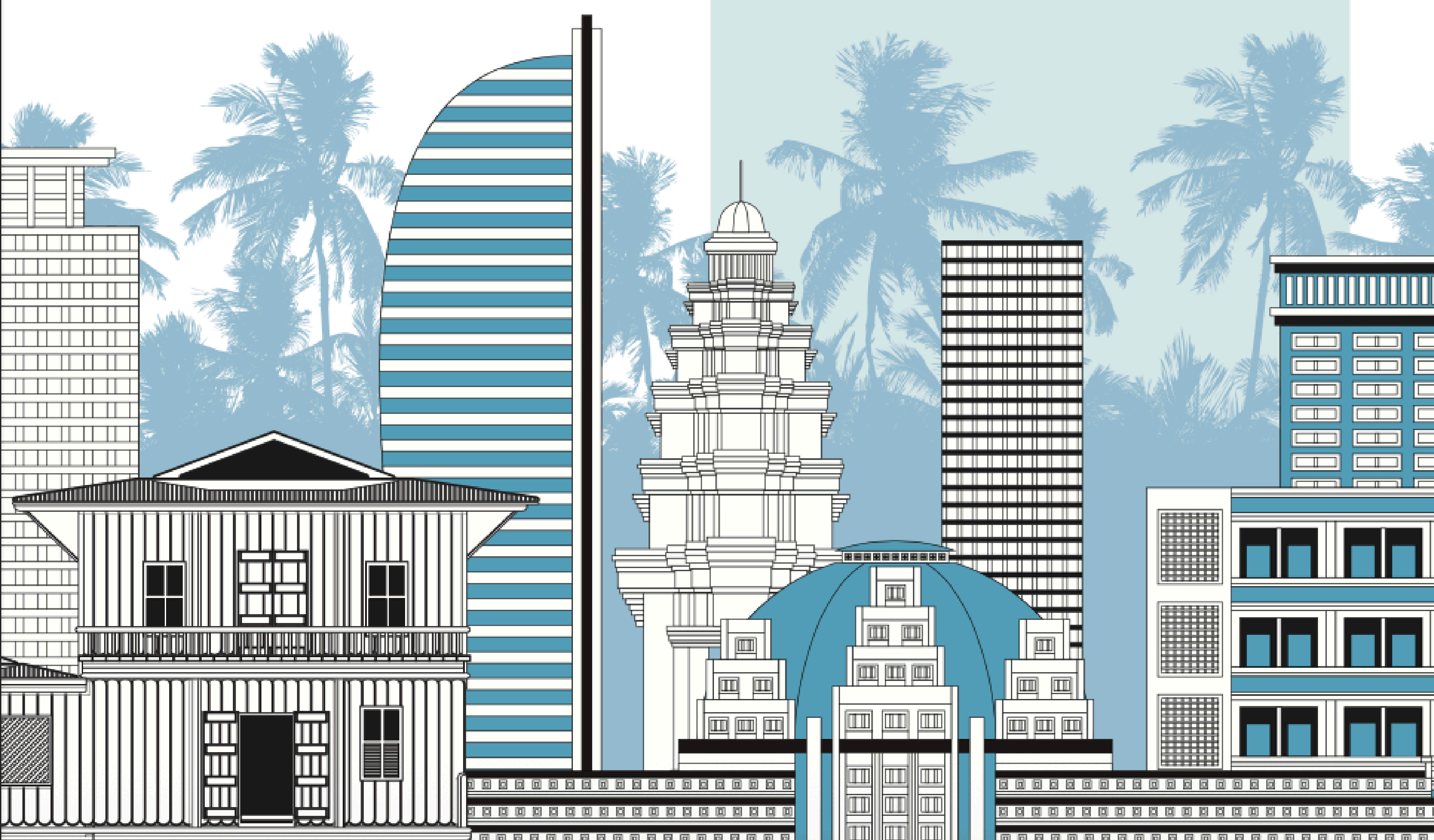
GUIDELINES FOR PASSIVE COOLING STRATEGIES IN CAMBODIA



GUIDELINES FOR PASSIVE COOLING STRATEGIES IN CAMBODIA

Foreword

Building on the peace and political stability established under the leadership of **Samdech Akka Moha Sena Padei Techo HUN Sen, President of the Senate**, and guided by Phase 1 of the Pentagonal Strategy led by **Samdech Moha Borvor Thipadei HUN Manet, Prime Minister of the Kingdom of Cambodia**, the nation is undergoing a period of rapid urbanization and economic growth. Concurrently, the country is facing rising temperatures and an increasing demand for cooling, placing pressure on energy systems, public health, and the built environment. In this context, the adoption of sustainable, energy-efficient, and climate-resilient solutions is both timely and essential. Passive cooling strategies, when integrated into building design and construction, offer an effective pathway to reduce energy consumption, enhance thermal comfort, and limit the environmental impacts associated with conventional mechanical cooling systems.

The *Guidelines for Passive Cooling Strategies in Cambodia* build upon the foundation established through Cambodia's National Cooling Action Plan (NCAP) and are aligned with the country's commitments under the Paris Agreement and the objectives set out in its Nationally Determined Contribution (NDC). The Guidelines provide practical and context-specific approaches that respond to Cambodia's climatic conditions, architectural traditions, and locally available materials. By reducing reliance on energy-intensive cooling technologies, these strategies support lower greenhouse gas emissions while improving indoor comfort, health, and well-being.

These Guidelines are intended to serve as a comprehensive and practical reference for architects, engineers, planners, policymakers, and other relevant stakeholders. Developed through a collaborative process involving national experts, technical institutions, and international partners, the document supports the integration of passive cooling strategies into building design, construction, and retrofitting. It presents a broad range of solutions, from site-level and urban design considerations to building-level interventions such as orientation, shading, natural ventilation, insulation, and the use of reflective and climate-appropriate materials.

Widespread adoption of passive cooling strategies can contribute significantly to reducing cooling-related electricity demand, improving thermal comfort, enhancing public health and productivity, and advancing Cambodia's climate and sustainable development objectives. It is hoped that these Guidelines will serve as an important technical resource in shaping a cooler, greener, and more resilient built environment across the country.

Sincere appreciation is extended to all partners who contributed to the development of these Guidelines, including the Ministry of Environment, through the General Directorate of Environmental Protection and the General Directorate of Policy and Strategy, with technical and financial support from the United Nations Economic and Social Commission for Asia and the Pacific (ESCAP) and the United Nations Environment Programme (UNEP) within the framework of the Cool Coalition. Appreciation is also extended to all relevant ministries, institutions, and stakeholders whose expertise and engagement were instrumental throughout the development process.

Minister of Environment

H.E. Dr. Eang Sophalleth

Acknowledgments

The Ministry of Environment of the Kingdom of Cambodia extends its sincere appreciation to all relevant ministries, development partners, academic institutions, private sector representatives, experts, and stakeholders who contributed to the development of the *Guidelines for Passive Cooling Strategies in Cambodi*a.

The Guidelines were developed under the leadership of the Ministry of Environment, through the General Directorate of Environmental Protection and the General Directorate of Policy and Strategy, with technical and financial support from the United Nations Economic and Social Commission for Asia and the Pacific (ESCAP) and the United Nations Environment Programme (UNEP), within the framework of the Cool Coalition.

Leadership and coordination in the development of the Guidelines were provided by H.E. Pak Sokharavuth, Under Secretary of State; Dr. Hak Mao, Director of the Department of Climate Change, General Directorate of Policy and Strategy; and Mr. Chea Nara, Director of the Department of Air Quality, Noise and Vibration Management, General Directorate of Environmental Protection. Valuable collaboration, technical inputs, and guidance were also provided by H.E. Dr. Mom Mony, Secretary General of the General Secretariat of the National Council for Building Technical Regulations of the Ministry of Land Management, Urban Planning and Construction; Mr. Sok Leng, Deputy Director of the Department of Technique and Energy Business Policies of the Ministry of Mines and Energy; and the Institute of Technology of Cambodia (ITC), contributing to the advancement of passive cooling research and practice in Cambodia.

The Ministry further recognizes the project team supporting the development of the Guidelines, including Michael Williamson (ESCAP), Lily Riahi (UNEP), Kimberly Roseberry (ESCAP), Marco Duran (UNEP), Manjeet Singh (UNEP), Leyla Prezelin (UNEP), as well as the technical experts Kanagaraj Ganesan, Raj Kumar Balasubramaniyan, Andeol Cadin, Lun Lido, and Philip Tephyuthyea. The Guidelines also benefited from valuable reviews and inputs from national and international experts representing government, academia, architectural practice, and the building sector, including Gennai Kamata, Aarti Nain, and Dr. Lorena Carvalho (UNEP Cool Coalition); Dr. Tetsu Kubota (Hiroshima University); Prof. Sheikh Ahmad Zaki Bin Shaikh Salim (Universiti Teknologi Malaysia); Yimei Chan (LOD); Dr. Sumedha Basu (University of Leeds); Vang Le (ISD Engineering); Mahfuzur Rahman (GGGI Cambodia); Sandy Kumar (UN-Habitat); Sovanchandara Heng (UNDP); Dr. Sarin Chan; and Dr. Kinnaleth Vongchanh (Institute of Technology of Cambodia).

Finally, the Ministry of Environment recognizes all individuals and institutions whose efforts and commitment and contributions made the development of these Guidelines possible. We sincerely hope that the Guidelines will serve as an important technical resource to support policy development, building regulations, and capacity building efforts, contributing to Cambodia's transition toward a climate-responsive, low-carbon, and climate-resilient future.

Technical and financial support was provided by:

ESCAP Economic and Social Commission for Asia and the Pacific · UN environment programme · Cool Coalition

Acronyms

AHU	Air Handling Unit
ASEAN	Association of Southeast Asian Nations
ASHRAE	American Society of Heating, Ventilation and Air-Conditioning Engineers
BAS	Building Automation Systems
BIPV	Building Integrated Photo Voltaic
BMS	Building Management Systems
CFD	Computational Fluid Dynamics
DBT	Dry Bulb Temperature
EGR	Extensive Green Roof
EMSyS	External Movable Shading Systems
EPI	Energy Performance Indices
EPS	Expanded Polystyrene
EPW	EnergyPlus Weather
ERVs	Energy Recovery Ventilation Systems
ESPC	Energy Savings Performance Contracting
GHG	Greenhouse Gases
GPS	Graphite Polystyrene
HRVs	Heat Recovery Ventilation Systems
HVAC	Heating, Ventilation, and Air-Conditioning
IDP	Integrative Design Process
IEQ	Indoor Environmental Quality
IPD	Integrated Project Delivery
KPI	Key Performance Indicators
LCCA	Life-Cycle Cost Analysis
LED	Light-Emitting Diode
MMV	Mixed-Mode Ventilation
MRT	Mean Radiant Temperature
NCAP	National Cooling Action Plan
NREL	National Renewable Energy Laboratory
PCS	Passive Cooling Strategies
PF	Phenolic Foam
PIR	Polyisocyanurate
PMV	Predicted Mean Vote
PPD	Percentage of People Dissatisfied
PPE	Personal Protective Equipment
PUF	Polyurethane Foam
PV	Photovoltaic
RAP	Reclaimed Asphalt Pavement
RCA	Recycled Concrete Aggregate
RCC	Reinforced Cement Concrete
RH	Relative Humidity
SC	Shading Coefficient
SHGC	Solar Heat Gain Coefficient
SPF	Spray Polyurethane Foam
SRI	Solar Reflectance Index
UESC	Utility Energy Service Contract
UHIE	Urban Heat Island Effect
UPVC	Unplasticized Polyvinyl Chloride
UTCI	Universal Thermal Climate Index
UV	Ultraviolet
VLT	Visual Light Transmission
VOC	Volatile Organic Compound
XPS	Extruded Polystyrene
WBT	Wet Bulb Temperature
WWR	Window-to-Wall Ratio

Definitions

Terminology	Definition	Unit
Clothing	One Clo is defined as the amount of insulation required to maintain thermal comfort in a resting person at room temperature (around 20°C) in typical indoor clothing.	Clo
Cooling Energy Performance	Cooling Energy Performance is evaluated in terms of energy consumption, typically measured in kilowatt-hours per square meter (kWh/m^2.year), reflecting the energy used for cooling relative to the building's floor area across the year, aiding in assessing energy efficiency.	kWh/m^2.year
Density	Density refers to the mass of a substance per unit volume it occupies. It quantifies how much mass is contained within a given volume of material.	kg/m^3
Heating and cooling loads	Heating and cooling loads measure energy needs for temperature control.	kW or Btu/h, ton of refrigeration for cooling)
Indoor Thermal Comfort	Indoor Thermal Comfort is assessed using the Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD), indicating occupants' perceived comfort levels based on environmental factors like temperature, humidity, and air movement.	PMV/PPD
Macroclimate	It refers to the long-term atmospheric conditions of a large region, including temperature, precipitation, and weather patterns. It offers a broader view of an area's climate.	
Mesoclimate	It refers to the climate characteristics of a specific, localized region within a larger macroclimate, such as a city, valley, or coastal zone. It is influenced by regional features like topography, elevation, and proximity to water bodies.	
Metabolic Rate	MET stands for metabolic equivalent, which is a unit used to estimate the metabolic rate of physical activities. One MET is defined as the energy expenditure at rest, which is approximately 3.5 milliliters of oxygen uptake per kilogram of body weight per minute (3.5 ml/kg/min).	MET

Microclimate	It refers to the atmospheric conditions within a specific area, influenced by terrain, vegetation, and human activities. It reflects the unique climate of the immediate site surroundings.	
Relative Humidity	Relative Humidity is the percentage ratio of the actual water vapor content in the air to the saturation water vapor content at the same temperature and pressure.	%
R-value	The R-value measures a material's resistance to heat flow, with higher values indicating better insulation. Its unit depends on the units used for thickness and thermal conductivity. If thickness is in meters and conductivity in watts per meter-kelvin, it's $m^2 \cdot K/W$. If thickness is in feet and conductivity in Btu per hour per foot-degree Fahrenheit, it's $ft^2 \cdot hr \cdot °F/Btu$.	$m^2 \cdot K/W$ or $ft^2 \cdot hr \cdot °F/Btu$
Specific Heat	Specific Heat denotes the amount of heat energy required to raise the temperature of one kilogram of a substance by one degree Celsius.	J/(kg.k)
Temperature Range	Temperature Range specifies the span of temperatures within which a material or system can effectively operate or function without adverse effects.	°C
Thermal Conductivity	Thermal Conductivity is a measure of a material's ability to conduct heat. It quantifies the rate at which heat is transferred through a unit thickness of the material per unit area per unit temperature gradient. A higher thermal conductivity value indicates that the material conducts heat more efficiently.	W/(m.K)
Energy Performance Index (EPI)	Energy Performance Index (EPI) normalizes the energy used across the year by the floor area of the building. "$kWh/m^2/year$" quantifies energy consumption per square meter of floor area annually, aiding in building energy efficiency assessments.	$kWh/m^2.year$
U-value	The "U-value," also known as the "U-factor" is a measure of the rate of heat transfer through a building material. Specifically, it quantifies how well a material allows heat to conduct through it.	$W/(m^2 \cdot K)$

Water Absorption	Water Absorption measures the amount of water a material can absorb, crucial for assessing its durability and suitability for various applications.	%
Wet Bulb Temperature	The temperature indicated when a thermometer bulb is covered with a water-saturated wick over which air is caused to flow at approximately 4.5 m/s to reach the equilibrium temperature of water evaporating into the air when the heat of vaporization is supplied by the sensible heat of the air	°C
Urban Heat Island Effect (UHIE)	A phenomenon where urbanized areas exhibit higher ambient temperatures compared to surrounding rural areas. This occurs because buildings, roads, and other infrastructure absorb and re-emit the sun's heat more efficiently than natural landscapes such as vegetation and water bodies. The concentration of heat-absorbing surfaces and limited greenery results in "islands" of elevated temperature within cities.	

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Purpose

The *Guidelines for Passive Cooling Strategies in Cambodia* establish a unified national framework to support the planning, design, construction, and operation of buildings that incorporate passive cooling strategies. The Guidelines define clear objectives, guiding principles, and expected outcomes to ensure that passive cooling is systematically integrated across the building sector, contributing to national priorities on energy efficiency, climate resilience, and sustainable development.

The Guidelines serve as a common reference to inform decision-making throughout the building lifecycle. They provide a basis for aligning technical practices, design approaches, and operational measures with the objective of reducing reliance on mechanical cooling while maintaining thermal comfort. In addition, the Guidelines offer direction to policymakers on the integration of passive cooling strategies into national energy and building regulations, as well as green building certification systems, ensuring coherence between regulatory frameworks and voluntary standards.

This document is intended as a comprehensive and practical resource for architects, designers, engineers, policymakers, industry stakeholders, and the general public. It presents climate-responsive analysis and passive cooling strategies applicable at the site, building, and component levels, with a focus on minimizing mechanical cooling demand while achieving thermal comfort across a range of building types. The Guidelines bridge theory and practice by addressing design approaches, technical options, on-site application, techno-commercial considerations, good practice guidance, and a portfolio of passive cooling measures relevant to the Cambodian context. The content is tailored to different building typologies, scales, climatic conditions, and project stages.

By providing a clear and consistent framework, the Guidelines aim to enable coordinated action across sectors and regions, supporting the effective adoption of passive cooling strategies that deliver measurable benefits in energy savings, environmental performance, and quality of life.

1 Introduction

In 2017, the estimated penetration rate for cooling equipment in Cambodia averaged around 2%. Given the country’s hot-humid climate and steady economic growth, the demand for energy in comfort cooling has been steadily increasing. Buildings account for more than one-third of Cambodia’s total final energy consumption, with space cooling alone contributing for 45% of it (Ministry of Envrionment Cambodia, 2022).

According to the 2021 Cambodia National Cooling Action Plan, demand for building space cooling is set to double between 2020-2040 to 3.7 million tons of refrigeration in Cambodia. To responsibly adapt to the increasing heat stress and mitigate the greenhouse gas emissions from energy consumption and refrigerant use by energy-intensive air conditioning systems, it is essential to adopt passive cooling strategies in buildings, which reduce the reliance on mechanical systems while supporting thermal comfort for occupants.

The technical analysis for the passive cooling in Cambodia draws from data collected in typology and compendium reports. Passive cooling categories, including site-oriented, design-oriented, and material-oriented measures, are explained in detail with technical descriptions, application processes, and analytical tools. The incorporation of passive cooling into new buildings can lead to significant energy savings and the reduction of greenhouse gas emissions. The document outlines the integration of passive cooling in different building typologies, encompassing aspects such as shading, insulation, and ventilation. Furthermore, it highlights a demonstration project in Phnom Penh, where identified strategies were piloted to assess their impact on energy conservation and comfort levels.

Cambodia's tropical climate necessitates substantial space cooling for thermal comfort. Buildings, through passive cooling integration, can potentially achieve significant energy savings and mitigate greenhouse gas emissions. A cumulative national energy savings potential ranging from 32 to 143 GWh/year is projected from 2024 to 2030, with a reduction of GHG from 22,000 tCO2e to approximately 99,000 tCO2e, contingent on adherence to different scenarios. The identified strategies, such as shading, insulation, and ventilation, are integrated into new buildings, addressing cooling demand and mitigating heat island effects.

A demonstration project in Borey Chankiri by Urbanland (Section 3.2.4) was chosen to assess the effectiveness of passive cooling strategies in reducing cooling demand. Theoretical analysis, simulations, and real-world implementations assist in correlating estimated cooling energy performance indices (EPIs) with demonstrated results. These insights have informed the formulation of the Guidelines, and a comprehensive portfolio of applicable passive cooling strategies for various building typologies, sizes, geometries, climates, and project stages.

2 Classification of Passive Cooling Strategies

Passive cooling strategies (PCS) are classified into three levels: site, building, and component. At the site level, the focus is on utilizing natural elements such as wind, trees and vegetation for shade, as well as leveraging topographical features to minimize heat gain. Building-level strategies involve optimizing orientation, window placement, shading and building envelope performance, to enhance natural ventilation and reduce heat gain. The component level deals with specific elements such as reflective roofing materials, thermal insulation, and efficient fenestration systems. This systematic classification helps architects and designers create sustainable, climate-responsive buildings tailored to specific challenges. Figure 1 lists the passive cooling strategies.

