caused by the gaps between the frame and the wall structure. Filling these gaps using liquid flushing or other technologies is useful for improving building airtightness. Note that we do want buildings to be naturally ventilated and to enhance the controllable indoor-outdoor airflow.

4.2 Building Fenestration Systems

Another important component of the building envelope system is the building glazing and fenestration system. The glazing system is a critical component enabling occupants to see the outdoor environment. The operable windows can also function as a path to exchange indoor and outdoor air.

4.2.1 Glazing

The thermal properties of windows, similarly to opaque envelope parts, can also determine the heat transfer between the indoor and outdoor environment. Often, the U-value or R-value of an exterior window is required by building codes and standards to slow heat transfer between the indoor and outdoor environment, and therefore reduce the cooling load. Lower U-value or higher R-value windows can effectively reduce heat transfer in both summer and winter seasons and improve a building's thermal integrity. Increasing the number of glass panes, using better thermal property glass materials, or adding inert gas in the gaps can improve the glazing system insulation level. However, heat can not only transfer through a window's glass panes but also through its window frame. Therefore, choosing a window assembly with an insulated and airtight window frame can also improve window assembly thermal integrity.

In addition to window thermal conductivity requirements, solar heat gain properties are also important. As the basic function of an exterior window is to enable exterior light to come into the indoor space, we often use visible light transmittance (VT) to describe the percentage of visible light transmitted through window glasses. A clear glass usually has a VT of 75%–92%, while color or coated glasses have a much lower VT value. When sunlight is transmitted from windows into buildings, heat is also transferred through solar radiation. The percentage of solar radiation admitted (transmitted and/or absorbed) through a window assembly is defined as the solar heat gain coefficient (SGHC) and is another important parameter when selecting a window. Building codes and standards often have requirements of minimum VT and SGHC values in different climate zones. To reduce cooling load, architects and engineers often want to use low SGHC value windows to reduce solar heat gain and cooling load. However, a low SHGC may also mean a low VT and reduce the building’s ability to utilize daylight. Low thermal emissivity (low-E) windows, which stop infrared heat exchange between indoor and outdoor environments, have become increasingly common. Spectrum-selective glasses can further block solar radiation by allowing the specific spectrum of solar rays transmitted and thus reduce a window assembly’s SGHC. Window film and coating technology developments have made “smart windows” possible. A thermochromic window can change its color based on the amount of solar radiation it receives, thereby changing the SGHC and VT values. When the solar radiation received by the window is ample, the thermochromic window reduces this transmittance. The electrochromic window uses electric control to adjust the window’s transparency level. Instead of passively adjusting as the thermochromic window does, the electrochromic window can engage occupants and integrate with a building’s modern control system to adjust the window’s transparency to reduce cooling load and utilize daylight.

To help building owners select energy-efficient fenestration systems, labels and rating systems are developed to disclose fenestration system performance data. The National Fenestration Rating Council (NFRC) in the United States has developed a windows rating label (Figure 7) to show building users the U-value, SGHC, VT, and air leakage data.

Figure 7: Window Label from the National Fenestration Rating Council in the United States



Source: US NFRC (2022).

4.2.2 Shades

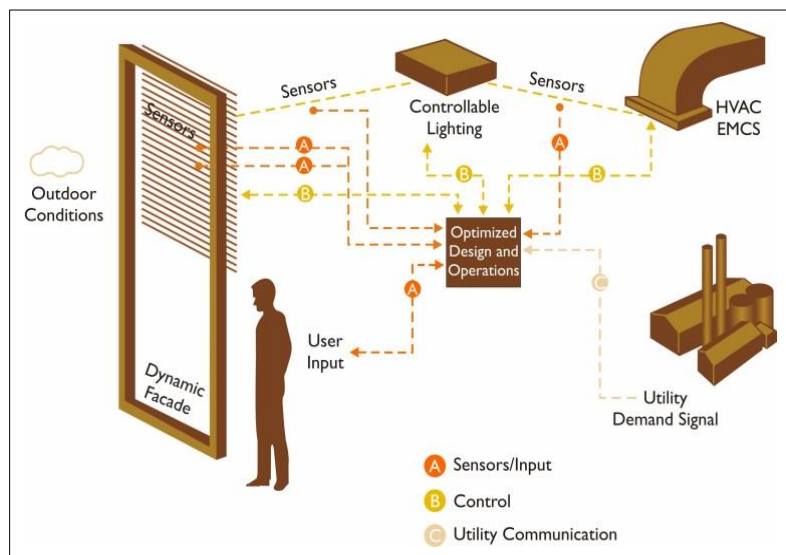
To further reduce cooling load, window shading devices are often attached to windows to block solar radiation heat gain. Shades can be installed on a building’s exterior surfaces, interior surfaces, or in the middle of glass window panes.

Exterior shading devices are effective in blocking solar heat gain outside of a building. Exterior shades can be installed horizontally as overhangs or vertically as fins. Overall, overhangs are effective in blocking solar heat gain when the solar altitude angle is high (e.g., at noon). Vertical fin shades are effective for blocking solar radiation when the solar altitude angle is not too high, and are especially helpful for mitigating direct solar radiation-caused glare.

Interior shades such as blinds and screens are also helpful for reducing a building’s solar heat gain and cooling load. Unlike exterior shades, interior shades are often installed for each window, so occupants have the freedom to adjust their position. Advanced shades not only block solar beam radiation but redirect some solar beams into the interior space to provide daylighting benefits. So choosing a shading device should balance cooling energy savings with its ability to utilize daylight. In some window assembly products, shades are also installed in the middle of windowpanes. Compared with interior shades, exterior shades are more effective in blocking solar radiation outside of a building instead of inside. However, with exterior shades, as they are directly exposed to outdoor environments, their maintenance and automatic operation could make a shading system expensive to operate, especially for high-rise buildings.

The advancement of window technology has made it possible to integrate windows and shades with a built environment control system and intelligently control the window operation and reduce the building’s cooling load. The opening of windows and the operation of window shades can be sensed as a part of the building control system; the system knows when the building is operated in natural ventilation mode and when it is operated using mechanical cooling (Figure 8). Lighting controls can also be integrated with the shade operation to make use of daylight and save lighting energy use.

Figure 8: Integrative Controls for Shading, Lighting, Heating, Ventilation, and Air-Conditioning

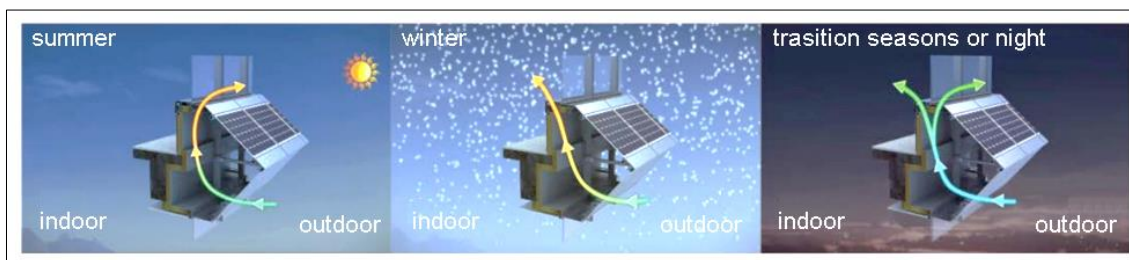


Source: Lawrence Berkeley National Laboratory (2015).

4.3 Examples of Advanced Envelope Design to Reduce Cooling Load

A building fenestration system and its shade can be used to enhance natural ventilation. Figure 9 shows how a high-rise building design in Zhuhai, PRC, uses solar photovoltaic (PV) shades as overhangs to block solar radiation and generate electricity. The overhang is designed with an airflow path to allow air to pass through the back of the PV panel to naturally cool down the PV panel and increase its efficiency. During shoulder seasons, when the building is operated in natural ventilation mode with a window open, the outdoor air can be slightly warmed by the PV panel overhang and reduce the building's heating energy demand (Feng et al. 2019).

Figure 9: PV Overhang Shades Design for a High-Rise Building in Zhuhai, PRC



Source: Xingye Solar Co. (2019), personal communication.

Traditional buildings are operated with a fixed WWR and external shades. A case building in Shandong Province, PRC, demonstrates the use of operable external shades to change the building's WWR and optimize shading effects. During a winter evening, the operable shades can fully close. The back of the shading panel has insulation material. When fully closed, it can reduce the building's heat loss. During daytime in the summer, the shades are optimized to open at different angles based on the orientation to allow the space to utilize daylight but block sunlight heat gain.

PV can not only be used in exterior shading devices but can also be installed in the middle of windowpanes to reduce cooling load and generate electricity. Results from one PV shade window technology (produced by Solaria) test at the Lawrence Berkeley National Laboratory showed that a window with PV shades can reduce energy by 15%, compared with traditional low-E windows.

4.4 Summary of Best Practices in Building Envelope Design to Reduce Cooling Load

To summarize, the advanced design of building envelope systems can greatly help buildings reduce their cooling energy demand. Below is a summary of the best practices in designing and operating building envelope systems:

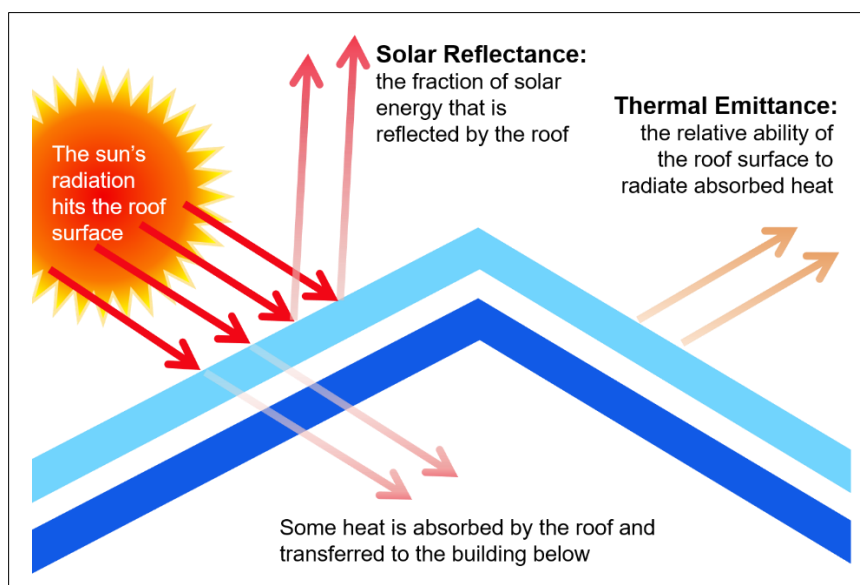
- Design a building to ensure its walls, roofs, and windows meet building energy codes and standard thermal property requirements.
- Select windows with a low SGHC value to avoid solar heat gain, but also pay attention to visible light transmittance so the building can utilize daylight.
- Use interior and exterior shading devices to shade solar radiation and reduce daylight glare.

- Develop and apply building fenestration system labels to enable customers to select high-performance windows.
- Integrate window and shade operation with building control systems to coordinate envelope operation with indoor cooling operation strategies.
- Use simulation software tools to assess building fenestration system daylighting and heat transfer performance.