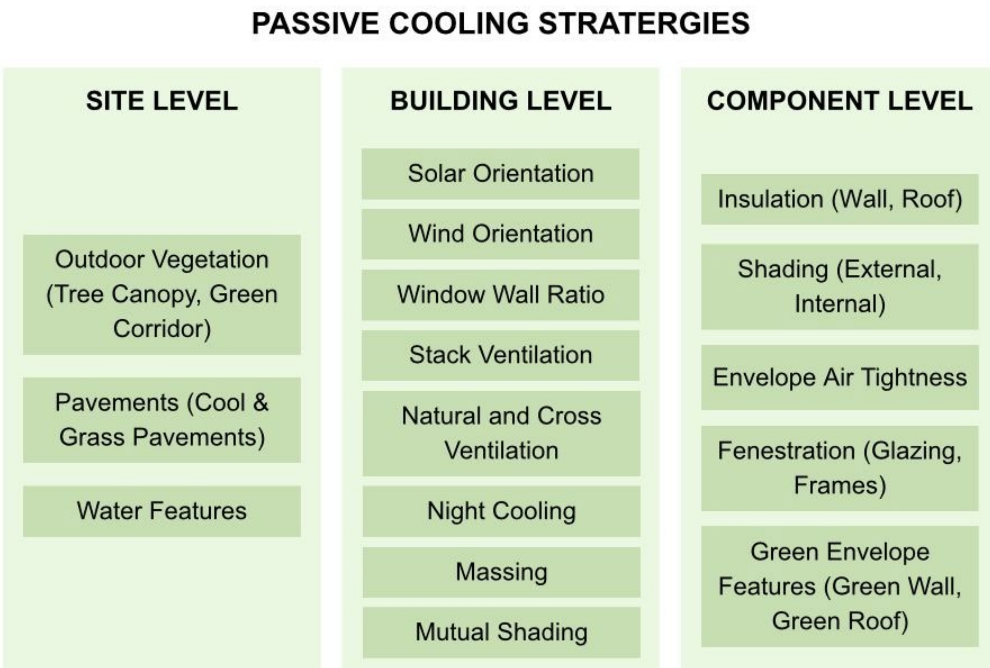


Figure 1 Classification of passive cooling strategies

2.1 Site Level Considerations

At the site level, the microclimate holds significant importance. It is shaped by existing elements surrounding the building site, whether on-site features with long-term prevalence or nearby off-site features that may change over time. Climate, the primary environmental factor, guides the selection of passive design strategies for any building. In Cambodia's tropical climate, where comfort is key, addressing high temperatures and humidity is vital, especially in urban areas like Phnom Penh, where the urban heat island effect (UHIE) intensifies heat. Effective building designs must consider both macro and microclimate levels, including regional patterns and site-specific conditions, to enhance comfort and reduce heat and humidity.

Figure 2 Climate levels

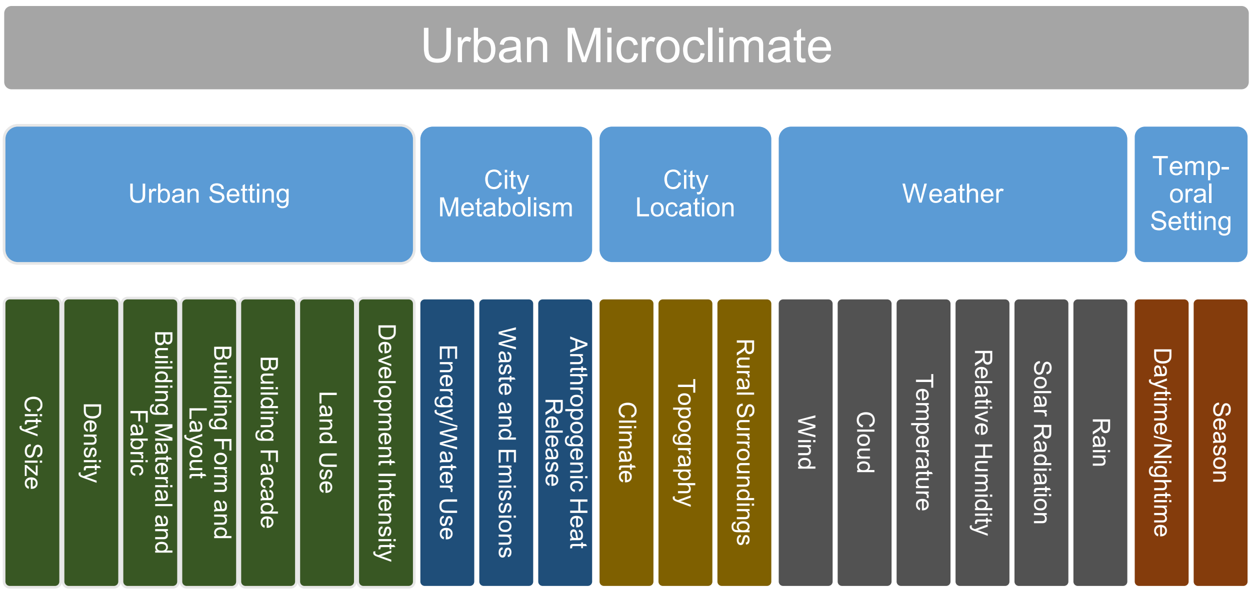


Figure 3 Factors influencing the urban microclimate

2.1.1 Site Level Passive Cooling Strategies

Site-level strategies focus on optimizing a building's energy efficiency and comfort by considering factors like solar exposure, wind patterns, topography, vegetation, and water features. This helps in reducing mechanical loads, creating a more sustainable and cost-effective environment.

2.1.1.1 Outdoor Vegetation

Strategically placed vegetation provides shade, reduces solar heat gain, enhances ventilation (Figure 5), and improves aesthetics while helping reduce street-level pollution. Replacing hard surfaces with grass boosts rainwater absorption and reduces glare. Trees act as buffers against noise and odors, and their height and density help block harsh winds. Where possible, local and endemic plant species should be used (Winrock International, 2017).

Vegetation cools the microclimate by absorbing solar radiation, aiding airflow, and reducing surface and air temperatures. Through transpiration, trees release water vapor, further cooling the surroundings. This natural cooling reduces energy demand and air conditioning needs (Figure 6). Studies show urban forests can be 0.8 to 2°C cooler than non-vegetated areas (Knight et al., 2016).

Thoughtful landscape design from the early design stages can reduce ambient temperatures and enhance a building's overall energy efficiency. The different conceptual models of placing vegetation at site level is showcased in the figures below.

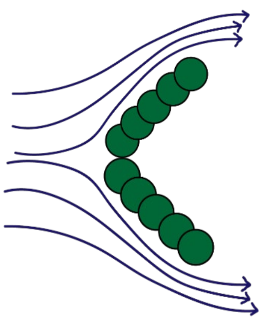


Figure 4 Deflection of undesirable wind by vegetation

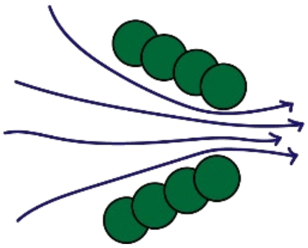


Figure 5 Channeling of desirable wind by vegetation

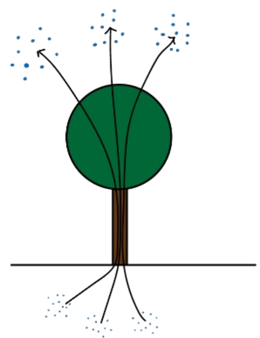


Figure 6 Evapotranspiration

2.1.1.2 Topography

Topography, referring to the slope and level of the land, plays an important role in building design. It provides information about the land's contours, slopes, and elevation changes, which engineers, architects, and designers use to integrate natural features into their designs. In Cambodia, topography helps optimize wind flow during different seasons and guides foundation design, drainage, and building orientation for natural light and views. Additionally, varied topography can act as a natural shading element, reducing energy consumption in buildings.

2.1.1.3 Water

In Cambodia, large water bodies like the Mekong River influence local climates by moderating temperature variations. Water heats up slower than land during the day and releases heat at night, creating more stable temperatures and reducing daily temperature swings. They also impact wind flow patterns due to temperature differences between land and water.

While water bodies support passive cooling, caution is needed in humid regions like Cambodia, where excessive moisture can be problematic. At the site level, creating water features may not always be suitable.

In urban areas, water bodies help reduce UHIE by absorbing heat and cooling the air through evaporation. Fountains and rainwater catchment areas can serve both cooling and social functions, acting as gathering spaces and enhancing microclimates.

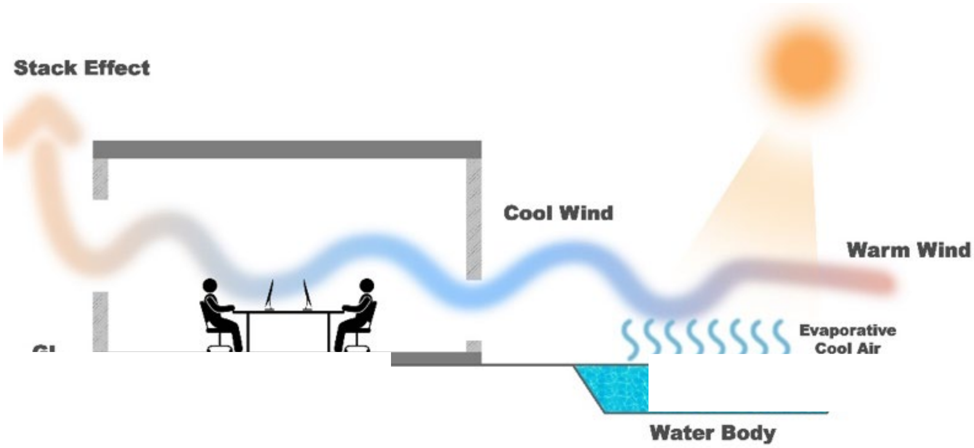


Figure 7: Pond cooling effect

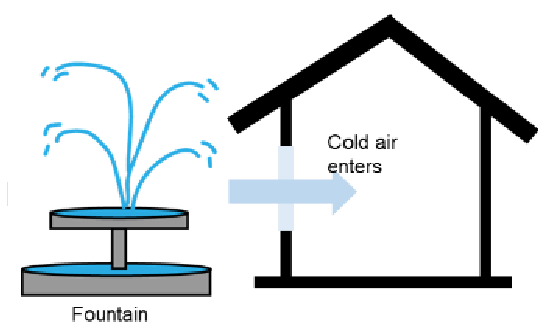


Figure 8: Fountain cooling effect

2.1.1.4 Pavements

Roofs and pavements cover 60% of urban areas and drive the urban heat island effect (UHIE) by absorbing up to 80% of sunlight. Cool, light-colored, and permeable pavements (like grass blocks, pervious concrete, and porous asphalt) lower surface temperatures, enhance water permeability, and improve urban microclimates. These systems also support stormwater infiltration and complement other passive cooling strategies, including vegetated roofs and shade trees. (Global Cool Cities Alliance, 2012). Cool pavements help reduce the UHIE by reflecting sunlight and emitting heat efficiently. Measured by the Solar Reflectance Index (SRI), they typically have high reflectivity and emissivity. Grass pavements offer a green, permeable option for parking lots and emergency access, supporting heat reduction and stormwater control. Using sustainable materials like warm-mix asphalt, recycled asphalt pavement (RAP), and recycled concrete aggregate (RCA) lowers embodied emissions, cuts embodied energy use, reduces waste, and brings long-term cost savings through lower maintenance and energy needs for cooling.

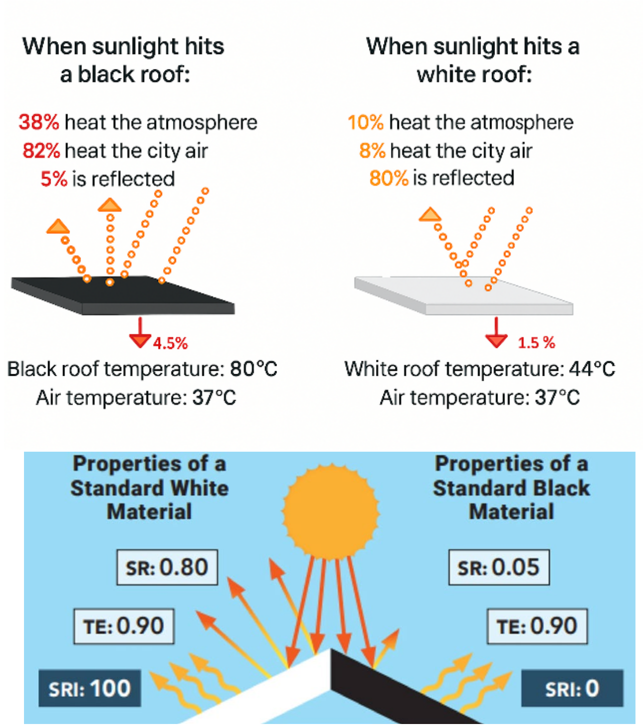


Figure 9: Comparison of solar reflectance (SR), thermal emittance (TE), and solar reflectance index (SRI) for standard white and standard black materials.

Source: Adapted from Altindag et al. (2024).

2.1.2 Microclimate Enhancement Strategies

Microclimate enhancement strategies at the urban level aim to improve local climate conditions, reduce energy consumption, and promote comfort. Reducing solar heat at the site level involves increasing greenery, tree cover, and water features to provide shade and natural cooling. Using cool roofs, reflective surfaces, and materials with low absorptivity and high emissivity helps limit heat stored in buildings and pavements. Shaded streets, permeable pavements, and well-oriented buildings improve airflow and reduce heat buildup. Together, these landscape and design measures lower surface temperatures and help mitigate Urban Heat Island effects.

These strategies include:

Increasing Green Spaces: Parks, trees, and green roofs provide shade, absorb heat, and cool the air through evapotranspiration.

Urban Canopy Cover: Taller buildings and trees shade streets and buildings, reducing solar heat gain and lowering outdoor temperatures.

Proximity to Water Bodies: Nearby water bodies offer evaporative cooling and microclimatic effects.

Urban Design Measures: Optimize building orientation, reflective materials, and create setbacks for airflow and natural light. Light-colored, permeable pavements reflect sunlight, manage stormwater, and reduce heat absorption.

2.2 Building Level Passive Cooling Strategies

Building-level strategies include optimized orientation, window-to-wall ratio optimization, architectural shading, insulation, and natural ventilation systems to enhance airflow, minimize solar exposure and reduce heat gain. These strategies offer sustainable, cost-effective ways to maintain indoor comfort and reduce reliance on artificial cooling. Figure 10 illustrates some key passive cooling strategies that will be discussed in further detail in following sections.

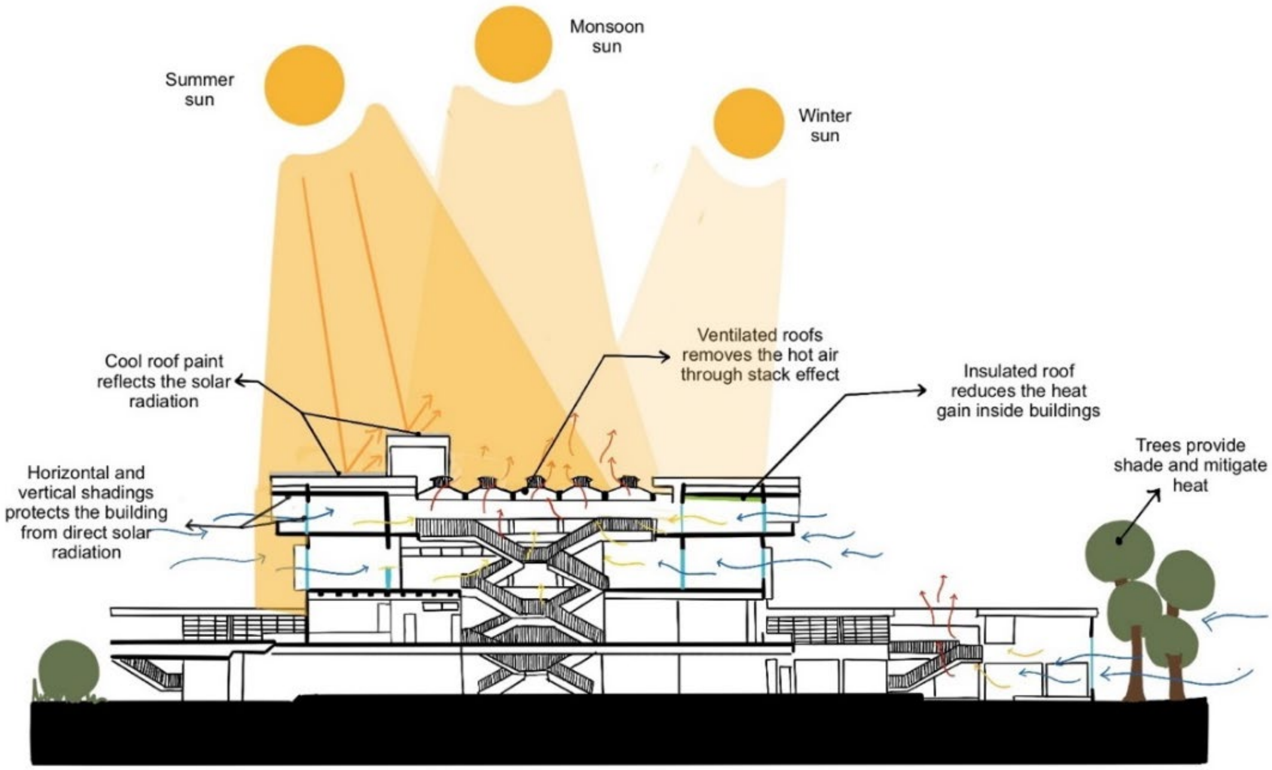


Figure 10: Illustration of passive cooling strategies

2.2.1 Solar Passive Design Strategies

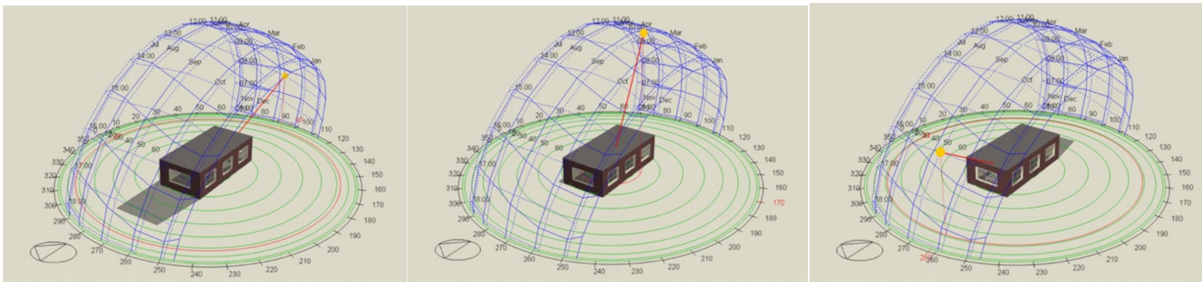
2.2.1.1 Solar Orientation

It is important to consider the orientation of the building to the sun to minimize solar exposure and maximize energy efficiency. Solar orientation involves positioning of a building and its facades to minimize incident solar radiation and heat gain in relation to the sun's annual path. This should be decided together with building massing early in the design process to maximize advantages from other strategies.

In Cambodia, aligning the building's long axis east-west maximizes benefits. Given Cambodia's tropical climate, buildings should have north-south facades to minimize direct sunlight and heat gain. Designers should ensure north and south-facing windows are horizontally shaded to reduce

Figure 11: Solar orientation at 8 AM, 12 PM & 4 PM

heat from the daytime high-latitude sunshine and east- and west-facing windows are small or vertically shaded to avoid strong morning and evening sunshine. Consider shape, size, and local regulations in the design process.

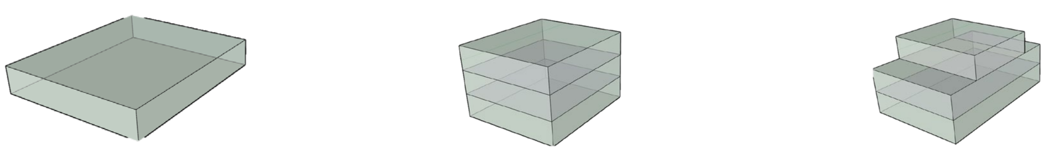


2.2.1.2 Building Form

To optimize energy efficiency in buildings, it is essential to consider their shape and internal volume. Heat escapes through external surfaces like walls and roofs, so compact building shapes, such as cubes, minimize heat transfer. Simple plan types like squares or rectangles also reduce heat loss and gain due to their smaller surface area (Yüksek & Esin, 2013). Smaller, efficiently used internal spaces require less energy for heating, cooling, and lighting compared to larger buildings. The building form influences the volume of space needing temperature control, with compact shapes being less wasteful in hot and cold climates. Additionally, the surface-to-volume ratio, determined by the building shape, affects thermal performance, ventilation patterns, and lighting needs, with deeper buildings requiring more artificial lighting (United Nations Industrial Development Organization [UNIDO], 2015).

At the same time, solar passive design also recognizes the importance of open and shared spaces even on higher floors to allow natural light and cross-ventilation to flow through the building. Such design approaches balance compactness with openness, enhancing occupant comfort while reducing dependence on artificial lighting and mechanical cooling systems.

The numbers shown in Figure 13 represent the surface-to-volume (S/V) ratio of each building shape. This ratio compares how much outer surface area a building has relative to the amount of usable space inside it. As shown in the image, compact forms like cubes and cylinders with values around 1.79 to 1.96 perform better thermally than elongated or stepped forms with values around 2.19 to 3.73. Buildings with high S/V ratios require more energy for cooling and lighting because a larger exterior area interacts with the outdoor climate. To improve performance, such buildings are often simplified by reducing projections, consolidating volumes or adding shading to achieve a more compact form.