5. COOL ROOFS AND SURFACES

Solar radiation is the major heat gain source and the reason for buildings to operate their cooling system in the summer. The roof is the key component in a building's envelope system and is directly affected by solar radiation. Dark materials tend to absorb more heat than light-color materials. Roofs are often made with dark colors and have a great capacity to absorb sunlight, heat buildings, and affect the surrounding environment. The roof-absorbed heat from solar radiation often transmits into the indoor space and adds cooling energy demand. Hot dark roofs, when emitting heat to the surrounding environment, can also cause urban heat island effects, which in turn aggravate building heat gain and reduce the efficiency of air-conditioning systems (Akbari, Menon, and Rosenfeld 2009). Figure 10 illustrates how a roof receives, absorbs, and reflects solar energy, and emits heat.

Figure 10: How a Roof Receives, Absorbs, and Reflects Solar Energy, and Emits Heat



Source: Lawrence Berkeley National Laboratory (2019).

5.1 Cool Roofs

Studies have found that a roof can be much cooler under sunlight if it reflects most of the sunlight instead of absorbing it. The ratio of reflected sunlight from a roof surface to the total sunlight solar radiation received is defined as "solar reflectance." Having high solar reflectance is one of the key characteristics necessary for a cool roof. Another

key characteristic of a cool roof is having high thermal emittance. “Thermal emittance” is the ability of a roof to emit heat primarily through infrared radiation. As thermal radiation happens in a much longer spectrum (4–80 microns) in sunlight compared with solar radiation (0.3–2.5 microns), these two parameters are intended as factors that characterize a cool roof. A dark roof usually has a solar reflectance value of 0.05–0.2 and a thermal emittance of 0.9, while a typical cool roof has a solar reflectance of about 0.7 and a thermal emittance of 0.2.

It should be noted that not all cool roofs are white, although white materials tend to reflect a significant amount of solar energy. Colored roofing materials can also have good solar reflectance. As more than half of solar energy is transmitted via invisible sunlight, a colored roof, if properly designed, can also be a cool roof (Levinson and Akbari 2010).

5.1.1 Types of Cool Roof Technology

Several cool roof technologies have been developed for both new constructions and retrofitting existing buildings. The single-ply membrane is a single-layer cool roof membrane material that can be rolled onto a roof. The technology is a good solution for the fast installation of a cool roof, and the membrane can be attached to an existing roof surface with fasteners, adhesives, or using ballasts. The single-ply membrane is also suitable for retrofitting an existing roof by placing the cool roof material on top of the existing roofing structure.

Elastomeric coating is a liquid surfacing material (acrylic, elastomeric, or asphaltic) and can be applied to different roof types, especially built-up and metal roofs. Elastomeric coating is available in different colors, not just white. Painted metal is a roofing product made with metal with painted or factory-coated cool roof colors. Finally, ballast roofing materials are used to combine a cool roof with a stone or concrete paver. The goal is to weigh down the waterproof layers of the roof. Ballast material can also add to the thermal mass of the surface layer, thereby reducing heat conduction into the interior space.

Low-cost cool roof solutions such as painting it a light or white color are effective methods for turning an existing dark roof into a cool roof. Paint is a cost-effective solution for developing countries that are not able to afford complex cool roof solutions. Paint can also be applied to pitched-roof surfaces. When applying cool roof paints, attention must be paid to the weatherization degradation effects of the paints. It is desirable to select durable paint and the cool roof reflectance can last longer throughout a building’s lifetime.

In addition to cool roofs, other roofing technologies can help reduce a building’s cool energy use. A “green roof” refers to using green plants and vegetation on a roof surface to create shade and using plants to absorb the solar heat gain. A green roof often includes several layers of roofing materials, including vegetation, growing soil, irrigation, a drainage layer, a root barrier, a waterproofing membrane, and a structure deck. A “PV roof” refers to a roof where PV panels are installed on a building’s rooftop. PV does not directly save cooling energy use, but the electricity generated by the panels can offset cooling energy consumption. PV panels can also create good shade and reduce a roof’s solar heat gain. A solar thermal panel is another way to harvest solar radiation. Solar thermal technologies can produce hot water and are popular in Asian buildings.

5.1.2 Standards and Labels

To promote the adoption of cool roofs in buildings, cool roof regulations are often embedded in building energy codes and standards. Based on applicable climate zones and the level of steepness of the roof, solar reflectance (SR) and thermal emittance (TE) values are often required for cool performance. Testing methods are needed to test roof product solar reflectance and thermal emittance. A few countries in Asia have developed cool roof testing standards based on analysis from Asia-Pacific Economic Cooperation (APEC) (Table 2).

Table 2: Testing Standards of Cool Roof Properties in Asia (APEC EWG 2020)

Economies	Roof Standards	Comment
People's Republic of China	GBT31389, JGJ287, JGJ359, JGT235-2014	GBT31389 specifies the testing standard for reflectance and emittance. JGJ and JGT are standards of product performance
Hong Kong, China	No specific standard for testing reflectance and emittance	Uses OTTV and OTTR in the economy's building code.
Indonesia	Currently no standard for reflectance or emittance of cool roof	Table for reflectance and emittance is provided in the economy's building code and standard
Japan	JIS_K05602, JIS_K_05675, JSTM-J-7601, JSTM-J-7602, JSTM-J-6151, JIS-R-3107	JIS R 3017 is the standard for measuring glazing product emittance and is also used for measuring opaque surfaces
Republic of Korea	Information not available	
Malaysia	Currently no standard for reflectance or emittance of cool roof	The economy's code MS1525 requires the calculation of RTTV; however, it does not reference the testing procedure. Table for reflectance and emittance is provided in the economy's building standard
Philippines	Currently no standard for reflectance or emittance of cool roof	The economy's building energy code is under public review
Singapore	Information not available	There is no known testing standard for reflectance and emittance measurement
Thailand	ASTM E 903-82, JIS R 3106 1998, ASTM E 1980-01, ASTM C 1371-98, BS EN 12898	To date, the tests for reflectance of coating have been done in compliance with JIS R 3106. However, changing to JIS K 5602:2008 is under consideration
Viet Nam	QCVN 09:2017/BXD	Specifies reflectance and emittance requirements for calculating resistance. However, there is no testing standard for reflectance and emittance measurement


Source: APEC (2020).

As roofing materials' performance always ages with time, cool roof standards often require initial and/or aged values of ST and TE. Some standards also allow the installation of a cool roof to be traded off against its roof insulation level, U-value, or R-value. That is, if a cool roof is used, a roof tends to absorb less solar radiation energy, so the roof's insulation level could be slightly reduced compared to a roof with no cool roof installed.

The US Green Building Council (USGBC) Leadership in Energy and Environmental Design green building standard awards up to two points for applying cool roofs and mitigating urban heat island effects. The Cool Roof Rating Council (CRRC) in the United States also developed cool roof labels to help customers select cool roof

products. On a rating label, the cool roof product's initial and aged SR and TE values need to be documented (Figure 11).

Figure 11: Cool Roof Rating Label

	Rated Product ID #: 0000-0000	
		<u>Initial</u> <u>Aged</u>
	Solar Reflectance	0.00 0.00
	Thermal Emittance	0.00 0.00
<small>The ratings above are subject to CRRC rating program conditions, requirements, and limitations. Visit coolroofs.org for important information and disclaimers about CRRC rating conditions, requirements, and limitations.</small>		

Source: US Cool Roof Rating Council (2022).

5.1.3 Potential Disadvantages of Cool Roofs

Using a white color roof can also cause glare when it reflects sunlight to adjacent buildings. To avoid glare impacts, a colored cool roof could be more appropriate for low-rise buildings. The application of a cool roof on a building needs to take into consideration its seasonal impacts. To develop cool roof standards, a comprehensive regional analysis in a country needs to be conducted to trade off cooling energy savings by applying a cool roof against its heating energy penalty.

5.2 Cool Walls

A wall only receives about 50% of solar heat gain compared with the same area of a roof. However, a building has a much bigger exterior wall surface area than its roof. Especially in cities with many high-rise buildings, walls could play much greater roles in reflecting sunlight and help mitigate the urban heat island effect. Cool color paints are the most common technology used for cool walls. Unlike a roof, half of the sunlight reflected from a wall may be sent to its neighboring buildings or absorbed by the city. Therefore, having retroreflective wall materials or coating could enhance the reflection of solar energy back to the sky, as well as reducing potential reflection glare.

5.3 Summary of Best Practices on Cool Roofs

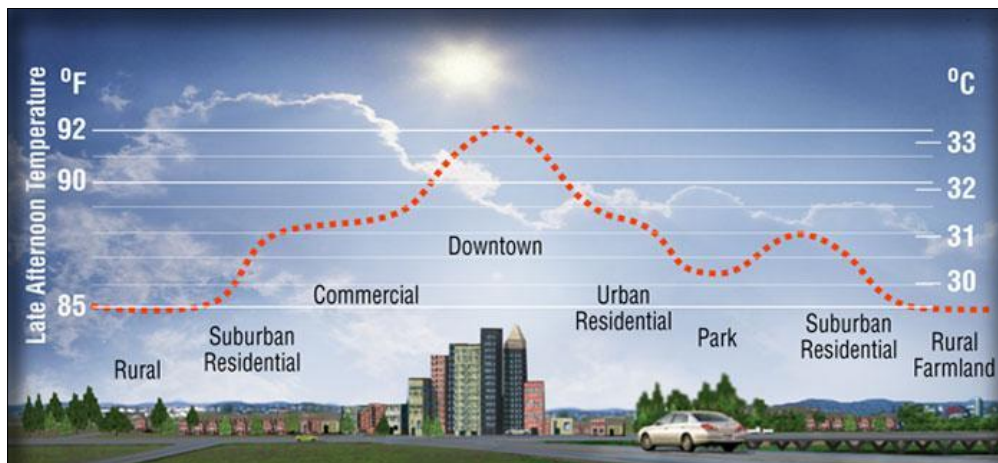
Below is a summary of the best practices for cool roofs:

- Develop cool roof-based building energy codes, standards, and green building labels.
- Develop various types of cool roof technologies.
- Develop standards and criteria for cool roof product performance testing.
- Set up cool roof product rating systems.
- Establish education and dissemination programs to teach designers and building owners to adopt cool surfaces.

6. URBAN PLANNING TO REDUCE THE URBAN HEAT ISLAND EFFECT

The urban heat island effect is a phenomenon that occurs during the daytime where an urban area has a much higher air temperature than its surrounding suburban and rural areas (Figure 12). Human activities such as vehicle exhaust heat emissions, energy use in factories, and exchange of heat from air-conditioning systems are major causes of urban heat island effects. Another major cause is urban infrastructure such as buildings and pavements that replace trees and enhance solar energy absorption in urban areas.

Figure 12: Urban Heat Island Effect



Source: Lawrence Berkeley National Laboratory (2019b).

Urban heat island effects can have several impacts in increasing building energy use and worsening outdoor air quality. A hot urban environment can increase heat transfer from the outdoor environment to the indoors and raise cooling energy demand. Also, a hot outdoor environment can slow an air-conditioner system condenser side heat exchange and reduce cooling system efficiency. The increased electricity demand on cooling energy use can also cause stress to the power grid and possible blackouts. Hot outdoor air can also accelerate the formation of ozone and outdoor pollutant emissions such as nitrogen oxides and volatile organic compounds. It can also cause human health effects such as respiratory syndrome and heat stroke.