3.73 1.96 2.29

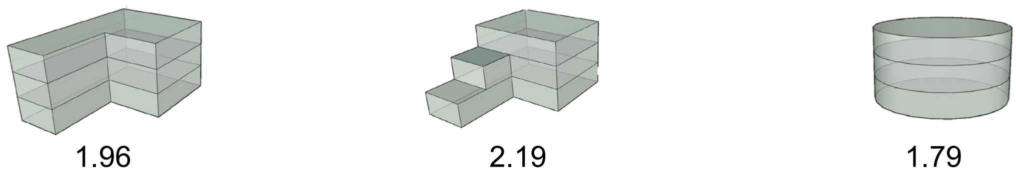


Figure 12: Heat Loss Form Factors for Different Forms of Buildings

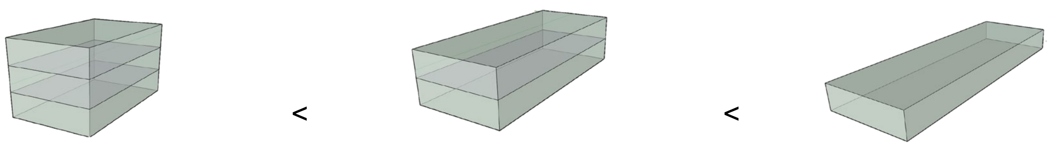


Figure 13 Surface to volume ratio

S/V ratios should be minimized in extreme climates and compactness increased by reducing surface area for the same volume.

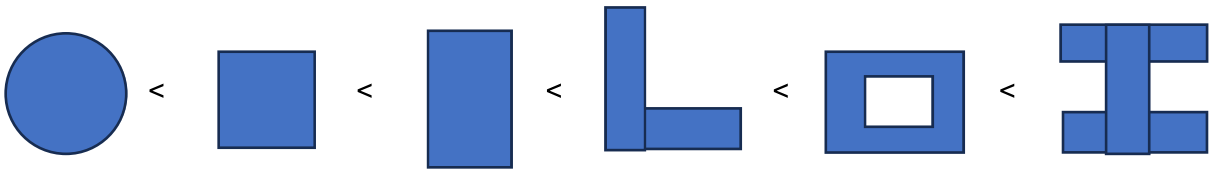


Figure 14: Buildings with low surface area

Perimeter areas should be minimized and mutual shading enhanced by using compact forms with low S/V ratios. These designs gain less heat during the day and retain heat better at night, making them ideal for extreme climates.

2.2.2 Insulation

2.2.2.1 Massing and Zoning

Massing and zoning considerations introduced early in a building's design reduce cooling demand by limiting heat gain and improving natural ventilation. Less used or buffer spaces such as storage or pantries should be placed on the east and west sides to shield main activity areas from morning and afternoon sun. Frequently used spaces can be positioned on the north side for softer daylight and reduced glare. Shallow floor plans and the avoidance of unnecessary partitions help maintain cross-ventilation.

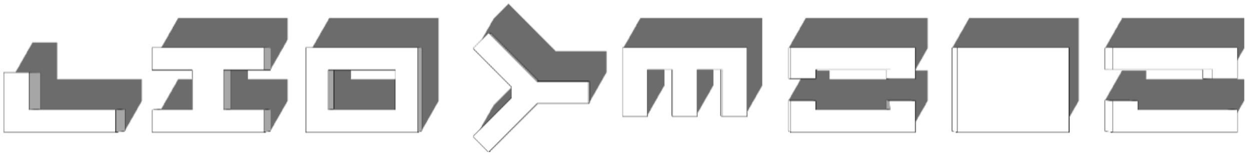


Figure 15: Building forms

Orientating the building's longer facades to face north and south reduces solar exposure on larger wall areas. Providing horizontal shading for the south facade blocks high midday sun, and similar protection for the north facade offer benefits when the sun is in the northern sky during part of the year.

2.2.3 Shading

2.2.3.1 Self-Shading

Self-shading through strategic design lowers surface temperatures and energy use by reducing direct sunlight exposure. This improves thermal performance, especially in hot areas, by casting shadows on walls and using elements like overhangs and shading devices. Staggering the building form and integrating shading features help minimize artificial cooling and maximize natural light.

2.2.3.2 Mutual Shading

Mutual shading occurs where structures and vegetation cast shadows on each other, it affects sunlight distribution and energy efficiency. In urban settings, this interaction influences solar exposure, and cooling demands. Shading from features like staircases and corridors can also reduce cooling loads, optimizing building design for better energy performance and comfort.

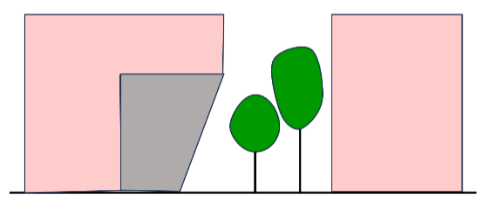


Figure 16: Maximize Mutual Shading with Built Forms

2.2.4 Ventilation

2.2.4.1 Window Wall Ratio (WWR)

WWR is the ratio of window area to the total wall area. Excessive windows in conventional buildings can increase cooling loads and account for 25-30% of heating and cooling costs (U.S. Department of Energy, n.d.-c). Optimizing WWR for various building orientations helps reduce heat gain. Additionally, deploying varying WWRs based on factors such as daylighting needs, privacy concerns, or views can further enhance energy efficiency and occupant comfort.

In addition to optimizing window proportions, the design and operability of windows are crucial for effective ventilation. In many high-rise buildings, especially in dense urban contexts, windows are often sealed for safety or noise reduction, which limits natural ventilation and increases reliance on mechanical cooling. Integrating operable windows or traditional passive shading devices such as wooden shutters, bamboo blinds *(sudare* in Japanese architecture), or perforated screens can block direct sunlight while allowing airflow. These strategies promote cross-ventilation, reduce solar heat gain, and maintain indoor comfort using locally responsive and culturally inspired solutions.

To optimize performance, natural light should be balanced with heat loss or gain through the WWR. Use high-performance, airtight windows with features like double glazing or solar films. Consider building form, orientation, and window distribution in the design phase to determine the ideal WWR. Building energy simulation tools can be employed to assess different WWR scenarios and their impact on energy efficiency, daylighting, and comfort (UN Office for Disaster Risk Reduction, 2020).

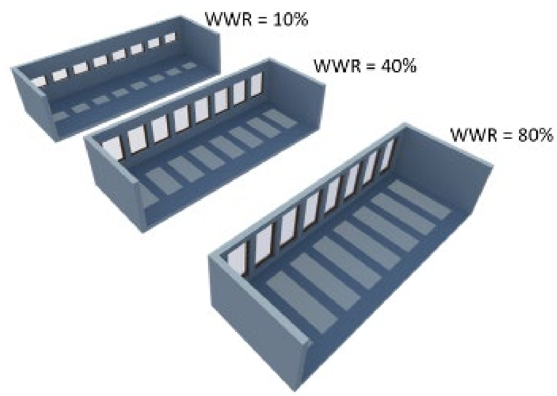


Figure 17: Window to Wall Ratio

2.2.4.2 Wind Orientation

The balance in wind orientation will offer shelter from hot winds, allowing cool breezes to pass through. For the Cambodian climate, which has high humidity, a constant flow of wind above 3 m/s can provide comfort for the people. In Phnom Penh, average wind speeds typically range between approximately 2.4–3.3 m/s depending on the season. Consideration of wind speed and direction is important when arranging multiple buildings for optimal airflow. Openings should be angled at around 20° to 30° relative to the prevailing dry season breeze to enhance cross ventilation and airflow in buildings and streets.

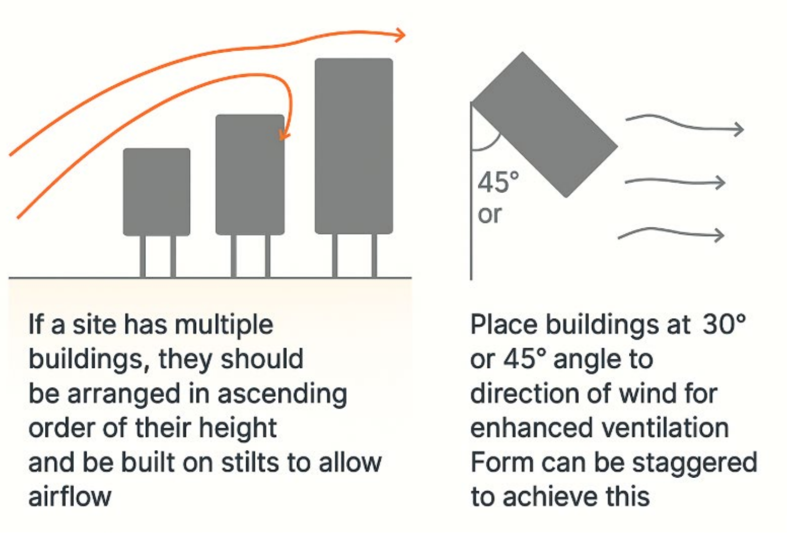


Figure 18: Orientation of building with respect to wind direction

Cambodia has a 443 km long coastline, and areas near this coastline are affected by land and sea breezes. Along tropical coastlines, sea breezes are frequently observed. The strength of the breeze depends on the temperature difference between the land and the sea, while its velocity is influenced by the prevailing wind direction and the temperature contrast between the land and the sea. Figure 19 offers an illustration of how these breezes work.

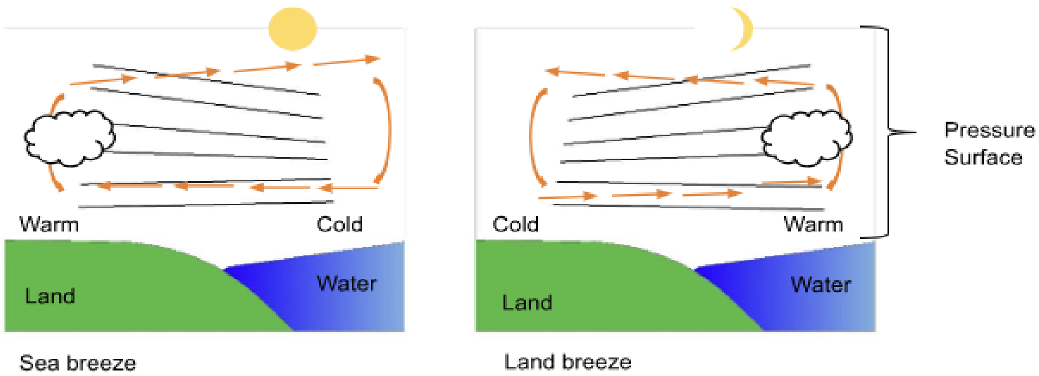


Figure 19: Sea breeze and land breeze

2.2.4.3 Stack Ventilation

The stack effect, or chimney effect, uses warm air rising to create a pressure difference that draws cooler air into a building through lower openings. This natural ventilation can be optimized by incorporating vertical openings like stairwells or atriums and placing ventilation openings like bamboo blinds or wooden shutters strategically. Taller buildings benefit more from the stack effect. To enhance airflow, designers should ensure proper ventilation, seal and insulate the building envelope, and integrate mechanical systems with the stack effect, considering local climate conditions. There are two types of stack ventilation:

- Wind-driven ventilation: Driven by pressure differences between the internal and external air around the building.
- Buoyancy-driven ventilation: Driven by temperature differences between the internal and external environments.

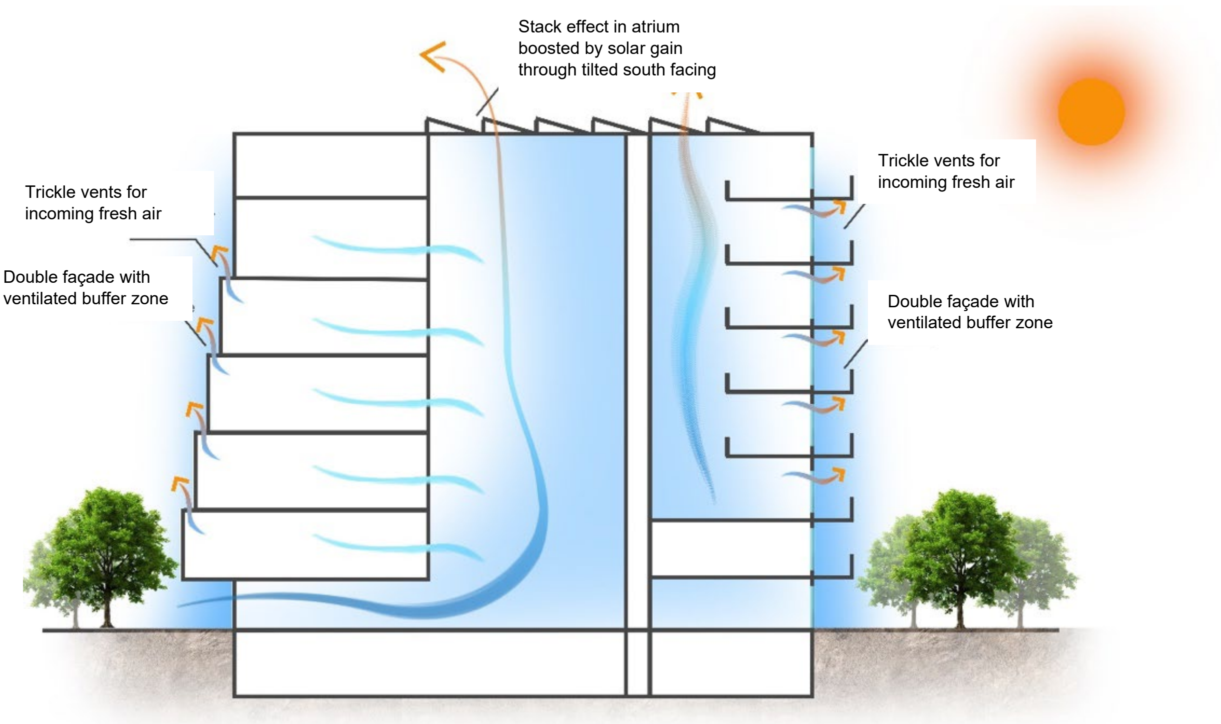


Figure 20: Stack ventilation

2.2.4.4 Natural and Cross Ventilation

Natural ventilation uses openings like windows, doors, and vents to allow fresh air into buildings without fans. It helps lower CO_2 levels and maintain cooler temperatures, especially in summer, by utilizing wind or temperature differences. In tropical climates, it can reduce energy use by 10%–30% compared to air conditioning. Effective design involves strategically placing inlet and outlet openings, considering wind direction, and using techniques like wing walls to enhance airflow.

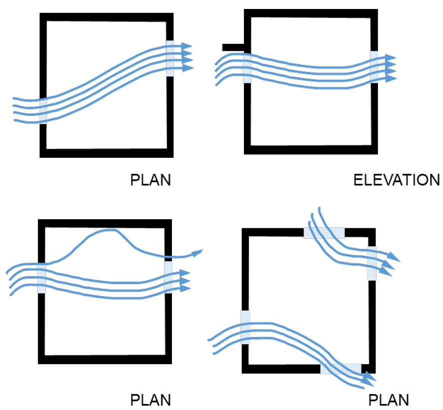


Figure 21: Cross ventilation

2.2.4.5 Night Cooling

Night cooling leverages cooler nighttime temperatures to cool indoor spaces, using the building's thermal mass to absorb and release heat. Natural ventilation systems are preferred for this process. Effective implementation involves assessing the building's thermal properties, such as insulation and ventilation, and using temperature sensors to identify suitable nights for cooling. To maximize night cooling, minimize daytime heat gain by closing windows and blinds, then open them in the evening to allow fresh air in. Ensure outdoor air quality is acceptable and educate occupants on using night cooling for optimal comfort and efficiency.

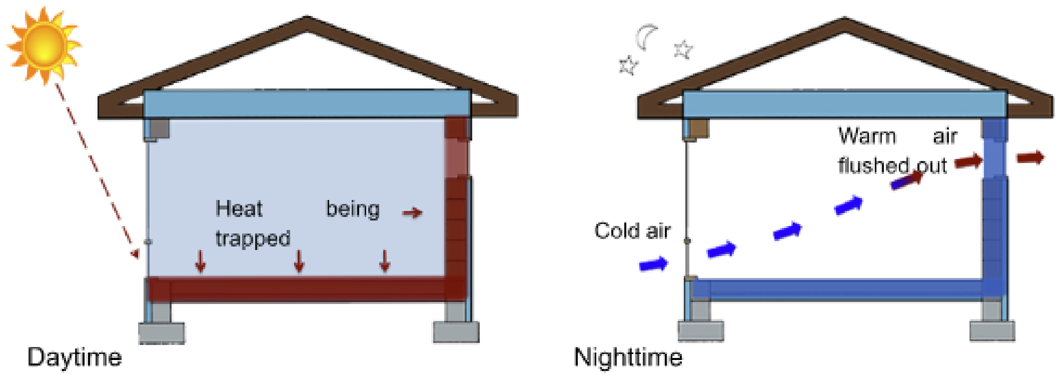


Figure 22: Night cooling

2.3 Component Level Passive Cooling Strategies

Component-level strategies involve implementing specific features or materials within a building's design to mitigate heat gain and enhance thermal comfort. These strategies focus on individual building elements or components, such as roofs, walls, windows, and shading devices.

2.3.1 Wall

Walls provide insulation to minimize heat transfer between indoor and outdoor environments, reducing reliance on heating and cooling systems. Effective insulation involves using materials with high thermal resistance, sealing gaps, and incorporating exterior insulation to reduce thermal bridging. High thermal mass materials, reflective coatings, and advanced framing techniques further improve energy efficiency. Choosing materials like autoclaved aerated concrete, terracotta, or insulated panels, local materials like Bamboo and Timber wood combined with insulation methods like fiberglass or mineral wool, enhances thermal performance. Building codes, climate conditions, and project needs should guide the selection and implementation of these strategies, with energy professionals assisting in optimizing wall efficiency and overall energy performance. (Market Research Cambodia, 2023)

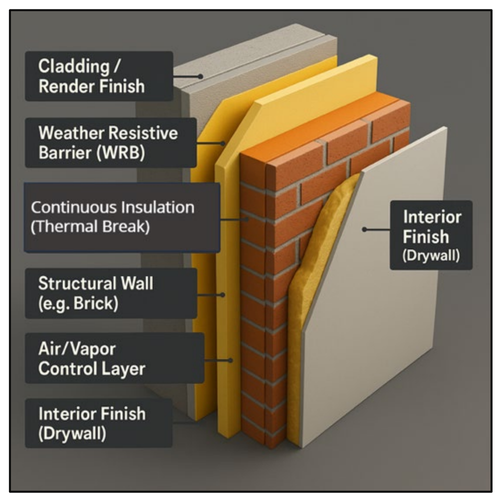


Figure 23: Layers of walls

Optimal thermal properties: SHGC – 0.2-0.35, U-value for wall – 0.52 to 1.2 W/m^2. K U-value for roof 0.4 to 0.6 W/m^2.K. Window Wall Area - <60%. VLT >40%.

2.3.2 Roof

Roofs significantly affect heat transfer in buildings. To maintain comfortable indoor temperatures and reduce heating and cooling needs, use insulating materials like fiberglass or foam boards, seal gaps, and apply reflective coatings or light-colored materials. Roofing materials such as metal, asphalt shingles, or tiles, combined with insulation like mineral wool or polystyrene, enhance energy efficiency. Cool or green roofs with added insulation or vegetation further reduce energy consumption and maintain cooler temperatures. In tropical climates like Cambodia, minimizing roof heat transfer is essential for energy efficiency and comfort.

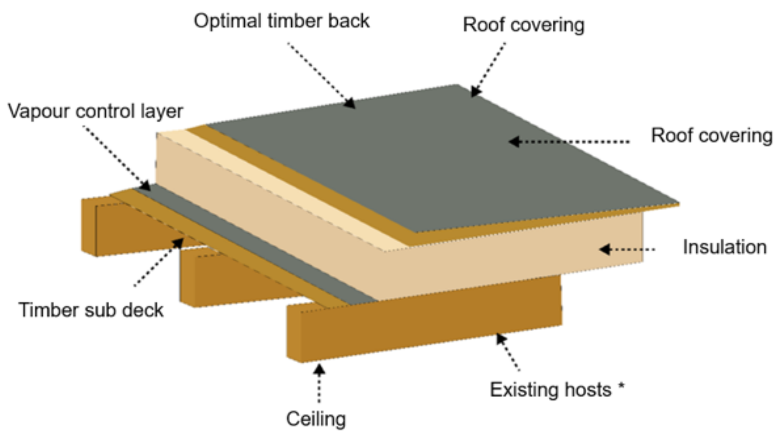


Figure 24: Layers of roof

2.3.3 Fenestration

Fenestration, involving the design and materials of windows, doors, and openings, which affects solar heat gain and airflow. Choosing appropriate glazing, like single or double-pane glass, impacts insulation and solar control. Key parameters include U-value and Solar Heat Gain Coefficient (SHGC). Window frames, supporting the glazing, also affect thermal insulation, security, and aesthetics. Materials for frames vary in insulating properties, so understanding their U-values helps select the best option for the building's needs.