Better urban planning can reduce urban heat island effects caused by human activities. Planning commercial-residential mixed-use urban districts can reduce commute distances and decrease the heat exhaust from cars. Urban planning to encourage the use of public transport can also reduce the urban heat island effect. Moving high energy demand industrial facilities outside of a city can shift the heat emission from cities to suburban or rural areas and relieve the increase in urban temperatures. There are several ways to mitigate the urban heat island effect through better urban and infrastructure planning:

- Good vegetation to create shades in an urban environment

Trees provide pleasant shade for the urban environment and can mitigate solar heat gain by urban surfaces. They can also absorb solar radiation from the sunlight without increasing outdoor air temperature and releasing moisture into the atmosphere.
- Cool roofs and walls

The cool roofs and walls discussed previously not only reduce the cooling energy demand for a building itself, but also, collectively, the reflective features of building envelopes can enable cities to absorb less solar radiation heat in the summer. Researchers have found that using a cool roof can effectively reduce the noon temperature of the PRC's Pearl River Delta cities by 0.8 degrees Celsius (°C) during ordinary summer days, and 1.2 °C during heatwave events (Figure 13).
- Cool pavement

Dark color pavements, often made with asphalt-based material, can absorb a great amount of solar energy. In the summer, we sometimes find that some pavements become "melted" due to a large amount of heat absorption and the high temperature of the road surface. The hot pavements continuously emit heat back into the urban air and aggravate the urban heat island effect. As pavements make up about a third of the urban surface, reducing pavement heat absorption and using cool pavements has become critically important. "Cool pavements," similarly to cool roofs, refer to pavements using reflective materials that reflect more solar energy than traditional pavements and stay cool. Concrete pavements can reflect 30%–50% of received solar energy. Some color-coated asphalt pavements can achieve solar reflectance of 50%. Cool pavements can also bring in better outdoor thermal comfort for people walking and exercising in cities.
- Water features

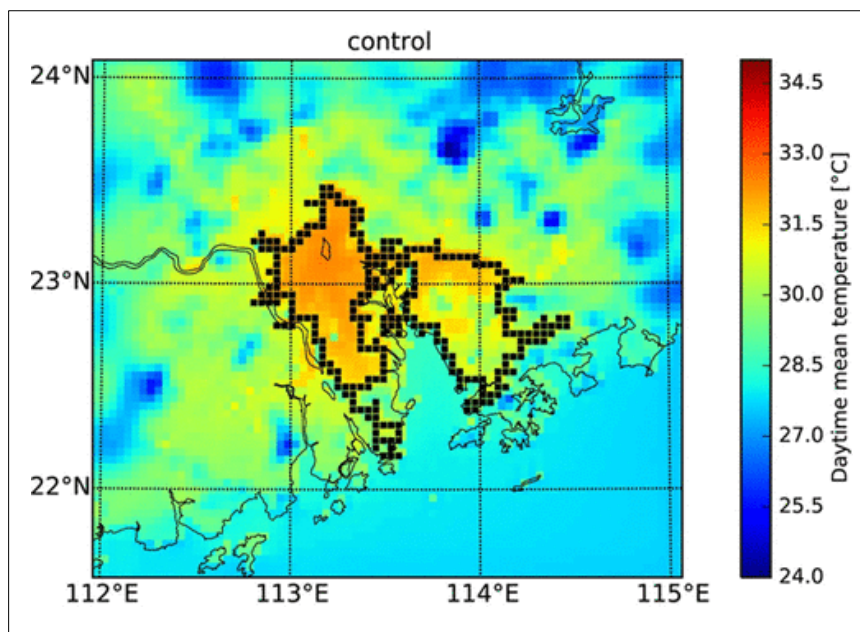
Water is a natural resource for free cooling. Lakes and ponds not only reflect solar energy, but their water temperature is often lower than the outdoor air temperature in the daytime, and the heat absorbed by water won't increase the outdoor temperature rise. The heat absorbed by water can also be converted into latent heat through water evaporation. Spraying water can create mists that can cool the surrounding environment.
- Create urban wind channels

Understanding the dominant wind directions in the summer, and planning for a city to take advantage of those winds, can help enhance air movement through a city and assist in mitigating the urban heat island effect. Planners often need to consider certain wind flow channels and refrain from using dense high-rise buildings that block upstream wind flow.
- District cooling

Air-conditioning systems need to exhaust heat to the outdoor environment and thus aggravate the urban heat island effect. However, district cooling systems can locate the cooling central plant in suburban areas, where the urban heat island effect is not significant, and provide centralized chilled water to buildings in cities. Some advanced district cooling systems can utilize water from underground, rivers, lakes, and even seawater to exchange heat. In this case,

heat is ejected into the water instead of to the outdoor air, and therefore will not worsen urban heat island effects.

Figure 13: Urban Heat Island Mitigation Using Cool Roofs



Source: Cao et al. (2015).

7. POLICY INSTRUMENTS TO REDUCE COOLING DEMAND

Several policy barriers to applying passive cooling measures exist. In some countries, codes and standards are not stringent enough to require the adoption of passive cooling design and technologies—the building and construction market lacks labels and certifications to disclose passive cooling products' key performance data; building owners lack incentives to develop passive construction; and architects, builders, and occupants are not aware of the importance of passive design and do not know how to design or operate passive technologies. There is also a lack of sustainable city policies to create a cooler outdoor environment and a need to establish international passive cooling programs such as the Million Cool Roof Challenge to scale up the global adoption of affordable passive cooling solutions.

Policy instruments are important to overcome existing barriers and accelerate passive cooling market adoption. Regulatory, information, and incentive policies are available to scale up green cooling applications. According to previous analysis, regulatory policy development should focus on upgrading building codes and standards to encourage the adoption of passive measures in buildings. Information policies should focus on developing label and certification programs to promote passive cooling technologies. Incentive programs are important in providing financial and/or building construction incentives for buildings to adopt passive cooling measures. Moreover, capacity building policies are needed to educate architects, developers, and occupants to take part in the passive cooling built environment and sustainable urban planning.