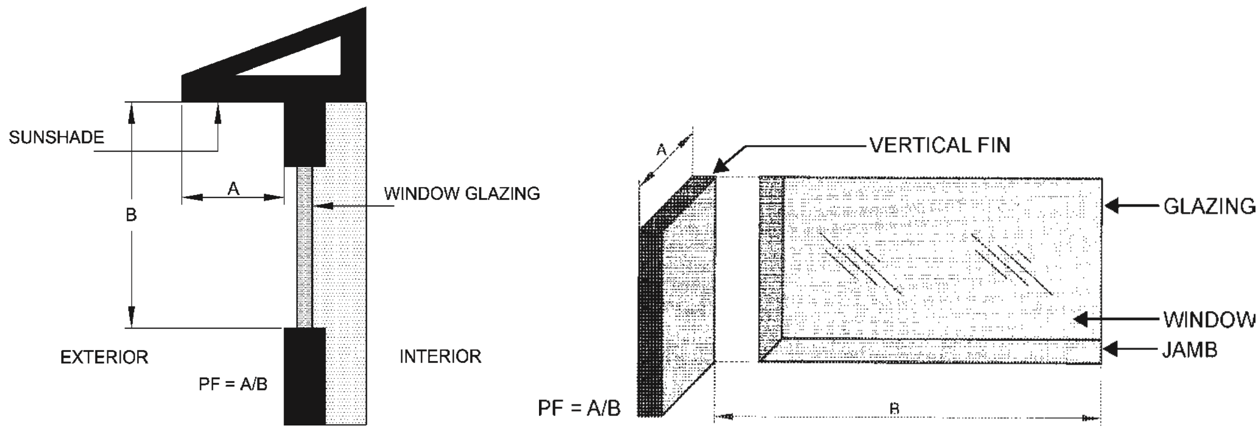


Figure 25: Layers of fenestration

2.3.4 Airtightness

Air leaks degrade insulation and increase energy consumption, leading to moisture issues like mold, structural damage, and poor air quality. Airtight buildings are essential for energy efficiency, moisture control, and effective ventilation. They reduce heating and cooling loads, allowing for smaller HVAC systems, minimize drafts and noise, and enhance indoor air quality and comfort.

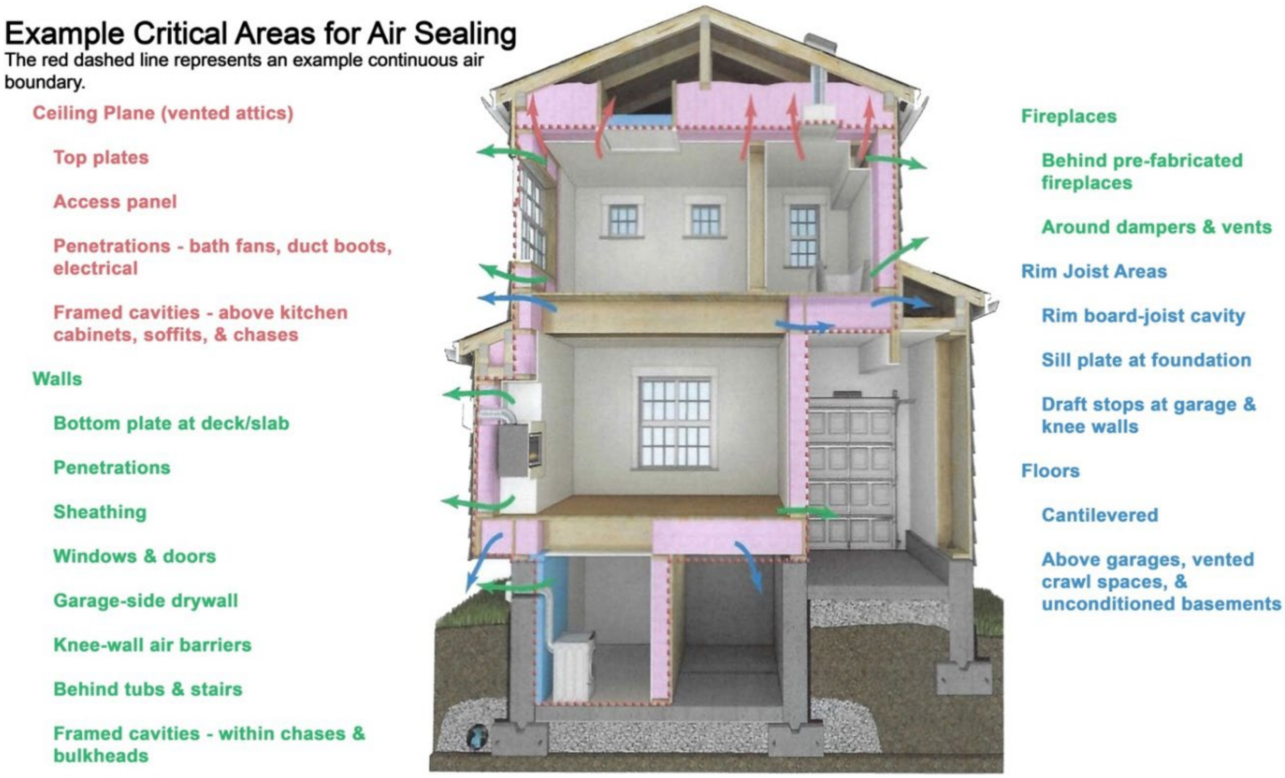
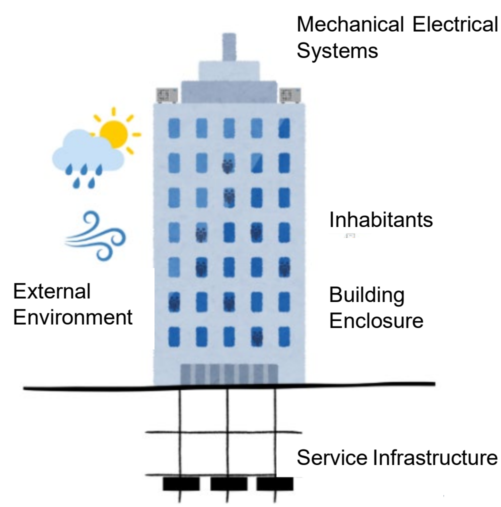


Figure 26: Critical areas for air sealing

3 Approach for Design of Passive Cooled Buildings

To design a passively cooled building, prioritize shading, natural ventilation, thermal mass, and insulation from the project's outset. Focus on building orientation, fenestration, and local climate to minimize mechanical cooling and enhance thermal comfort. This section will provide a step-by-step guide to optimizing passive cooling and energy efficiency in the design process.



3.1 Principles of Building Physics

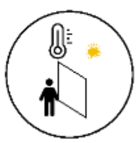
A building functions as a dynamic system, interacting with its environment and occupants to create a comfortable space. To achieve this, it must address thermal, visual, and acoustic comfort, as well as indoor air quality. Understanding building physics is crucial for designers, engineers, occupants, and stakeholders to ensure thermal comfort. This involves viewing the building as a system and applying techniques that address design challenges effectively. Key elements like the building envelope, occupants, services, site, and external environment must be carefully considered to develop well-performing buildings. In Cambodia's tropical climate, the demand for space cooling to maintain thermal comfort is significant.

3.1.1 Thermal Comfort

Thermal comfort, as defined by ASHRAE, is a state of mind indicating satisfaction with the thermal environment, where individuals feel neither too hot nor too cold. It is crucial for occupant satisfaction, productivity, and well-being in various indoor spaces. Thermal comfort is achieved when the heat generated by occupants' metabolism equals the heat dissipated, maintaining thermal neutrality. This balance depends on environmental factors and personal parameters, including heat exchange mechanisms and the insulation properties of clothing.

Environmental Parameters

Mean Radiant Temperature (MRT)

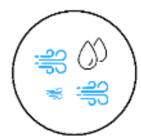


MRT is the average temperature of the surfaces surrounding a person in an indoor or outdoor environment.

Air Temperature

Air temperature is the measure of the average thermal energy present in the air surrounding occupants.

Humidity



Humidity is the amount of moisture in air, expressed in percentage.

Air Speed

Air speed, or velocity, measures the flow of air in a space, typically in m/sec

Personal Parameters

Metabolic Rate

Metabolic rate is the rate at which the body generates heat through metabolism, varying by individual, measured in MET.

Clothing

Clothing insulation measures thermal resistance of clothing, expressed in "Clo."

ASHRAE’s Standard 55-2020 on Thermal Environmental Conditions for Human Occupancy discusses the use of two thermal comfort models: the Predicted Mean Vote-Percentage of People Dissatisfied (PMV-PPD) model and the Adaptive Comfort Model.

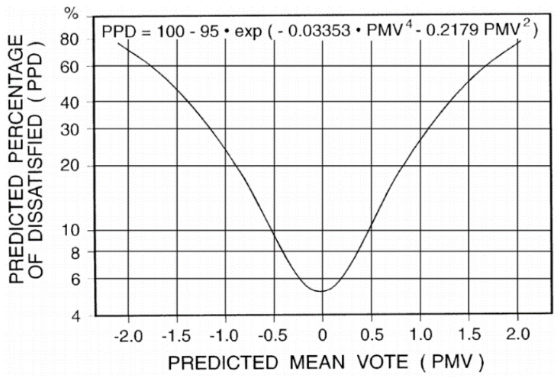


Figure 29: PMV graph

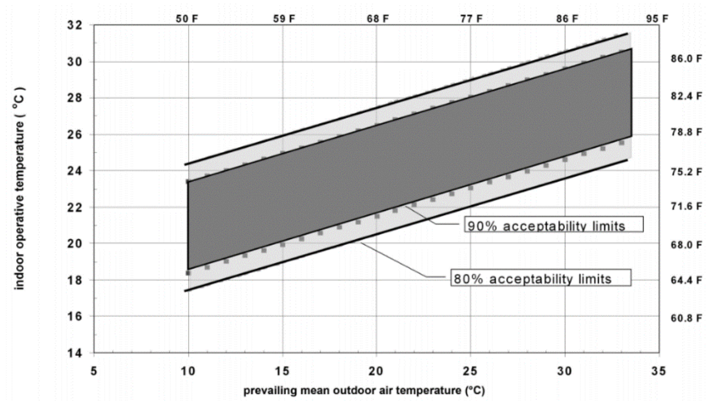


Figure 30 Adaptive Comfort ph

The PMV-PPD model is based on the principle of energy balance. It predicts the average thermal sensation of a group of people in each environment. The PMV scale ranges from -3 to +3, where negative values indicate a cold sensation, zero represents thermal neutrality, and positive values indicate a warm sensation.

The Adaptive Comfort Model is applicable for occupant-controlled naturally conditioned spaces. It is suitable for naturally conditioned spaces with no mechanical cooling or heating, where the metabolic rate ranges from1.0 to 1.5 MET, occupants can adapt their clothing within a range of 0.5 to 1.0 °C , and the prevailing mean outdoor temperature is greater than 10 °C and less than 33.5 °C.

3.1.2 Modes of Heat Transfer in Buildings

Understanding heat transfer in buildings is crucial for comfort, energy efficiency, durability, and indoor air quality. Effective heat management reduces reliance on mechanical systems, lowers energy costs, and prevents issues like condensation and mold. Heat transfer always occurs from warmer to cooler areas. Three modes of heat transfer are:

- Conduction
- Convection
- Radiation

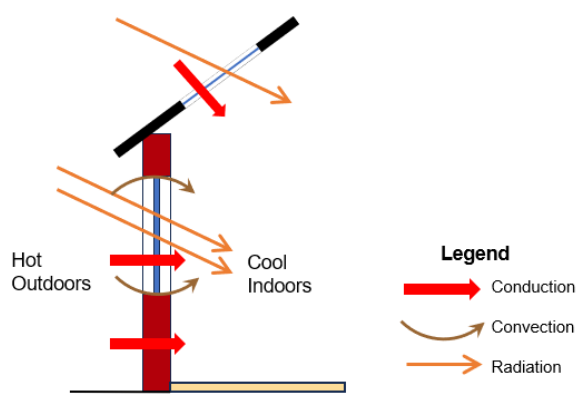


Figure 31 Modes of heat transfer

Conduction

Conduction is the transfer of heat through a solid material due to a temperature difference. It happens when objects with different temperatures are in contact, like an uninsulated wall absorbing heat from the outdoors. Heat moves from hotter to cooler regions at the atomic level, forming a thermal gradient. Conductive heat transfer depends on temperature difference, material area, thickness, and thermal conductivity. Materials are rated by R-values (resistance to heat transfer) and U-values (overall heat transfer properties of assemblies).

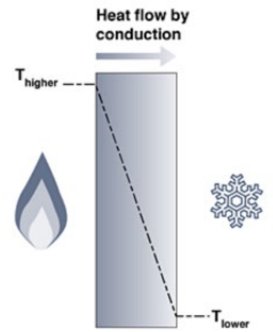


Figure 32: Conduction

Convection

Convection is the transfer of heat through fluid movement combined with conduction, for example when warm outdoor air enters through wall cracks and raises indoor temperatures It happens between a solid or fluid and a moving fluid, driven by natural buoyancy or mechanical means like fans. Controlling convection in buildings involves air barriers and maintaining uniform interior surface temperatures.

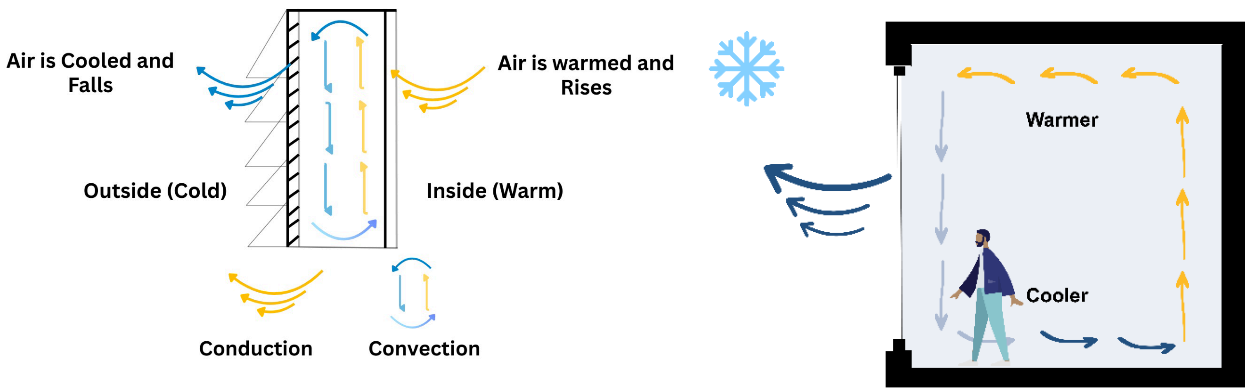


Figure 33: Convection

Radiation

Radiative heat transfer involves heat movement through electromagnetic radiation. For example, sunlight through windows increases indoor temperatures. Objects emit radiation based on temperature: hot objects emit short-wave radiation, while cooler ones emit long-wave radiation.

Low-emissivity coatings on glass help manage heat retention or rejection. In buildings, radiative heat transfer mainly occurs through fenestration.

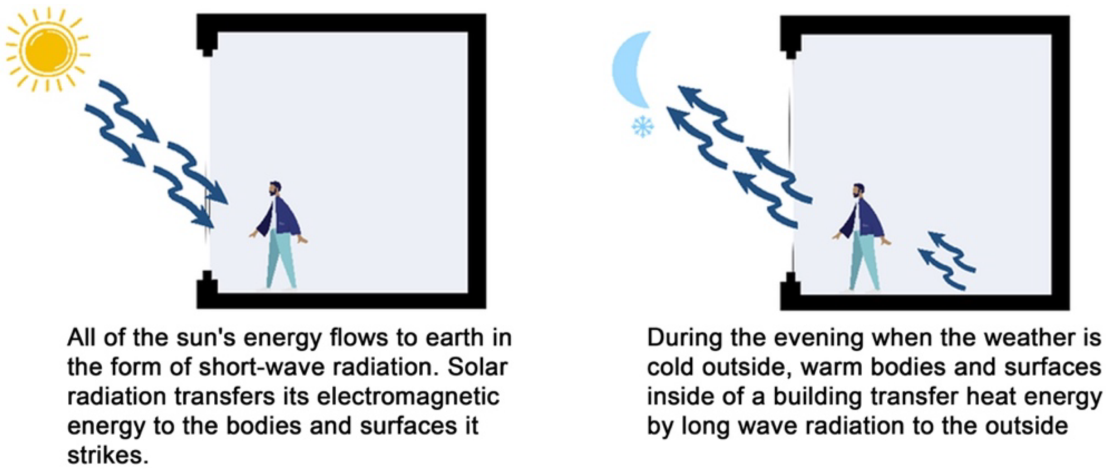


Figure 34: Radiation

3.1.3 Heat Gain and Loss

The exchange of heat within a building can disrupt thermal comfort, necessitating the use of heating and cooling systems. In Cambodia's tropical climate, managing heat exchange is crucial for thermal comfort, often requiring cooling systems. The cooling load, which measures the heat energy needed to maintain indoor comfort, affects both air temperature and moisture content.

- Sensible cooling load: Results from changes in air temperature, including heat gain from the building envelope and internal sources like occupancy, lighting, and equipment.
- Latent cooling load: Arises from variations in air moisture content, linked to sources like occupancy, infiltration, and equipment increasing indoor humidity.

Further classification of cooling load is based on its source:

- Building: Heat gain through building components - walls, windows, roofs, and floors.
- Transmission heat load: Heat transfer through the building envelope.
- Infiltration heat load: Heat exchange due to air movement through cracks, gaps, and other openings.
- Thermal bridge heat load: Increased heat transfer caused by materials or components with higher thermal conductivity within the building envelope.

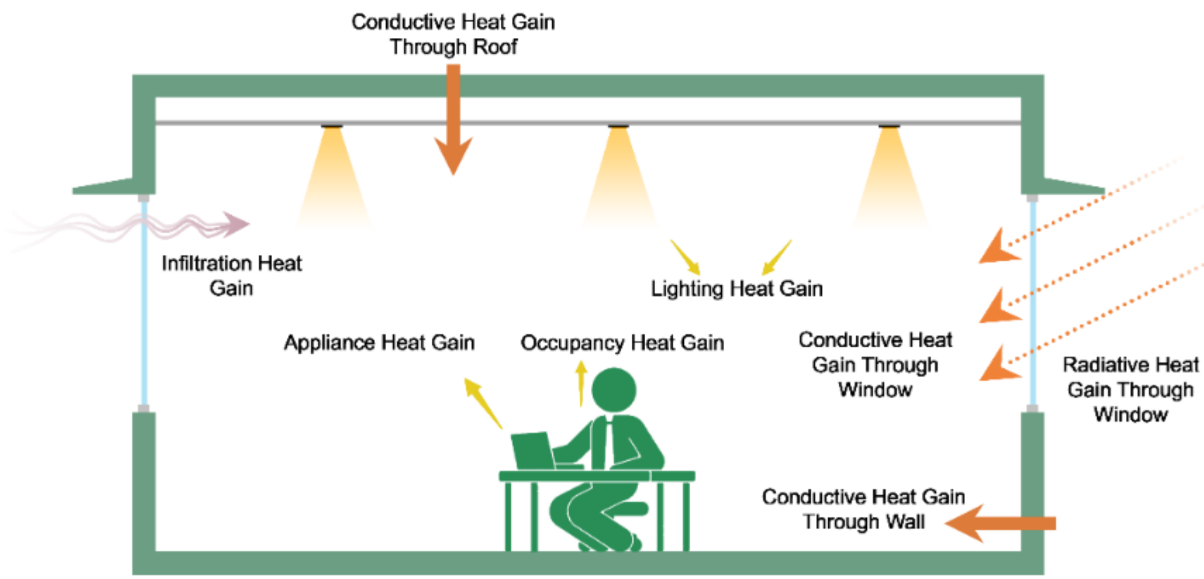


Figure 35: Heat gain

- Internal Load:
    - Occupancy load: Heat generated by occupants, influenced by their number, activity level, and metabolic rate.
    - Lighting load: Heat emitted by artificial lighting sources like fluorescent, or LED.
    - Equipment load: Heat produced by various electrical and mechanical equipment.

Table 1: Heat transfer properties of walls and roofs

Property	*Description*
Thermal Conductivity	Materials with high thermal conductivity allow heat to pass through quickly; low thermal conductivity materials slow heat transfer.
Thermal Resistivity	Thermal resistivity measures how much a material resists heat flow. It is the inverse of conductivity.
Absorptivity	Absorptivity is the fraction of sunlight absorbed by a surface. Darker materials tend to absorb more heat.
Emissivity	Emissivity is a surface's ability to release heat as infrared radiation.
Reflectivity	Reflectivity is the proportion of sunlight reflected by a surface. Higher reflectivity reduces heat gain.
Thermal Storage Capacity	Thermal storage capacity indicates how much heat a material can absorb and retain before changing temperature.

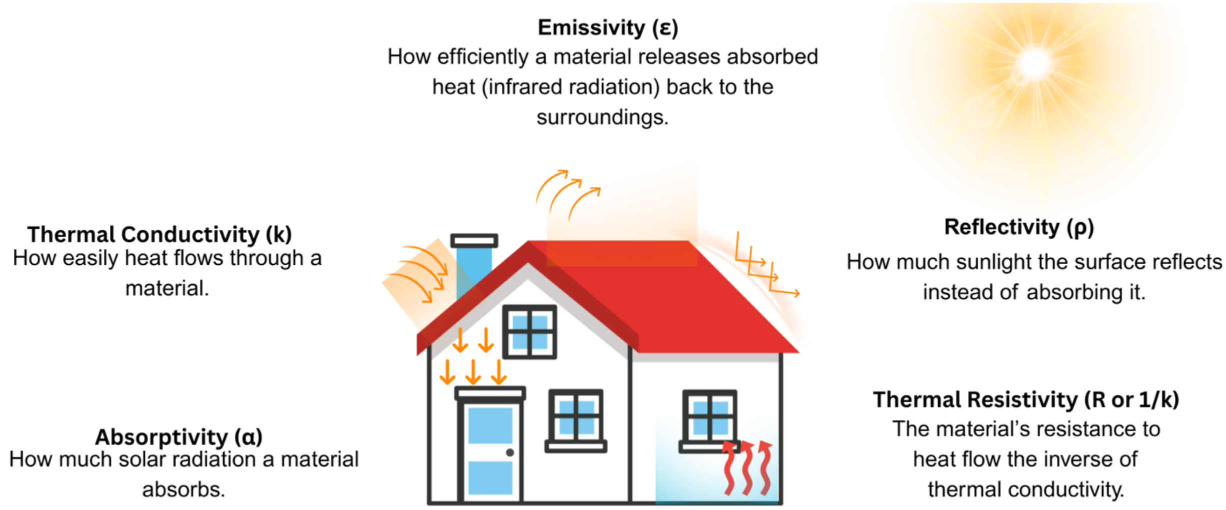
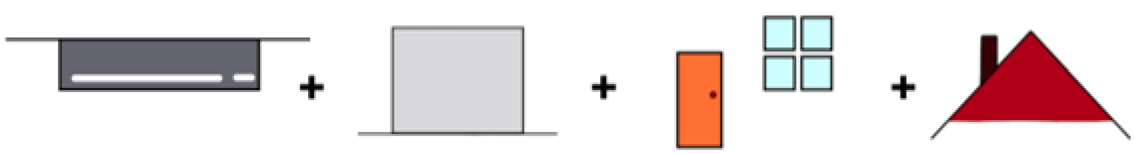


Figure 36: Heat transfer properties

3.1.4 Components of Building Envelope

The building envelope refers to the exterior enclosure of a building that separates the interior conditioned spaces from the external environment. Opaque components include walls, roofs, slabs, basement walls and opaque doors.



Flooring	Wall	Fenestration	Roof
Flooring act as a barrier between the interior and the ground below. To optimize thermal performance of flooring, it is essential to consider the interface between the flooring and the ground to minimize undesired heat transfer.	Wall in a building includes opaque elements which are inclined at an angle of 60° or more from the horizontal. It constitutes of above and below grade walls.	Fenestration comprises of transparent and translucent elements in the building envelope, including glazing, frames, and shading devices. This encompasses windows, clerestories, skylights, glass block walls and doors with significant glass areas.	The roof is the uppermost covering of a building, providing protection against weather elements and serving as a barrier between the topmost floor interior space and the external environment.

Figure 37: Components of a building envelope

3.2 Integrative Design Process (IDP)

The integrative design process involves cross-disciplinary collaboration from the start, engaging architects, engineers, sustainability experts, and economists. This approach fosters innovative strategies to optimize building performance, energy efficiency, and occupant comfort. It promotes synergy, creativity, and results in sustainable, resilient, and cost-effective buildings. By addressing complex construction challenges, it ensures buildings meet occupants' needs, minimize environmental impact, and maximize energy efficiency.

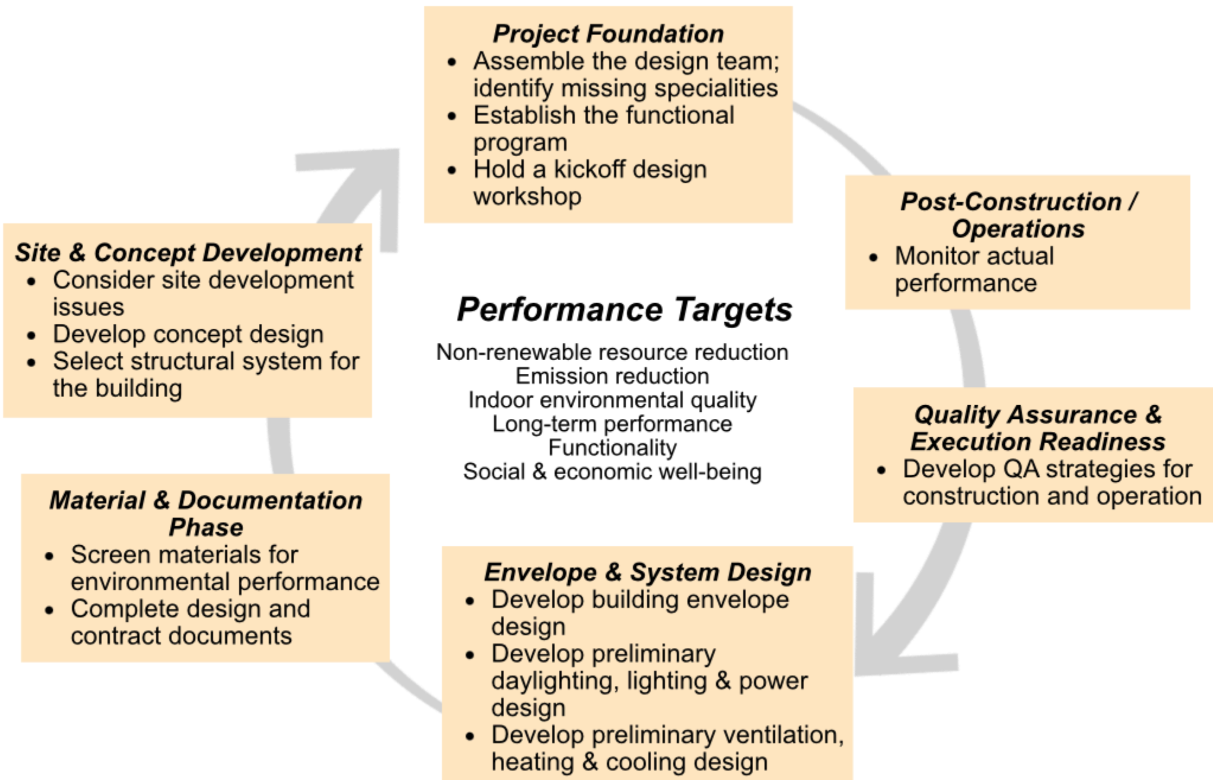


Figure 38: Performance targets - IDP

3.2.1 Integrative vs Traditional Design Process

An integrative design process contributes to more efficient and effective design outcomes that better meet the needs of stakeholders and the environment alike. The following table compares integrated versus design processes.

Table 2: Comparison between integrative and traditional design processes

Aspect	Integrative Design Process	Traditional Design Process
Collaboration	Involves early, interdisciplinary teamwork among architects, engineers, and stakeholders to develop holistic solutions.	Follows a linear approach with separate disciplines working in isolation, collaborating mainly in later stages.
Problem-Solving Approach	Uses a holistic approach, considering sustainability, energy efficiency, occupant comfort, aesthetics, and functionality together.	Focuses on individual design aspects separately, with less emphasis on comprehensive solutions.
Innovation	Fosters innovation by integrating diverse perspectives, encouraging creative and unconventional solutions.	May limit innovation due to segmented design phases and fewer cross-disciplinary inputs.
Flexibility and Adaptability	Allows for iterative adjustments based on feedback and evolving needs, enhancing flexibility.	Less flexible, with difficulties in making changes once the process is underway, often leading to rigid adherence to initial plans.
Time and Cost Efficiency	Initial time investment can lead to overall savings by reducing redesign and rework during later stages.	May result in increased time and costs due to conflicts or discrepancies resolved later, requiring extensive revisions.
Sustainability	Prioritizes sustainability from the start, aiming to optimize performance and minimize environmental impact.	Sustainability may be considered late in the process, making it harder and costlier to integrate eco-friendly measures.

3.2.2 Process and Technical Inputs of the Integrated Design Process

The Integrative Design Process follows a series of steps that link project planning, design, and evaluation. It begins with setting project goals and forming a team to guide decisions. Workshops are used to collect input from stakeholders and define priorities. Data is gathered and analyzed to compare design options, monitor outcomes, and adjust where needed. Technical inputs such as sub-metering, HVAC, lighting, indoor environmental quality, water, solid waste, and planted roofs are considered at each stage to align with project objectives.

Figure 39: Technical inputs of an integrative design process

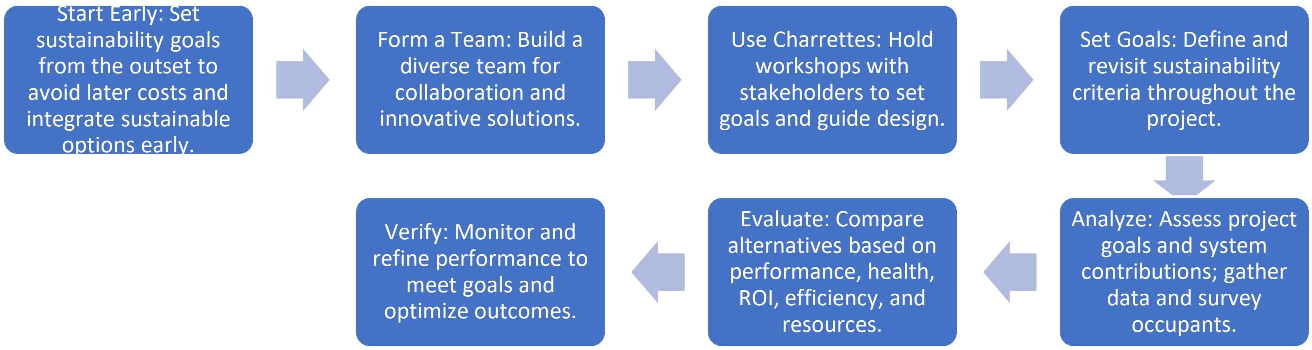


Figure 40: Overview of the integrative design process

3.2.3 Cost Economics of integrative design

The IDP provides a holistic approach to building design, aiming to reduce initial costs while maximizing long-term savings. By investing in high-performance strategies early on, which may have higher upfront costs, the IDP can lead to savings through smaller or fewer systems. Enhanced collaboration among stakeholders streamlines decisions and optimizes resource use, reducing operational and lifecycle costs.

The IDP also offers intangible benefits, including improved occupant satisfaction, better building performance, and reduced environmental impact. Although it may involve initial costs for workshops and team resources, the long-term savings and benefits make it a financially sound choice.

3.2.4 Case Study – Demonstration Project (Borey Chankiri)

Two residential buildings at Borey Chankiri, a baseline Phase I unit (BRBU) and a passive cooling-integrated Phase II unit (IRBU), were evaluated to understand the impact of passive cooling strategies in Cambodia's hot–humid climate. Both buildings share similar three-story configurations, allowing a direct comparison of thermal envelope improvements and passive design measures such as reduced window-wall ratio, roof insulation, external shading, and enhanced cross-ventilation.

3.2.4.1 Passive Cooling Strategies

Simulations incorporated cool paint on external elevations, solar-control window film, and low-E glazing to reduce envelope heat gain and improve thermal performance.

Figure 41: Simulation model

3.2.4.2 Data Calibration

Weather data from the Phnom Penh EPW file was calibrated using on-site temperature, humidity, and wind-speed measurements. Linear regression yielded the following adjustments:

- **Temperature:** Calibrated = 1.0691 × EPW
- **Wind speed:** Calibrated = 0.87 × EPW + 0.25

Monitoring occurred from July 2024–June 2025, with gaps during renovations and after IRBU handover in May 2025.

3.2.4.3 Energy Simulation

Simulations were performed using Rhino with Ladybug/Honeybee:

- 3D models developed for BRBU and IRBU
- Calibrated weather data integrated into Ladybug
- Base-case and passive cooling-enhanced variants simulated
- Common internal loads and HVAC setpoints used
- Outputs included cooling load, envelope heat gain, and total energy demand

Results – BRBU

Passive cooling measures reduced envelope heat gain by 0.6 kW median (0.2 TR), with a peak reduction of 1.6 kW (0.45 TR). Cooling-energy savings ranged from 130–255 kWh/month, with 140–183 kWh/month in peak months.

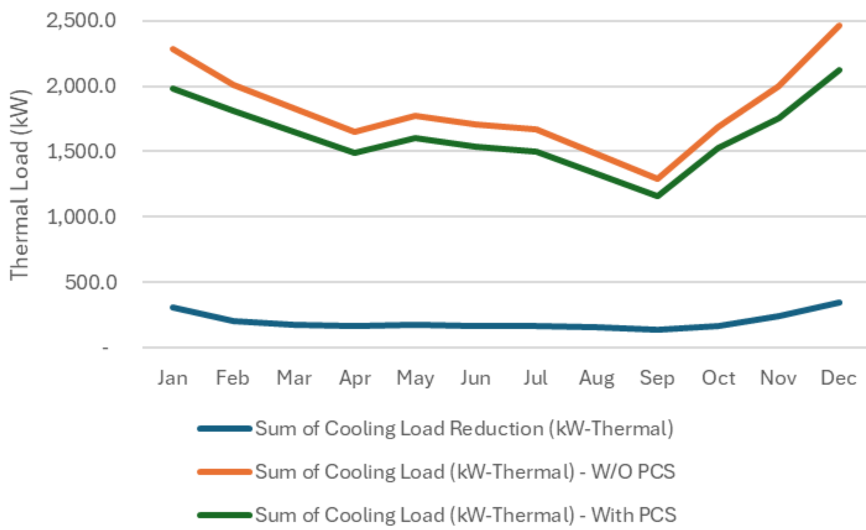


Figure 42: Monthly thermal load

Results - IRBU

Since IRBU already incorporates several passive cooling strategies, the addition of cool roof and solar-reflective film delivered further performance improvements. Annual energy savings reached **9.9%**, unmet comfort hours reduced by **31%**, and emissions reduced by **1.4 tCO_2e/year.**

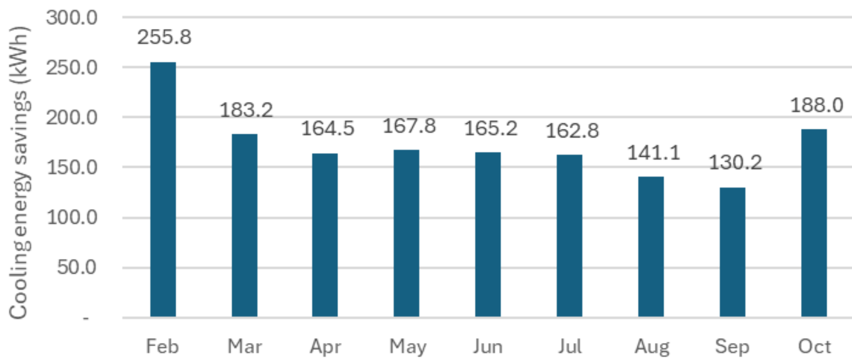


Figure 43: Monthly cooling energy savings (kWh) with integration of passive cooling

3.3 Design Methodology for Passive Cooling at Site Level

Design methodologies for passive cooling at the site level involve strategic site planning, orientation, and landscaping to optimize natural ventilation, shading, and thermal comfort, ensuring energy-efficient and sustainable building performance. The design methodology for the site level considers both on-site and off-site elements that could affect the cooling demand of the building.

3.3.1 Site Level Passive Design Strategies

3.3.1.1 Landscaping

The landscape design methodology is a systematic approach to create functional and visually appealing outdoor spaces. It includes site analysis, conceptualization, design development, and management strategies to integrate natural and built elements, ensuring sustainable and harmonious environments.

Assess off-site trees for location, size, health, and impact on shading, wind flow, and microclimate. Consider their orientation for optimal shading and minimize risks like falling branches or root damage. Integrate their benefits into the building design to enhance thermal comfort, reduce energy use, improve aesthetics, and increase biodiversity.

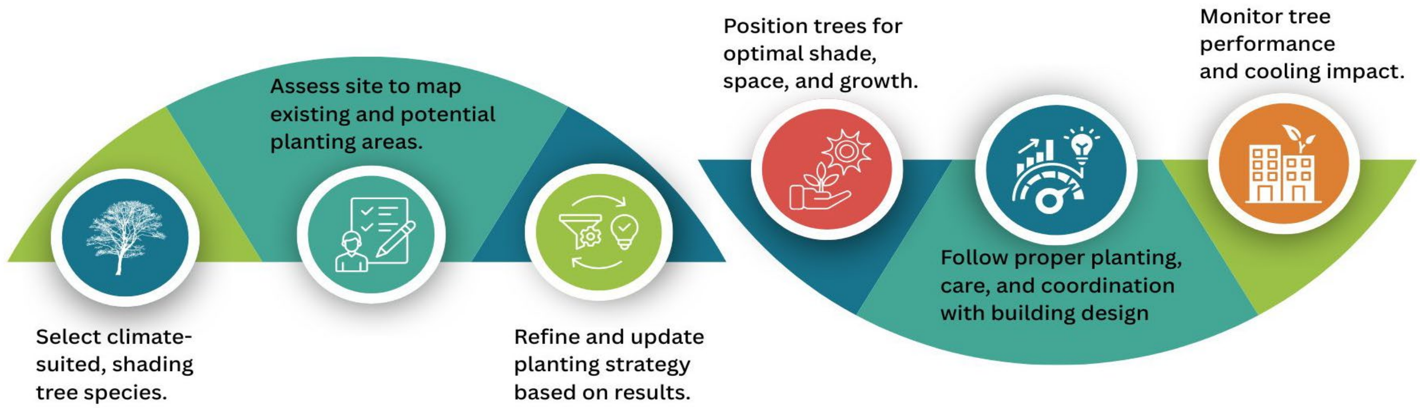


Figure 44: Design methodology for landscaping

3.3.1.2 Topography

Design methodology for topography involves analyzing and integrating landforms into architectural plans, considering elevation, slope, and natural features to create harmonious and functional spaces. By understanding how topography impacts site conditions, designers can develop strategies that optimize site utilization and enhance environmental sustainability.

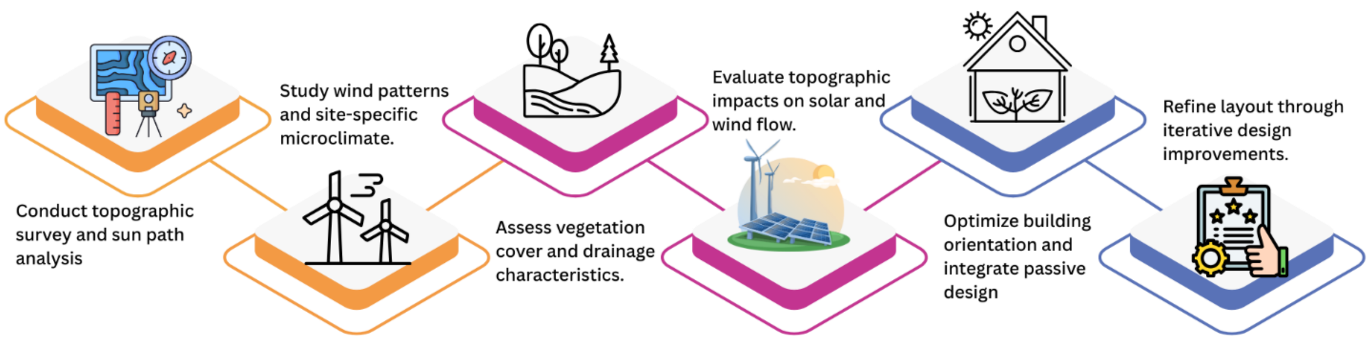


Figure 45: Design methodology for topography

Understanding the site's topography reveals opportunities for passive cooling strategies (PCS) such as natural ventilation, shading, and heat dissipation. By analyzing factors like prevailing winds, solar orientation, and land contours, designers can optimize building placement for airflow and shade, reducing mechanical cooling needs. Natural features like hills and water bodies can create microclimates and moderate temperatures. Additionally, soil and topography affect radiation absorption and reflection, helping to design floors that minimize heat transfer. This approach enhances energy efficiency, occupant comfort, and environmental sustainability.

In urban areas without natural ponds or lakes, features such as rain gardens or small landscaped ponds offer effective nature-based alternatives. They capture stormwater runoff, allow it to infiltrate into the ground, and filter pollutants such as sediment, nutrients, and oils. These features also support local biodiversity by providing habitat for native plants, pollinators, and urban wildlife.

3.3.1.3 Water

The design methodology for water encompasses strategies and approaches aimed at sustainable water management in various contexts, including urban planning, architecture, and landscape design. It integrates principles of water conservation, reuse, and stormwater management to address issues of water scarcity, quality, and resilience in built environments.