7.1 Building Codes and Standards

Building codes and standards usually provide good definitions of the minimum performance requirements of passive measures and active cooling technologies. The passive cooling measure requirements are usually defined based on climate zone conditions. According to the discussion in previous sections, the following building envelope measures are critical to reduce cooling energy demand and need to be explicitly defined in building codes and standards:

- U-value of building envelope opaque walls and roofs
- Solar reflectance and thermal emittance of building envelope opaque walls and roofs
- U-value and SHGC of building fenestration system
- Window-to-wall ratio

Indoor thermal comfort criteria are not a technology requirement but can significantly influence buildings' cooling energy demand. Besides building energy standards, thermal comfort standards should also be established and define the occupants' thermal comfort zones. It is worth noting that several countries have established adaptive thermal comfort requirements to encourage natural ventilation and passive cooling. The development of thermal comfort standards should include both mechanical cooling and adaptive thermal comfort for passive cooling, and allow both passive and active cooling equipment to operate in buildings based on outdoor weather conditions.

Trade-offs between building envelope measures are needed to provide flexibility to architects to design energy-efficient buildings. The recent development of building codes and standards tends to allow trade-offs between the window-to-wall ratio requirements and energy savings from HVAC and daylight utilization. The adoption of a cool roof can also be traded off against the level of a building's roof insulation.

Building energy codes and standards can require a mechanical air supply system to be used to blow in cool outdoor air without conditioning it and achieve free cooling. This often happens when the outdoor air temperature and relative humidity levels are satisfactory and directly supplying outdoor air can help cool indoor space without causing any discomfort issues. Based on the climate zone's characteristics, energy codes and standards should encourage the use of air-side economizers to achieve free mechanical cooling. In some countries, the use of air-side economizers can be traded off against chiller systems' coefficient of performance (COP). That is, if air-side economizers are not used in a building, its cooling system efficiency needs to be more stringent compared to a building in the same climate using air-side economizers.

The compliance pathway of codes and standards should also encourage whole building performance evaluation. The whole building compliance method not only requires a building to meet the requirements of prescriptive measures, but it also encourages the adoption of passive measures such as natural ventilation to comprehensively calculate the whole building's energy performance.

7.2 Labels and Certifications

Labels and certifications are rating mechanisms for certifying technology or whole-building sustainability performance. Both technology and whole-building-level certifications are needed to advance passive cooling in buildings. Technology-based certification includes the following technologies:

- Windows
- Cool roof
- Insulation materials

In technology-based certification, key technology parameters are often articulated in the certification labels. These parameters include U- (or R-) value, solar heat gain coefficient, visible light transmittance, solar reflectance, and thermal emittance.

Developing testing standards of building technologies to support label and certification programs is also necessary. Testing procedures to test windows, cool roofs, and insulation materials need to be standardized. Capacity building of local laboratories on testing building technologies to comply with testing procedures standards is also needed.

Some passive cooling measures such as natural ventilation may not be explicitly labeled as technologies but could be promoted through whole-building-level rating programs. In whole-building rating systems, an integrative building design can comprehensively consider the outdoor environment, building orientation and massing, and combining passive cooling strategies with HVAC systems. Several whole-building performance rating systems such as Leadership in Energy and Environmental Design (LEED) are widely used in Asian countries. However, it is more important for a country to establish its own green building rating system.

7.3 Incentive Policies

Incentive policies can encourage building owners and designers to adopt passive cooling designs and technologies. Incentive policies can be financing incentives that a building owner receives, such as certain monetary incentives, financial rebates, or low-interest loans. Incentive policies can also be associated with the building permit application process, allowing a building to have extra space built or public recognition programs for green buildings to adopt passive cooling measures.

7.4 Capacity Building and Cultivating Passive Cooling Behaviors

Teaching people the importance of passive cooling measures through design, construction, and operation can greatly advance the application of passive cooling measures. Education programs can be set up to build the capacity of designers and constructors to adopt more passive cooling technologies in new building construction. Occupants are the core of energy-efficient building operations. We have seen cases where, even with good passive cooling technologies installed, buildings still use a lot of cooling energy because the occupants are not aware of the importance of passive cooling measures or don't know how to use them. Policies are needed to ensure that occupants are educated to apply passive cooling measures as a higher priority before they turn on mechanical air-conditioning systems. The green campaign and education

programs are especially important for students, who are our future building occupants and sustainable cooling practitioners.

7.5 Sustainable Urban Planning Policies

Buildings frequently exchange heat with their ambient environment. Creating a sustainable and cool urban environment can greatly reduce buildings' need for cooling energy. Policy development should focus on how to plan our urban system to enhance airflow and create urban airflow pathways to facilitate building-level natural ventilation. Cities should also develop policies to build reflective urban pavements and create more green outdoor space to mitigate the urban heat island effect. A pleasant outdoor environment also attracts occupants to undertake more outdoor activities and therefore reduces the amount of time people spend indoors and thus saves cooling energy consumption.

7.6 Million Cool Roof Challenge

The Million Cool Roof Challenge program was created to accelerate affordable passive cooling through the rapid deployment of cool roofs. The program emphasizes improving access to cooling and promoting sustainable cooling solutions in the developing world. Given the existing barriers in low-income communities, such as the lack of awareness of cool roofs, the lack of financing, and the lack of heat mitigation policies and implementation frameworks, the Million Cool Roof Challenge works with demonstration projects, training programs, and policy development to help developing countries set up cost-effective cool roof policies.

8. PASSIVE COOLING BUILDING DESIGN AND CASE STUDY

8.1 School of Design and Environment 4 Net-Zero Energy Building

The School of Design and Environment 4 (SDE4) building at the National University of Singapore (Figure 14) is the first net-zero energy building in Southeast Asia's tropical climate. The building received a net-zero energy certification from the International Living Future Institute due to its excellent energy performance. The building also received Green Mark Platinum Zero Energy Building certification—a super-low-energy building with all energy consumption, including plug load, supplied from renewable energy sources (see Box 3.3 in Azhgaliyeva and Rahut 2022). SDE4 is a mixed-use office building with a library, design studio, research and development center, and workspace. The building employs the integrated design process to combine several passive design features with occupant activities to reduce its energy consumption.