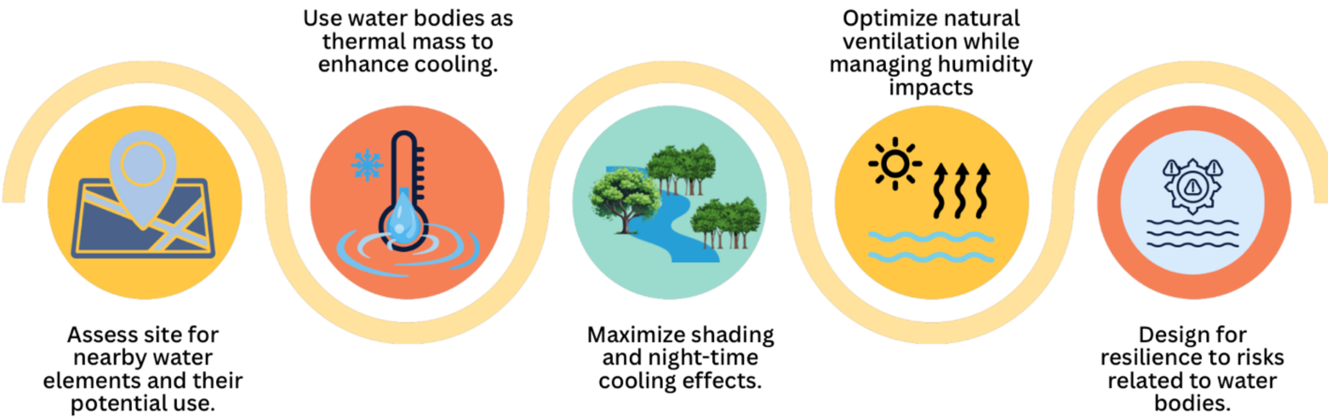


Figure 46: Design methodology for water

Water bodies such as ponds, lakes, or even artificial water features like fountains or reflecting pools act as natural heat sinks, absorbing and dissipating heat through evaporation. This process helps lower ambient temperatures in the surrounding area, creating a cooling effect. Additionally, the presence of water bodies can enhance natural ventilation by generating breezes and increasing humidity levels, which can further improve thermal comfort through differences in temperatures. Integrating water elements into the design not only provides aesthetic appeal but also promotes passive cooling, reducing reliance on energy-intensive cooling systems and minimizing environmental impact. However, it may also increase the humidity inside the building, causing uncomfortable situations. Therefore, proper analysis should be done before executing water bodies or implementing humidity preventive solutions in such cases.

Water features can contribute to cooling spaces. However, in regions like Cambodia, where humidity is consistently high, their effectiveness requires careful consideration. When atmospheric moisture is already high, additional water bodies may offer limited cooling benefits because high humidity suppresses evaporation, potentially increasing thermal discomfort among residents (United Nations Environment Programme, 2025). Therefore, comprehensive climatic analysis is essential to evaluate the cooling potential of water features and prioritize the most appropriate passive cooling strategies. Water bodies can also bring risks such as mosquito breeding, mold growth, and moisture damage. To limit mosquito breeding, use moving water elements like a thin-sheet fountain, pumps, or deeper water zones, these design choices discourage standing water that supports larvae. To prevent mold and discomfort from elevated humidity, maintain indoor relative humidity, supported by ventilation, exhaust fans, and dehumidifiers. Protect building structure by incorporating moisture management strategies (e.g. rainscreen assemblies, air gaps, vapor-permeable membranes, and proper drainage systems)

3.3.1.4 Pavement

The design methodology for pavement involves systematic planning and implementation strategies to create durable, safe, and cost-effective surfaces for roads, parking lots, and walkways. It integrates factors like traffic volume, soil conditions, climate, and material properties to optimize performance and longevity.

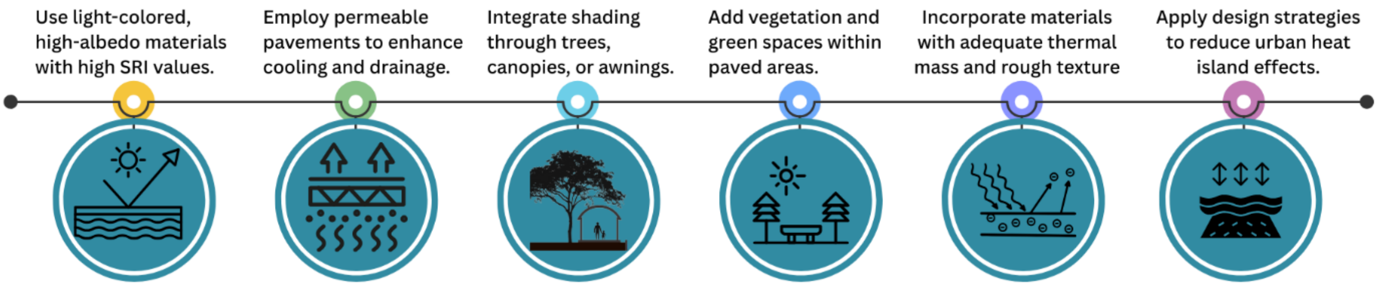


Figure 47: Design methodology for pavement

Cool pavements are typically made of materials with high solar reflectance and thermal emissivity, helping to reduce the absorption of solar heat and thereby lowering surface temperatures, thus minimizing the UHIE. Green pavements, featuring vegetation or permeable surfaces, enhance evaporative cooling and reduce heat buildup in urban areas. By decreasing surface temperatures and improving microclimate conditions, cool and green pavements contribute to overall thermal comfort, reduce the need for mechanical cooling systems, and mitigate environmental impacts associated with heat-related issues.

3.3.2 Micro-climate Enhancement Strategies

Enhancing the microclimate at the site level involves optimizing local climatic conditions for improved thermal comfort and energy efficiency. Begin by conducting a comprehensive site analysis to understand existing microclimate factors such as solar exposure, wind patterns, and temperature variations. Following the site analysis, proceed to implement passive design strategies, which include orientation optimization, natural ventilation pathways, and shading elements. These strategies aim to mitigate heat gain and enhance airflow. At the site level, the entire should be analyzed at an initial stage to identify opportunities for microclimate enhancement.

By systematically analyzing site conditions and integrating energy-efficient design principles, stakeholders, designers, architects, and engineers can collaborate to create buildings that harmonize with their surroundings, minimize environmental impacts, and enhance occupant comfort and well-being.

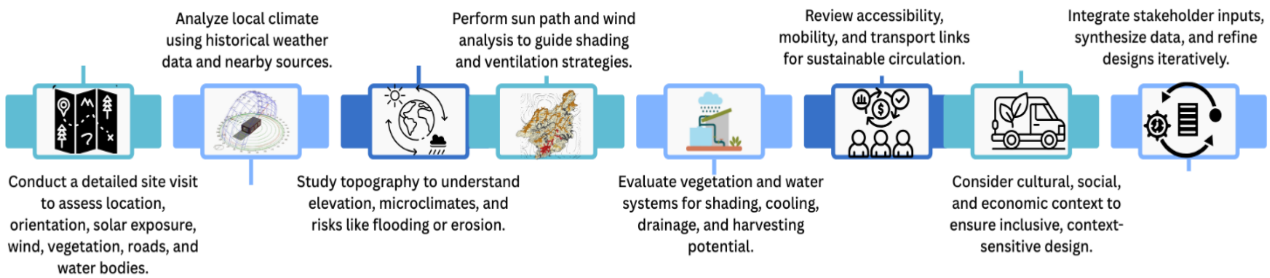


Figure 48; Design methodology for microclimate enhancement

3.4 Design Methodology for Passive Cooling at Building Level

Passive cooling at building level involves integrating various elements such as optimizing building orientation, thermal mass, natural ventilation systems, and shading and glazing options to minimize heat gain and reduce energy consumption. This methodology emphasizes an iterative design process that considers site-specific climatic conditions, building form, and user requirements to achieve optimal passive cooling performance.

3.4.1 Solar Passive Design Strategies

3.4.1.1 Orientation

Design methodology for orientation involves strategically positioning buildings to optimize natural light, minimize solar heat gain, and enhance overall energy efficiency, considering factors like site characteristics, prevailing winds, and solar path. Through careful analysis and planning, architects aim to create spaces that promote comfort, sustainability, and well-being.

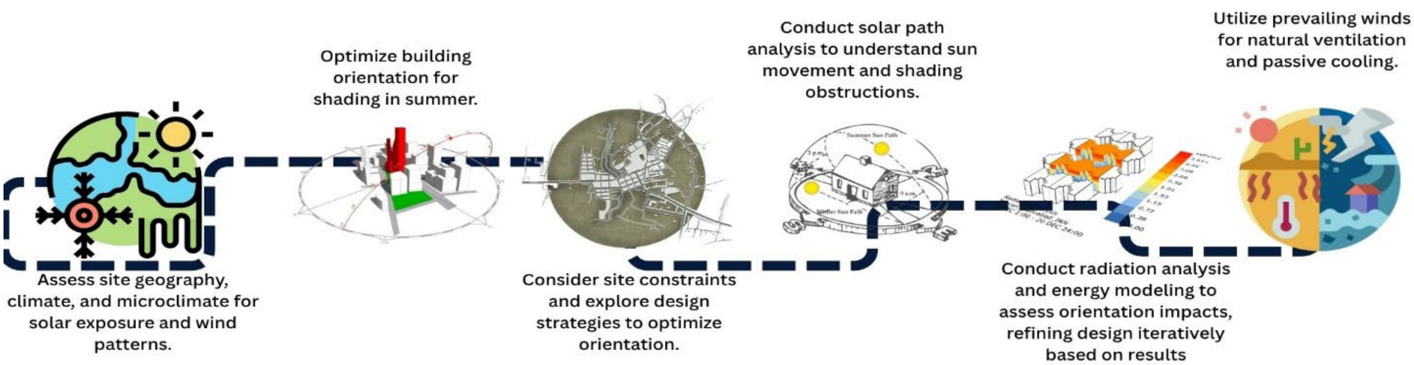


Figure 49: Design methodology for orientation

Selecting the right building orientation is key to optimizing solar gain, maximizing passive heating in winter, and minimizing heat gain in summer, reducing reliance on mechanical systems. Proper orientation also enhances daylighting, cutting down on artificial lighting needs and boosting occupant comfort and productivity. Aligning openings with prevailing winds supports natural ventilation, improving indoor air quality and further reducing mechanical system usage. Overall, correct orientation improves energy efficiency, comfort, and sustainability, contributing to resource efficiency and environmental stewardship.

In Cambodia, shared areas as lounges, semi-open halls, or multi-use corridors can shift roles throughout the day based on sunlight and breezes. In the cooler parts of the day, spaces that get sunlight can be used for group activities. When the heat peaks, people can move to shaded spots or change the layout using sliding screens or adjustable panels, making the space cooler and more useful.

3.4.1.2 Form and Shape of the Building

The design methodology for the form and shape of a building encompasses the systematic approach to conceptualizing and creating its physical structure, considering factors such as functionality, aesthetics, environmental impact, and user experience. It involves iterative processes of research, analysis, experimentation, and refinement to achieve the desired architectural expression and performance goals.

Figure 50: Design methodology for form and shape of the building

Optimizing solar orientation, maximizing natural daylighting, and facilitating passive ventilation, can significantly reduce the building's energy consumption for heating, cooling, and lighting. Additionally, strategic use of thermal mass and shading elements helps regulate indoor temperatures and minimize solar heat gain, enhancing occupant comfort and well-being.

3.4.2 Insulation

3.4.2.1 Massing and Zoning

Developing a thorough massing and zoning design methodology is essential for optimizing spatial arrangements to enhance functionality, occupant comfort, and energy efficiency in built environments. It ensures efficient utilization of space while considering site-specific factors like solar exposure, wind patterns, and environmental impact for sustainable architectural solutions.

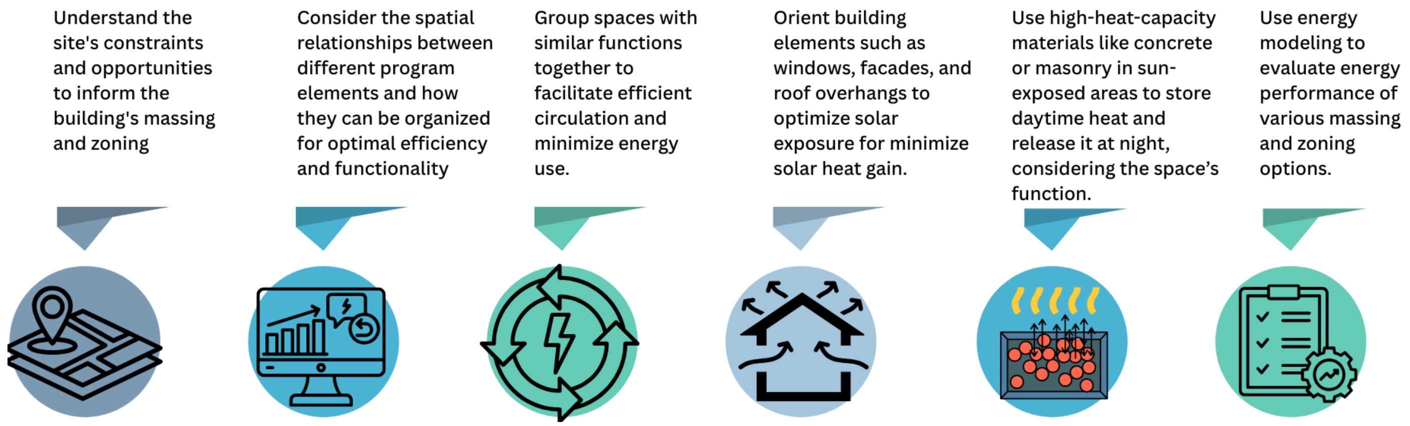


Figure 51: Design methodology for massing and zoning

3.4.3 Shading

3.4.3.1 Self-Shading

Self-shading optimizes natural shading within a building's layout, reducing reliance on external shading devices and minimizing solar heat gain. This approach enhances energy efficiency, improves occupant comfort, and promotes sustainable building practices.

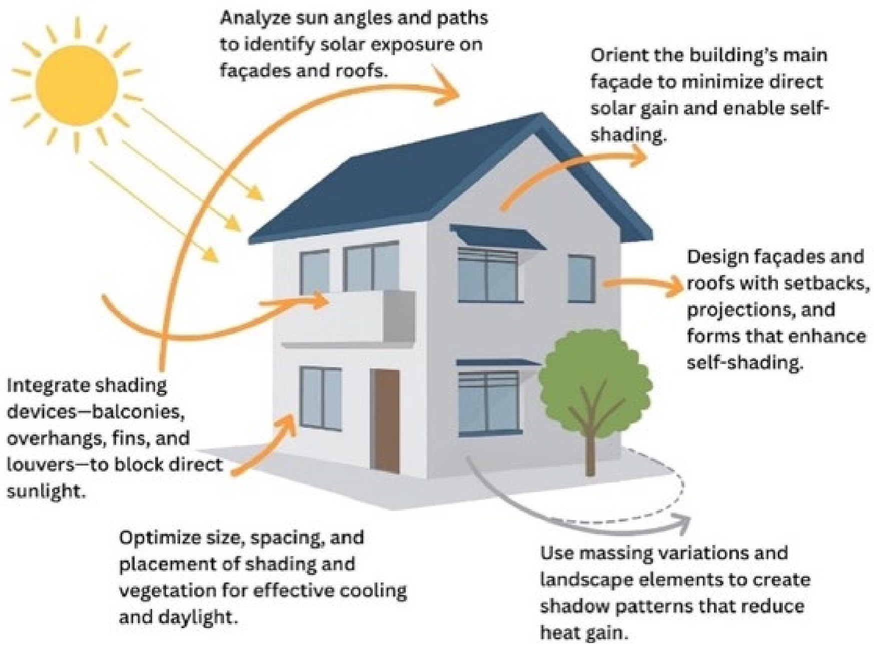


Figure 52: Design methodology for self-shading

3.4.3.2 *Mutual Shading*

Mutual shading design optimizes building layouts to minimize direct sunlight exposure and reduce heat gain, enhancing thermal comfort and energy efficiency. By strategically positioning structures to shade each other, it mitigates overheating and creates more comfortable indoor environments.

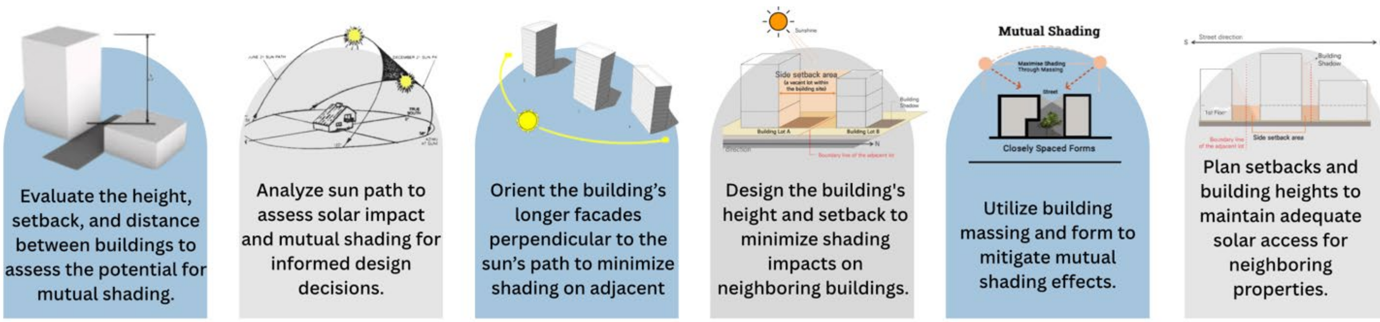


Figure 53: Design methodology for mutual shading

3.4.4 Ventilation

3.4.4.1 *Window Wall Ratio (WWR)*

Optimizing WWR in building design balances daylighting, energy efficiency, and thermal comfort. Proper management of this ratio can minimize heat gain, maximize natural light, and enhance occupants' well-being.

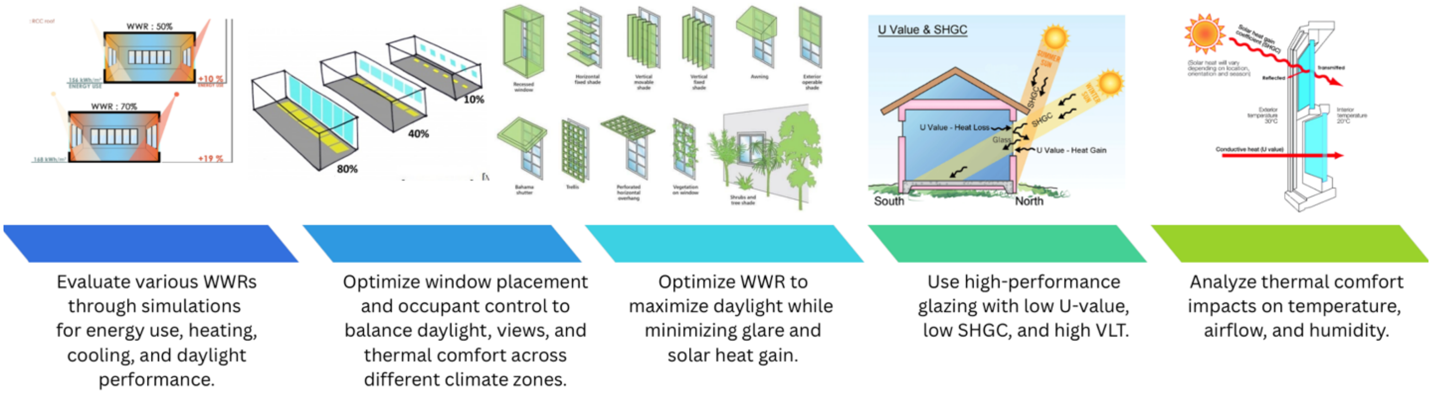


Figure 54: Design methodology for window wall ratio (WWR)

3.4.4.2 *Wind Orientation*

Wind orientation is essential to optimize natural ventilation and minimize heat buildup within buildings, enhancing occupant comfort and reducing reliance on mechanical cooling systems. By strategically aligning buildings with prevailing wind directions, designers can promote airflow and create more sustainable and energy-efficient built environments.

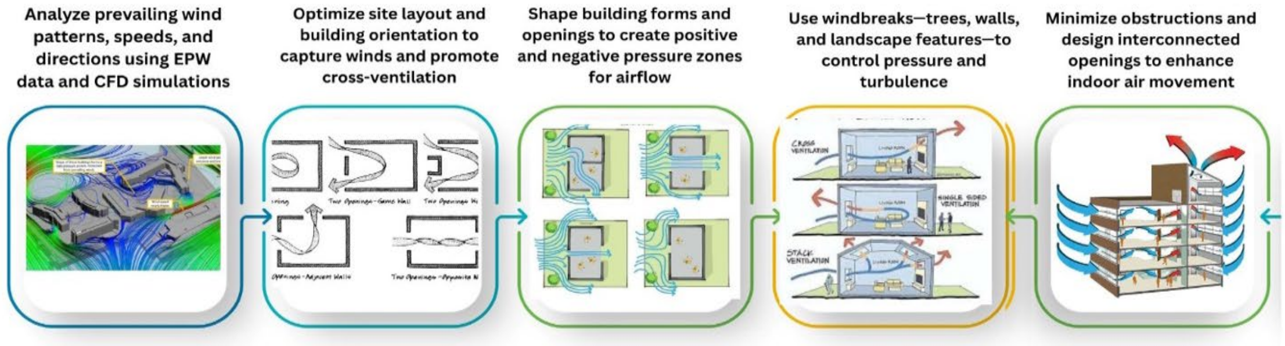


Figure 55: Design methodology for wind orientation

3.4.4.3 Stack Ventilation

Stack ventilation design optimizes airflow by utilizing temperature differentials to induce natural convection, enhancing indoor air quality and reducing reliance on mechanical ventilation systems. This approach fosters energy efficiency and sustainable building practices while promoting occupant comfort.