The building is designed with a large canopy overhang on its south side to shade from direct solar heat gain. The big canopy also shades the building's outdoor perimeter areas to provide a pleasant outdoor environment for outdoor teaching and other activities. The green vegetation around the building provides useful shade as well as a cool urban micro-environment for the building's surroundings. The east and west sides of the facade feature perforated aluminum panels that provide good shade for the facade as well as satisfactory daylight for the interior space. These panels can be replaced with other shading designs for teaching and research purposes.

Even though the building is located in a tropical climate, more than 50% of the interior space can be naturally ventilated during the summertime. Most of its rooms can be open and cooled by the prevailing wind. Thanks to this natural ventilation, air-conditioning is only operated when needed. The building's interior is designed with a variety of terraces, boxes, and landscape spaces. The mix of these different functional spaces can enhance air movement among the spaces and promote natural ventilation. Ceiling fans are used in the building to better circulate the air and provide good thermal comfort. Fans are also an important component of the building's hybrid cooling system. In the cooling season, its hybrid ventilation and air-conditioning system can operate the room temperature at 27°C–28°C with 65% relative humidity with the help of ceiling fans. These operating conditions improve the efficiency of the mechanical cooling system compared with traditional 23°C–24°C and 50% relative humidity operating conditions.

The building uses information technology to manage occupant thermal comfort (Sood *et al.* 2019). It clusters occupants in open offices and a library based on users' thermal comfort preferences. With more uniform thermal comfort criteria in each cluster, the building can provide specific cooling methods for different occupant clusters and achieve energy savings and better occupant satisfaction.

Figure 14: The School of Design and Environment 4 Zero Energy Building



Source: National University of Singapore (2022).

8.2 Passive Design of the Shenzhen Institute of Building Research

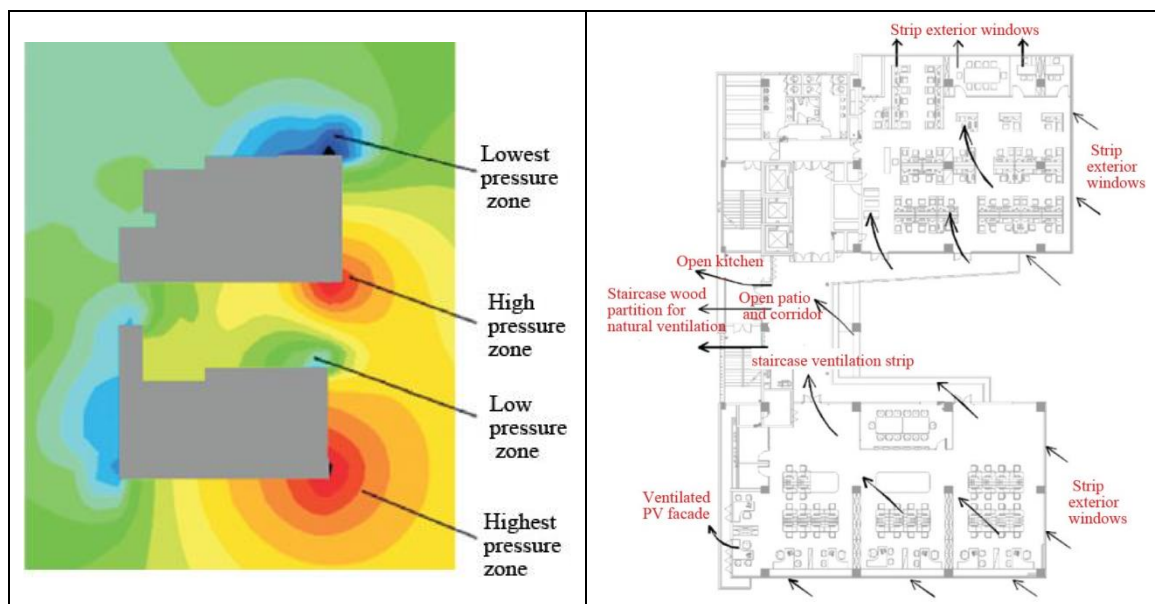
The Shenzhen Institute of Building Research headquarters is a 12-story office building, located in Shenzhen, PRC, a typical subtropical climate region that often requires six months of air-conditioning operation each year. The building embraces the concept of passive cooling from design to operation and includes several passive design measures (Diamond and Feng 2014).

The building envelope is designed with different strategies to reduce solar heat gain. The building's WWR on its south side is strictly controlled at 40% to reduce solar heat gain transferred through exterior windows. Overhang shades are also installed on its south side. The upper side of the overhang is coated with reflective materials, so daylight can be reflected from the overhang to the ceiling. The west side is designed with only an 11% WWR to minimize solar heat gain in the afternoon.

To maximize natural ventilation, the building is designed with a "hollow shape." This design enables the wind to blow in the middle area between the north and south towers to generate good wind pressure for natural ventilation (Figure 15). All windows in the case building are operable. The types of window openings are studied based on the dominant wind direction and ensure that occupants can adjust the window opening angles to control the airflow (ADB 2021). For large spaces such as the auditorium, fully opening doors were designed to allow cross-space natural ventilation.

Vegetation and ponds are also widely used in the building to create a pleasant micro-environment for free cooling. The zoning designs of the case building arranged all corridors, restrooms, and staircases so that they were exposed to the outdoor environment directly, without space conditioning.

Figure 15: CFD Simulation of Wind Pressure Field (Left) and Airflow Analysis (Right)



Source: Diamond and Feng (2014).

9. CONCLUSION AND POLICY RECOMMENDATIONS

This paper introduces designs, technologies, and best practices aimed at reducing the cooling energy demand in buildings. It covers the basic principles of why occupants need cooling to meet thermal comfort requirements and how heat is transferred into buildings from the outdoor environment. Passive designs help buildings make use of natural cooling resources and maximize free cooling opportunities such as natural ventilation. This paper introduces passive building designs and solutions, including integrative design, free cooling, natural ventilation, high-performance building envelope, cool roofs and surfaces, and sustainable city development. To scale up

passive cooling designs and technologies, policy instruments are recommended, such as improving building codes and standards requirements on passive cooling, using label and certification programs to demonstrate the performance of passive cooling technologies, establishing incentive programs to promote the adoption of cooling solutions, and building the capacities of architects, developers, and occupants to apply passive cooling measures. This study mainly considers technical solutions; future studies should conduct in-depth techno-economic analyses for passive cooling that consider energy savings, human comfort, and productivity. Techno-economic analysis with a research focus on the developing countries in Asia could provide good data for future green cooling policy development.

This paper summarizes best practices for each passive strategy used in buildings. Architects and engineers can also better orient functional spaces and design cooling operation strategies to provide cooling for spaces where and when needed. The building envelope provides the necessary insulation to stop heat transfer from a hot outdoor environment to an indoor one. Criteria for designing a high-performance building envelope are introduced. For fenestration systems, this paper covers energy-efficient technologies for glazing and shades to reduce solar heat gain. Cool roofs can effectively reflect sunlight back to the atmosphere, and also significantly reduce buildings' solar heat gain. Also, to create a cooler outdoor environment in cities, strategies are introduced to mitigate the urban heat island effect. Finally, policy recommendations are provided, such as improving building codes and standards; creating labels and certifications for passive cooling technologies; establishing incentive programs to promote passive green buildings; educating architects, builders, and occupants; and developing sustainable city policies.

REFERENCES

- ADB (2021) People's Republic of China: Developing a Climate Friendly Cooling Sector through Market and Financing Innovation, Project Number: 52249-003, September 2021, <https://www.adb.org/sites/default/files/project-documents/52249/52249-003-tacr-en.pdf>.
- Akbari, H., S. Menon, and A. Rosenfeld. 2009. Global Cooling: Increasing World-Wide Urban Albedos to Offset CO₂. *Climatic Change* 94 (3–4): 275–286.
- American Society of Heating Refrigeration Air-Conditioning Engineers (ASHRAE). 2000. ASHRAE Standard 55 – Thermal Environmental Conditions for Human Occupancy. <https://www.ashrae.org/>.
- American Society of Heating Refrigeration Ventilation and Air-Conditioning Engineers (ASHRAE). 2021. *ASHRAE Handbook Fundamentals*. ISBN(s): 9781947192898.
- APEC Energy Working Group (EWG). 2020. Coordinating Standards for Cool Roof Testing and Performance. www.apec.org.
- ASHRAE 55. (2017). Thermal environmental conditions for human occupancy.
- Azhgaliyeva, D., and D. B. Rahut. 2022. Promoting Green Buildings: Barriers, Solutions, and Policies. In *Climate Change Mitigation: Policies and Lessons for Asia*, edited by D. Azhgaliyeva and D. B. Rahut. ADBI. <https://www.adb.org/sites/default/files/publication/838246/climate-change-mitigation.pdf>.
- Cao, M., P. Rosado, Z. Lin, R. Levinson, and D. Millstein. 2015. Cool Roofs in Guangzhou, China: Outdoor Air Temperature Reductions During Heat Waves and Typical Summer Conditions. *Environmental Science & Technology* 49(24): 14672–14679. DOI: 10.1021/acs.est.5b04886.
- Diamond, R., and W. Feng. 2014. *Sustainability by Design: How One Building in China Could Change the World*. ISBN-13978-0692341155: Amazon.com.
- Feng, W. et al. 2019. A Review of Net Zero Energy Buildings in Hot and Humid Climates: Experience Learned from 34 Case Study Buildings. *Renewable and Sustainable Energy Reviews* 114: 109303. October.
- Lawrence Berkeley National Laboratory (LBNL). 2015. Window Retrofits & Attachments: Energy Saving Potential. <https://windows.lbl.gov/energy-saving-potential>.
- Levinson, R., and H. Akbari. 2010. Potential Benefits of Cool Roofs on Commercial Buildings: Conserving Energy, Saving Money, and Reducing Emission Of Greenhouse Gases and Air Pollutants. *Energy Efficiency* 3: 53–109.
- Lu, S., Y. Chen, S. Liu, and X. Kong. 2016. Experimental Research on a Novel Energy Efficiency Roof Coupled with PCM and Cool Materials. *Energy and Buildings* 127: 159–169.
- National University of Singapore (NUS). 2022. SDE4, Singapore's first purpose-built net-zero energy building. <https://sustainability.nus.edu.sg/>.
- Peters T. and L. Sayin 2022a. Future-Proofing Sustainable Cooling Demand. In *Climate Change Mitigation: Policies and Lessons for Asia*, edited by D. Azhgaliyeva and D. B. Rahut. ADBI. <https://www.adb.org/sites/default/files/publication/838246/climate-change-mitigation.pdf>.

Peters, T., and L. Sayin 2022b. The Cold Economy, ADBI WP No. 1326, June 2022.
<https://www.adb.org/sites/default/files/publication/805756/adbi-wp1326.pdf>.

Sood, T., M. Quintana, P. Jayathissa, M. A. Rahman, and C. Miller. 2019. The SDE4 Learning Trail: Crowdsourcing Occupant Comfort Feedback at a Net-zero Energy Building, Journal Physics: Conference Series **1343** 012141, DOI 10.1088/1742-6596/1343/1/012141,
<https://iopscience.iop.org/article/10.1088/1742-6596/1343/1/012141/meta>.

US NFRC. 2022. What does the NFRC label tell you? National Fenestration Rating Council. <https://www.nfrc.org/>.