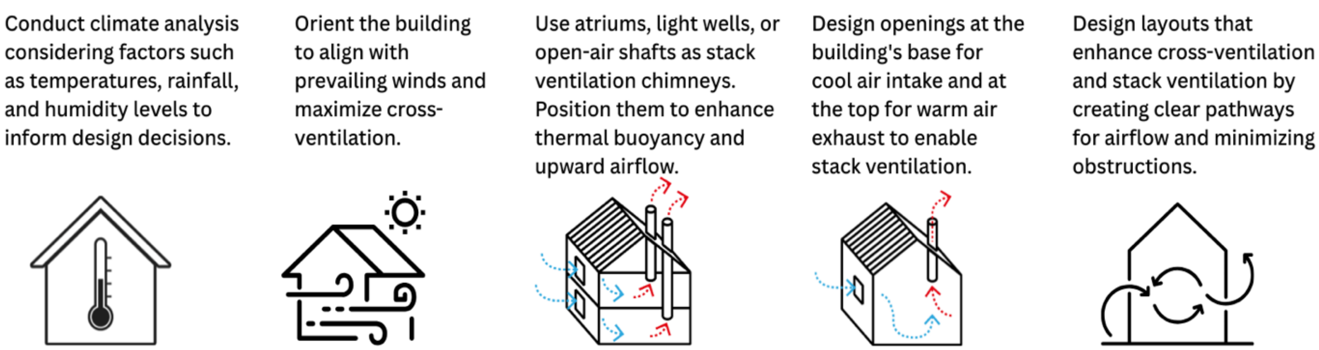


Figure 56: Design methodology for stack ventilation

3.4.4.4 Natural and Cross Ventilation

Implementing natural and cross ventilation enhances indoor air quality, reduce reliance on mechanical cooling systems, and promote energy efficiency in buildings. By harnessing natural airflow patterns, these strategies mitigate heat buildup, enhance occupant comfort, and contribute to sustainable building practices.

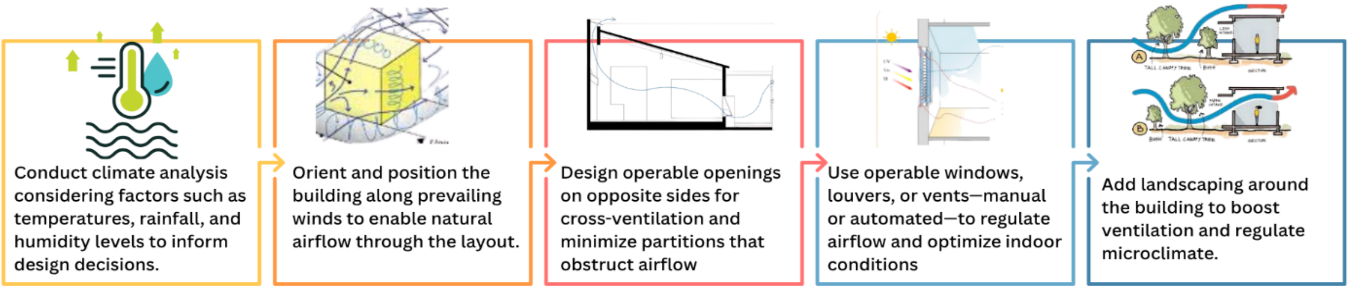


Figure 57: Design methodology for natural and cross ventilation

3.4.4.5 Night Cooling

Night cooling aims to harness cooler outdoor temperatures during the night to reduce indoor heat buildup, enhancing thermal comfort and minimizing reliance on mechanical cooling systems, thereby promoting energy efficiency and sustainability.

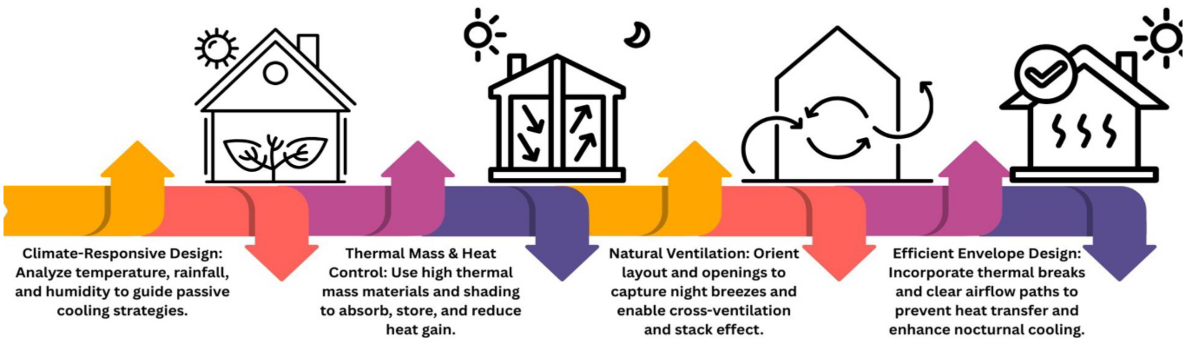


Figure 58: Design methodology for night cooling

3.5 Design Methodology for Passsive Cooling at Component Level

3.5.1 Walls

Implementing an insulated wall ensures optimal thermal performance and energy efficiency, contributing to enhanced comfort and reduced energy costs in buildings. It also enables the integration of appropriate materials and construction techniques to mitigate heat transfer and maintain indoor comfort levels.

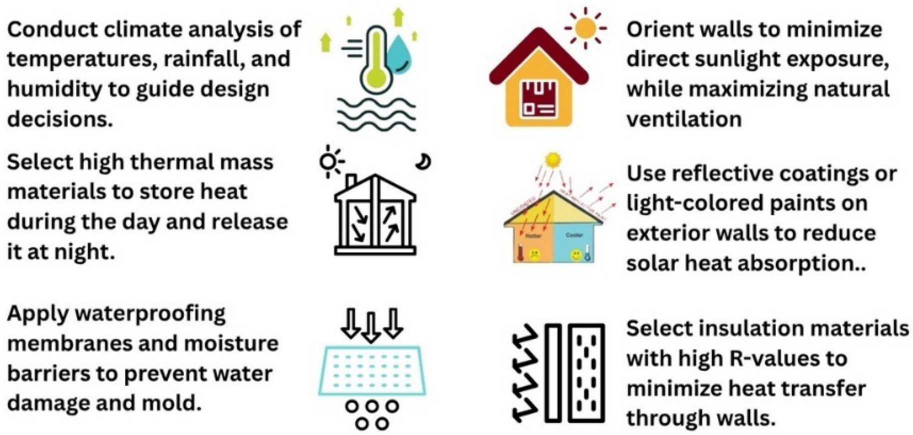


Figure 59: Design methodology for walls

3.5.2 Roofs

Roof design methodology is essential to ensure optimal performance and durability of the roofing system, safeguarding the building from weather elements and enhancing energy efficiency. By employing proper design techniques, such as slope calculation and material selection, roofs can effectively manage water runoff, prevent leaks, and contribute to overall building sustainability.

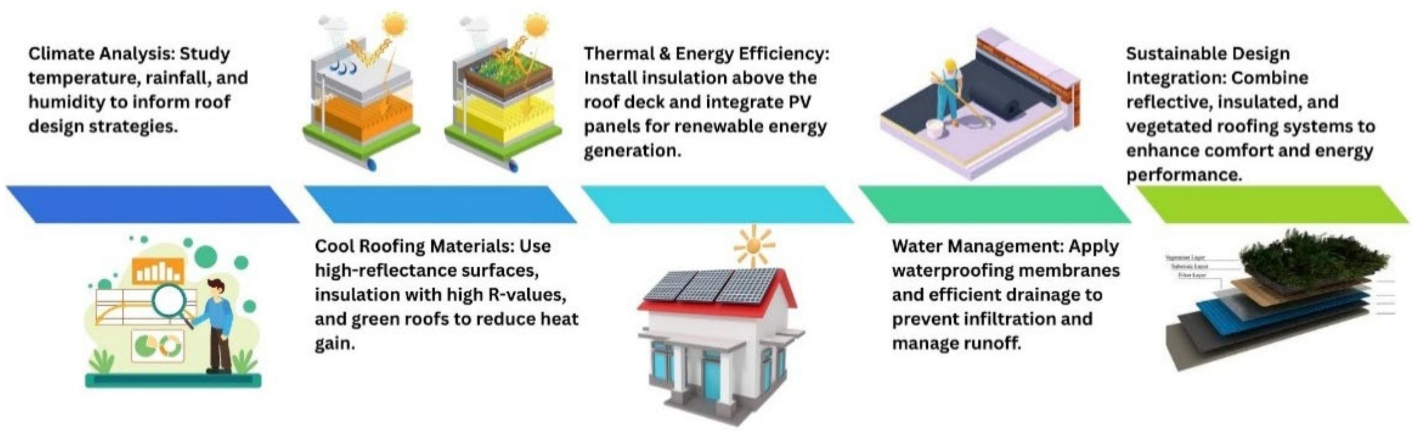


Figure 60: Design methodology for roofs

3.5.3 Fenestration

Fenestration helps to optimize natural light, ventilation, and thermal comfort within buildings, enhancing occupant well-being and energy efficiency while minimizing reliance on artificial lighting and HVAC systems.

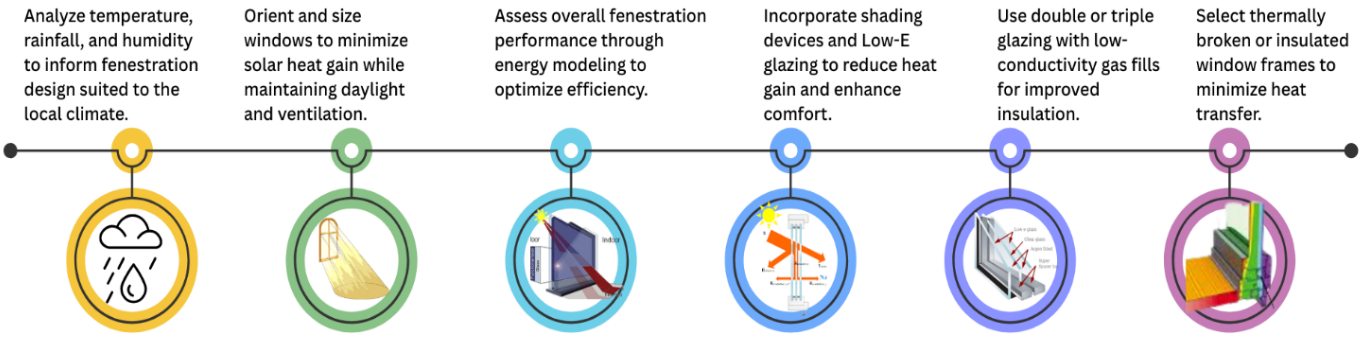


Figure 61: Design methodology for fenestration

3.5.4 Airtightness

Air tightness ensures minimal uncontrolled airflow in buildings, enhancing energy efficiency by reducing heat loss or gain through leaks in the building envelope. Additionally, it helps maintain indoor air quality and comfort by preventing infiltration of pollutants and outdoor allergens.

Figure 62: Design methodology for airtightness

4 Technical Approach to Select Passive Cooling Strategies

4.1 Climate Analysis

Climate analysis provides the basis for selecting suitable passive cooling strategies (PCS) by identifying the key environmental factors that drive heat gain and comfort conditions. In Cambodia's hot–humid climate, high Dry Bulb Temperature (DBT) and UTCI values point to the need for shading and insulation, while high Relative Humidity (RH) highlights the importance of ventilation and moisture control. These insights help prioritize passive cooling strategies that effectively reduce cooling loads and improve comfort.

Climate analysis includes assessments of sun path, radiation levels, wind patterns, DBT, wet bulb temperature (WBT), RH, UTCI, and rainfall distribution.

4.1.1 Sun Path

Sun Path analysis helps optimize building orientation and shading strategies by understanding solar exposure, improving energy efficiency and comfort. Using Energy Plus Weather files (EPW), architects can generate annual or seasonal sun path diagrams. These visualizations, including diagrams and 3D models, show the sun's position relative to the site, helping assess solar exposure, shading, and glare. This information allows for better window placement, shading, and overall design to maximize daylighting and minimize heat gain.

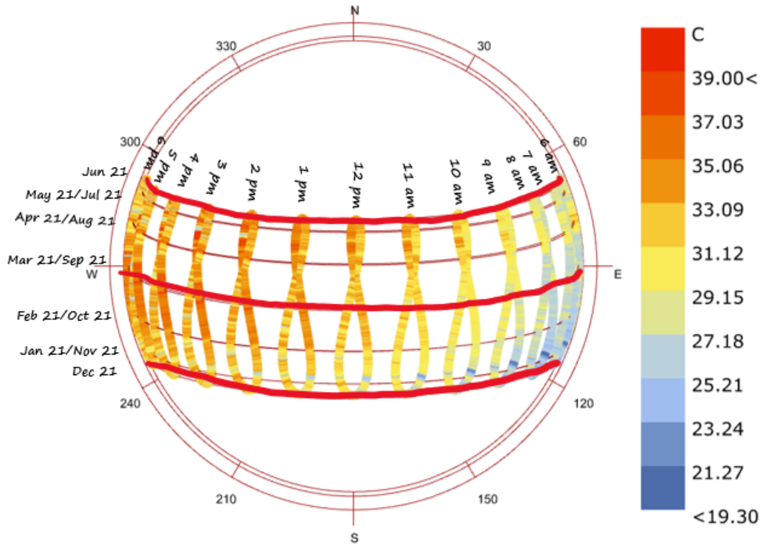


Figure 63: Sun Path Diagram - Phnom Penh

The sun path diagram for Phnom Penh shows the sun's movement and intensity throughout the year. In June (Summer Solstice), it rises in the northeast, reaches its peak in the north at noon, and sets in the northwest. In December (Winter Solstice), it rises in the southeast, peaks in the south at noon, and sets in the southwest. During the equinoxes in March and September, the patterns balance. Solar intensity is highest from 11:00 am to 6:00 pm from February to October, and from 1:00 pm to 6:00 pm from November to January. These patterns are crucial for urban planning and solar energy use in Phnom Penh.

Implication: With intense solar gains especially in equatorial and tropical climates solar radiation analysis and sun path diagrams inform the strategic placement of shading devices (e.g. deep overhangs, louvers) and orientation of building elements to control heat gain while preserving daylight.

4.1.2 Radiation

Radiation analysis involves evaluating direct and indirect sunlight to optimize building design for energy efficiency and occupant comfort. It helps in understanding solar exposure, minimizing heat gain, and assessing renewable energy potential.

4.1.2.1 Direct Radiation Analysis

Direct radiation analysis evaluates sunlight intensity and distribution on a site by examining solar azimuth, altitude angles, shadows, and obstructions. This helps optimize building orientation, solar panel placement, and shading to reduce heat gain and enhance solar energy use. Radiation data, visualized through diagrams, charts, or 3D models from EPW files, aids in designing energy-efficient buildings and improving indoor comfort.

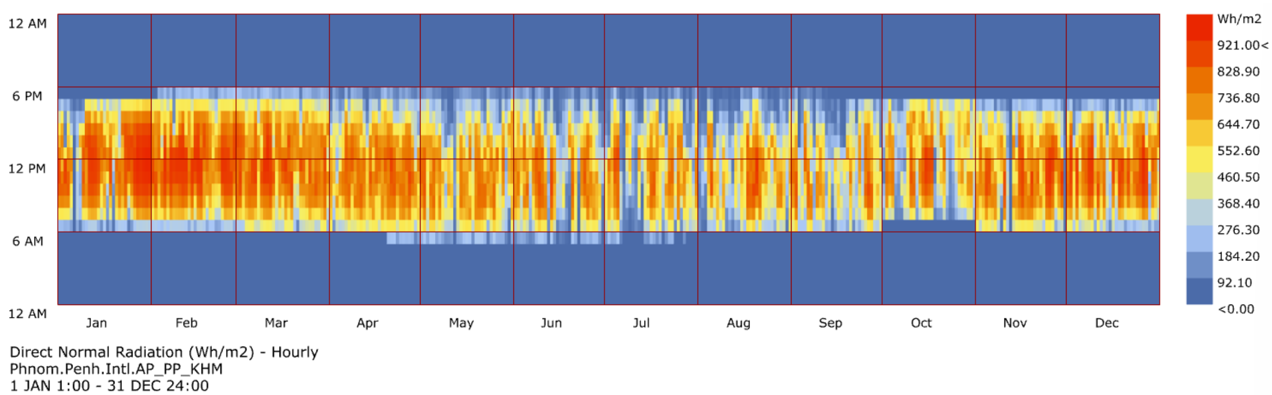


Figure 64: Heat map of direct radiation analysis - Phnom Penh

The heat map of direct radiation for Phnom Penh shows moderate solar intensity. Maximum direct radiation reaches 921 Wh/m² from 6:00 am to 6:00 pm, indicating unobstructed sunlight. Compared to global standards, Phnom Penh's solar intensity is moderate.

Prolonged direct radiation between 6:00 am and 6:00 pm necessitates solar shading systems, self-shading forms, and reduced glazing exposure on west façades. For rooftops, cool coatings or green roofs are essential to control peak heat gain during afternoon hours.

4.1.2.2 Indirect Radiation Analysis

Indirect radiation refers to solar energy reaching a site after being scattered or reflected by the atmosphere and surroundings. Analysis of diffuse radiation, sky conditions, and surface albedo helps assess overall solar exposure, including diffused and reflected sunlight. This information aids in optimizing building layouts, material selection, and shading strategies to reduce glare, lower lighting energy use, and improve occupant comfort.

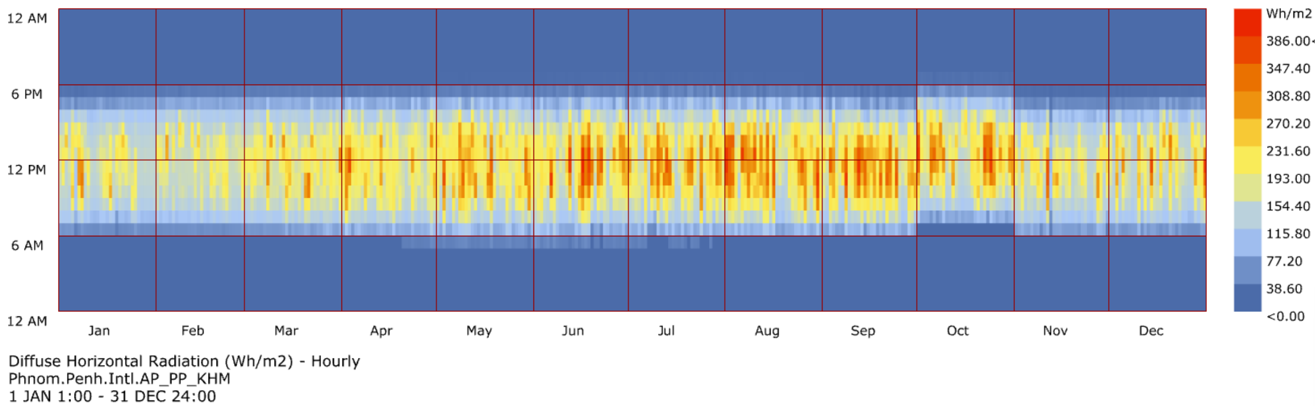


Figure 65: Heat map of indirect radiation analysis - Phnom Penh

The heat map of direct radiation for Phnom Penh shows a peak of 386 Wh/m² from 6:00 am to 6:00 pm. This diffuse radiation, influenced by cloud cover and humidity, increases from June to September due to higher humidity and cloudiness. Light-diffusing fenestration, overhangs, and external shading are recommended to maintain daylight quality while limiting heat ingress.

4.1.3 Dry Bulb Temperature (DBT)

DBT measures air temperature without considering humidity. DBT analysis involves tracking seasonal variations, diurnal changes, and temperature gradients to assess thermal comfort, energy use, and HVAC performance. Data, obtained from EPW files or similar sources, is visualized through diagrams, charts, or 3D models to aid in optimizing building design and ensuring indoor comfort.

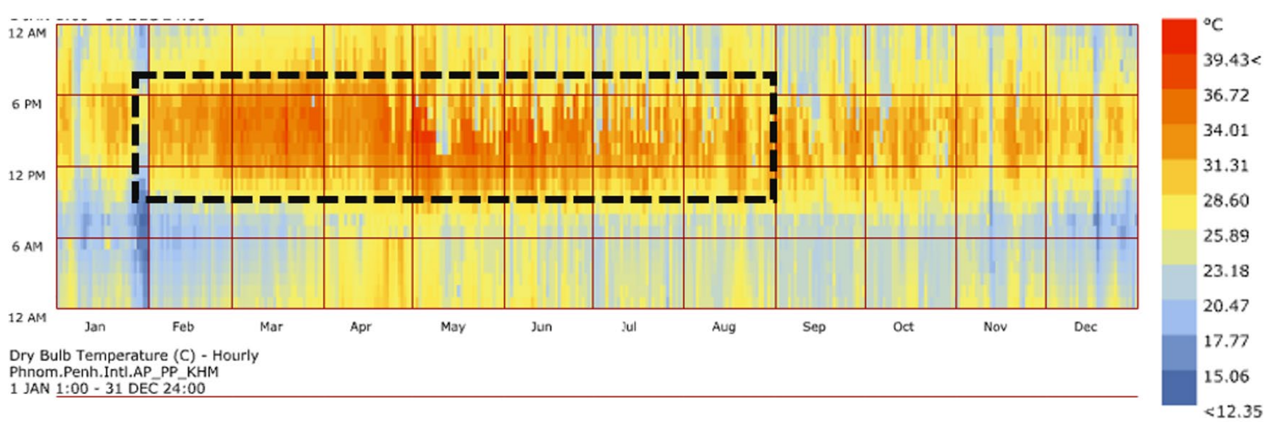


Figure 66: Heat map of dry bulb temperature (DBT) - Phnom Penh, Cambodia

The heat map illustrating the DBT analysis in Figure 39 depicts Phnom Penh, Cambodia. The city experiences high DBT exceeding 31°C from February to August between 12:00 pm and 6:00 pm. DBT represents the actual air temperature measured without accounting for humidity or other factors. This elevates the requirement for effective solar shading, reflective materials, and high-performance insulation in building envelopes.

4.1.4 Relative humidity

RH measures moisture in the air relative to its capacity at a given temperature. RH analysis considers indoor and outdoor levels, moisture sources, ventilation, and seasonal changes. It involves using hygrometers or data loggers to assess moisture levels and condensation risks. Understanding RH is key for indoor air quality, mold prevention, and occupant comfort, helping designers optimize ventilation and HVAC systems.

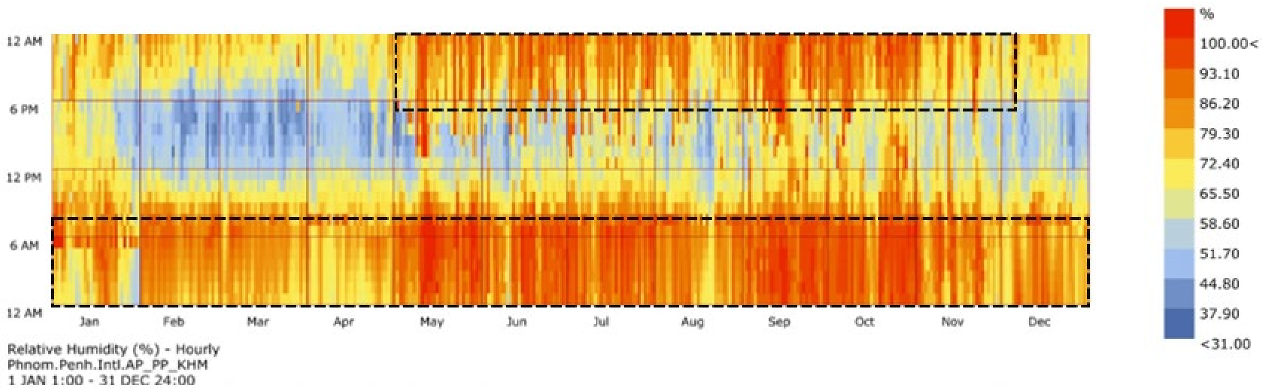


Figure 67: Heat map of relative humidity - Phnom Penh, Cambodia

The RH heat map for Phnom Penh shows consistently high humidity levels, remaining above 70% at night. Elevated RH persists from May to November, with averages above 70%, while from November to April, daytime RH ranges from 40% to 70%, offering a more comfortable environment. Understanding these variations is key for assessing comfort and implementing appropriate measures in Phnom Penh.

It amplifies the latent cooling load, making strategies like ventilation, dehumidification, and moisture control vital components of passive cooling.

4.1.5 Wet Bulb Temperature (WBT)

WBT measures the lowest temperature air can reach through water evaporation. WBT analysis considers humidity, air velocity, and surface temperatures, using a wet bulb thermometer. It helps assess humidity, evaluate evaporative cooling, and determine thermal comfort. Data from EPW or similar files, visualized through diagrams and charts, aids in optimizing cooling strategies and ensuring comfort, especially in hot, humid climates.

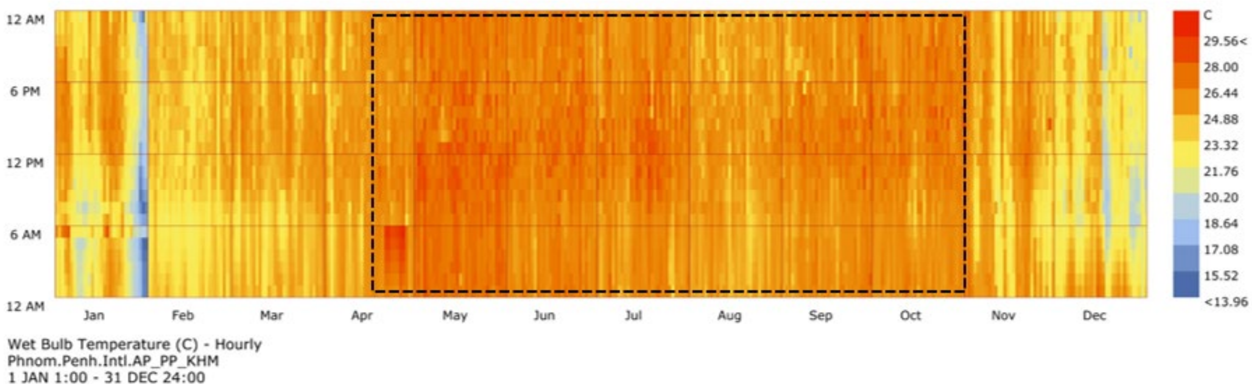


Figure 68: Heat map of wet bulb temperature (WBT) - Phnom Penh, Cambodia

The WBT heat map for Phnom Penh shows temperatures exceeding 35°C can be hazardous. The highest WBT recorded is 30°C, indicating the maximum achievable temperature through evaporative cooling. WBT is notably high from April to October, presenting challenges for thermal comfort and health risks due to heat and humidity. From November to April, WBT ranges from 22°C to 26°C, offering a more comfortable environment.

Persistently high wet-bulb temperatures (often above 26 °C) in Cambodia's hot-humid climate limit the effectiveness of evaporative cooling. Greater emphasis should therefore be placed on solar shading, reflective materials, natural ventilation, and dehumidification to maintain indoor comfort and reduce latent cooling loads.

4.1.6 Universal Thermal Climate Index (UTCI)

UTCI assesses thermal comfort by combining air temperature, humidity, wind speed, and radiation. UTCI analysis uses mathematical models to evaluate thermal sensation and physiological strain. It helps in assessing comfort, heat stress risks, and designing conducive spaces. Data, from EPW files or similar sources, provides a comprehensive view of thermal comfort and helps mitigate heat effects in Phnom Penh.

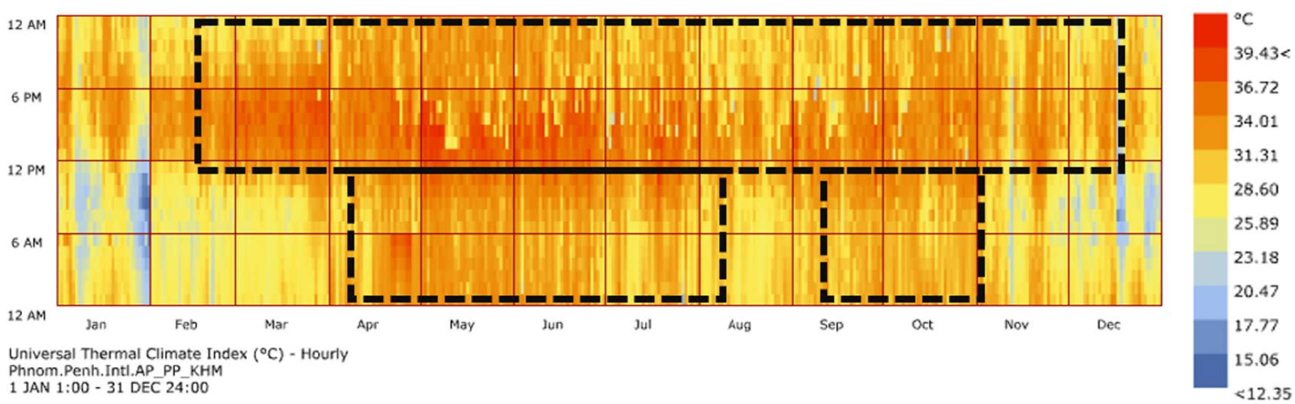


Figure 69: Heat map of Universal Thermal Climate Index (UTCI) - Phnom Penh, Cambodia

The heat map illustrating UTCI analysis in Figure 64 depicts Phnom Penh, Cambodia. When considering the UTCI, which factors in parameters such as humidity and wind speed, the felt temperature surpasses 31°C throughout the day from April to July, September, and October, as well as from 12:00 pm to 12:00 am in the other months (excluding January and December).

UTCI values above 31 °C indicate significant thermal discomfort for much of the year. This calls for comprehensive passive cooling integration, including natural ventilation, vegetated shading, reflective surfaces, and microclimate-enhancing site features to mitigate outdoor heat exposure and support occupant comfort.

4.1.7 Wind Rose

A wind rose graphically represents wind speed and direction data in a circular format. It shows prevailing wind patterns by plotting wind speed, direction, and frequency. Each sector indicates wind direction, and petal length shows frequency or intensity. Wind rose analysis aids in urban planning, building design, and renewable energy projects, helping optimize building orientation, outdoor spaces, and wind energy installations. In high-humidity areas, wind speeds above 3 m/s can improve indoor comfort.

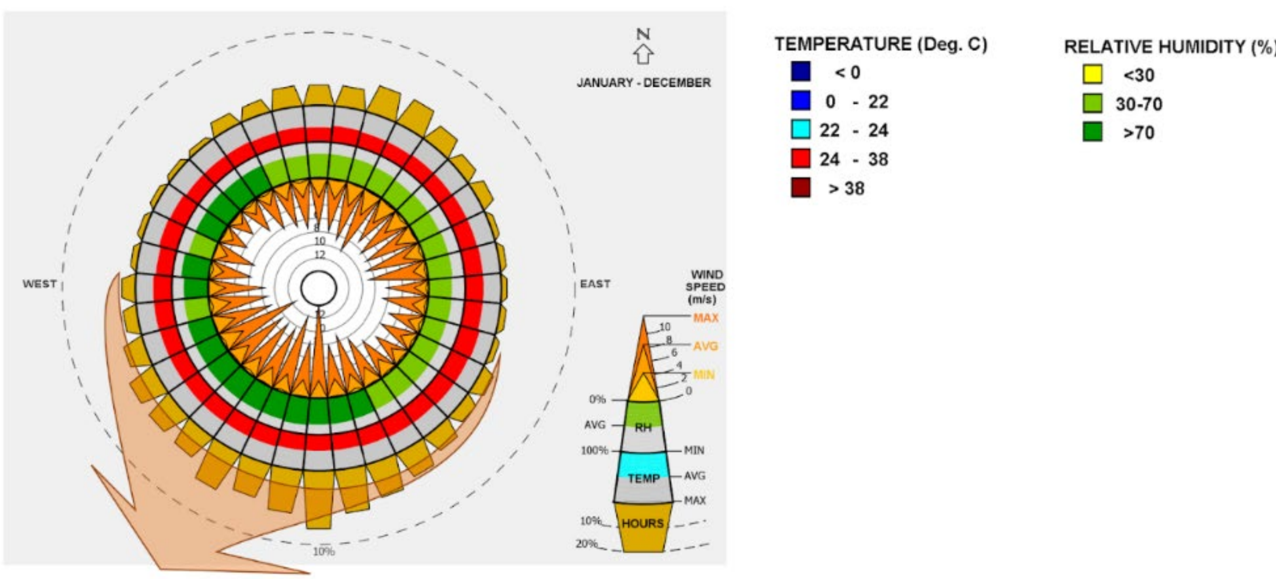


Figure 70: Wind rose diagram - Phnom Penh, Cambodia

The Wind Rose diagram for Phnom Penh, based on 8760 hours of EPW data, shows wind frequency, direction, and speed, along with their correlation to humidity and temperature. From February to September, winds peak from the southwest, south, and southeast. From October to January, winds shift to the north and northeast. Southerly and southwest winds often bring higher humidity, exceeding 70%, affecting comfort and perceived temperature. The average wind temperature ranges from 24°C to 38°C, influencing overall thermal perception.

Understanding prevailing south–southwest wind directions allow designers to orient openings and courtyards to capture breezes and improve cross-ventilation, particularly during humid months.

Optimizing porosity in the building layout enhances air exchange and reduces mechanical cooling dependency.

4.1.8 Psychrometry

Psychrometry studies the properties of air and water vapor mixtures, focusing on temperature, humidity, pressure, and dew point. This analysis uses instruments like psychrometers to measure these parameters and evaluate relative humidity, specific humidity, enthalpy, and dew point. It's essential for HVAC design, indoor air quality, thermal comfort, and building performance. Psychrometric analysis helps optimize HVAC systems, improve ventilation and humidity control, and enhance building performance and energy efficiency.

Plotting local temperature and humidity on a psychrometric chart helps pinpoint when evaporative cooling is viable versus when dehumidification or thermal mass becomes critical to maintain comfort. This ensures passive cooling strategies are matched to the actual comfort zone under specific climate conditions. On a psychrometric chart, the distance between the dry-bulb and wet-bulb temperatures indicates the potential for evaporative cooling. A larger gap suggests greater feasibility, while a smaller gap indicates limited effectiveness. In Cambodia's climate, where high humidity is prevalent, this gap is often narrow, signaling that evaporative cooling may not be the most effective strategy.

4.1.9 Climate-Based Decision Matrix for Passive Cooling

The Climate-Based Decision Matrix (Figure 66) links temperature and humidity conditions with their impact on comfort, energy demand, and passive cooling strategy (PCS) selection.

In Cambodia’s predominant hot-humid climate, key needs include effective ventilation, solar control, and optimized WWR to manage heat and moisture.

During hot-dry periods, shading, envelope insulation, vegetation, and night ventilation help reduce heat gain and improve comfort. In cool-humid conditions, managing infiltration, condensation, and mold risk through controlled ventilation and moisture-resistant materials becomes important. The rare cool-dry scenario allows passive heating, thermal mass, and vegetation to maintain comfort with minimal energy use.

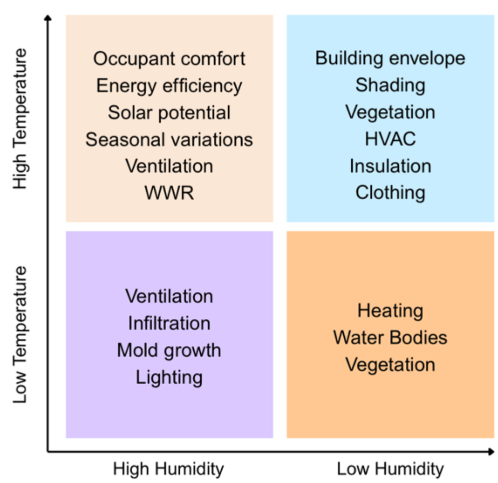


Figure 71: Climate-based decision matrix for passive cooling

Overall, the matrix highlights that Cambodia’s design focus should be on solar control, ventilation, and moisture-responsive envelope strategies to reduce cooling loads and improve year-round comfort. comfort, thereby guiding the selection of appropriate passive cooling strategies. The four quadrants represent key climatic scenarios that dictate design responses.

4.2 Thermal Performance Analysis

Cambodia's climate includes periods of high temperature with both high and low humidity, as well as occasional cooler conditions. For high temperature and high humidity, ventilation is used to move air and reduce moisture. Shading and window-to-wall ratio adjustments help control heat gain. Building orientation supports airflow, and solar exposure is considered for energy use. Rainfall patterns influence roof design and drainage. HVAC systems are selected based on temperature and moisture levels.

In high temperature and low humidity conditions, shading and insulation are used to reduce heat transfer. The building envelope is planned to limit solar radiation. Vegetation is placed to lower surrounding temperatures. Cooling systems may include evaporative methods. Clothing and interior materials are considered in spaces like schools and offices.

For low temperature and high humidity, ventilation and infiltration control help manage moisture. Materials are selected to resist mold. Lighting is planned to support indoor conditions. Air movement is maintained to prevent dampness.

In low temperature and low humidity conditions, heating systems may be used. Vegetation is placed to allow sunlight. Water bodies are used to adjust dry air in specific areas. These strategies guide decisions on insulation, openings, and systems to match Cambodia's climate throughout the year.

Thermal performance analysis evaluates how a building manages heat transfer to ensure comfort and energy efficiency. It assesses insulation, solar heat gain, and ventilation to optimize indoor conditions. Through simulations and measurements, it helps design buildings with stable temperatures, reduced energy consumption, and enhanced comfort by identifying heat loss or gain areas and guiding insulation, fenestration, and HVAC decisions.

4.2.1 Thermal Performance Estimation Methods

4.2.1.1 Manual Calculation Method

Estimating thermal performance typically involves calculating parameters such as thermal resistance, heat transfer rates, and temperatures using manual methods.

- Identify all components of the system, including heat sources, materials, and heat sinks.
- Get the thermal conductivity values (k) of the materials.
- Calculate Thermal Resistances (R)
    - For Conduction: $R = \frac{L}{kA}$, where L is the length, A is the cross-sectional area perpendicular to the direction of heat flow, and k is the thermal conductivity.
    - For Convection: Calculate convective heat transfer coefficients (h), then use the formula $R = \frac{1}{hA}$, where A is the surface area.

- For Radiation: Use $Q = \varepsilon\sigma A(T_h^4 - T_c^4)$ where Q is the heat transfer rate, ε is the emissivity of the surface, σ is the Stefan-Boltzmann constant, A is the surface area, and T_h and T_c are the temperatures of the hot and cold surfaces respectively.

- If there are multiple resistances in series or parallel, combine them appropriately. For series, $R_{total} = R1 + R2 + \ldots\ldots$ For parallel, $\frac{1}{R_{total}} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots\ldots$
- Calculate Heat Transfer Rate (Q): Use Fourier's law for conduction $Q = \frac{\Delta T}{R_{total}}$
- Then use the Q value to find temperatures at different points within the system.

4.2.1.2 Energy Simulation Method

Estimating thermal performance for a building envelope using energy simulation involves using specialized software to model the building's geometry, materials, occupancy, HVAC systems, and weather data to simulate energy usage and thermal performance.

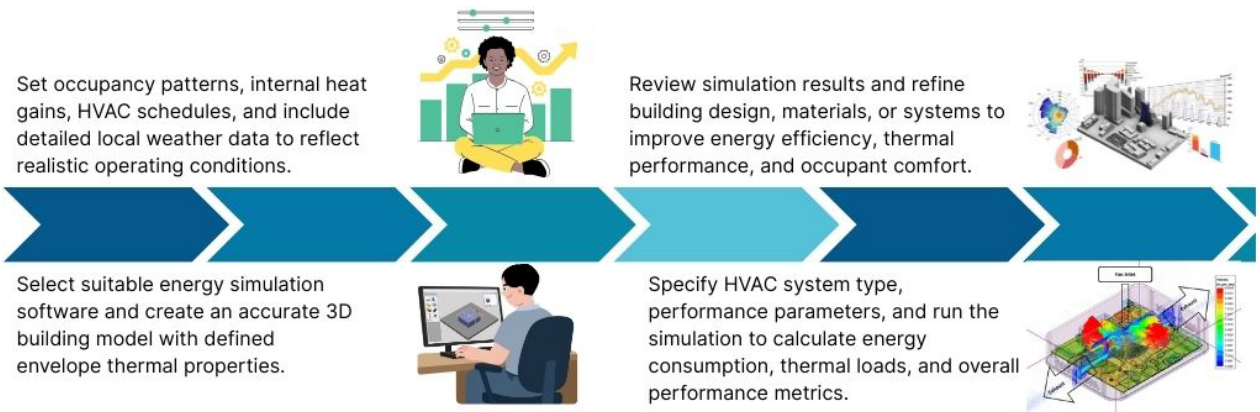


Figure 72: Energy simulation method

Energy Simulation Tools

Several energy simulation tools are available for analyzing the thermal performance of building envelopes.

Table 3: Energy simulation tools

Simulation Tools	Description
EnergyPlus	EnergyPlus, developed by the U.S. Department of Energy, is a comprehensive building energy simulation program for modeling geometry, materials, HVAC systems, and controls to analyze thermal performance and energy consumption.
DesignBuilder	DesignBuilder, integrating with EnergyPlus, provides 3D modeling, building templates, and an intuitive interface for simulating energy use, thermal comfort, daylighting, and HVAC systems.
eQuest	eQuest is a free, open-source energy modeling tool by the U.S. Department of Energy, offering detailed building modeling, including geometry, materials, HVAC systems, and energy analysis.
OpenStudio	OpenStudio, developed by NREL, is an open-source platform for building energy analysis, offering tools for geometry modeling, simulation, optimization, and visualization.

THERM	THERM, developed by Lawrence Berkeley National Laboratory, models 2D heat transfer in building components like windows and doors. It analyzes thermal performance, heat flow, temperature distribution, and condensation risk, considering material properties, glazing types, frame constructions, and weather conditions.
WINDOW	WINDOW, by Lawrence Berkeley National Laboratory, simulates the thermal and optical properties of fenestration systems, including glazing, coatings, gas fills, and shading. It evaluates their impact on energy performance, daylighting, and comfort, and is often used with THERM for detailed analysis.
Rhino and Grasshopper	Rhino and Grasshopper, with plugins like Ladybug and Honeybee, enable energy simulation and analysis for designing energy-efficient buildings.

Energy Simulation Inputs

Table 4: Energy simulation inputs

Energy Simulation Inputs	**Description**
Building Geometry	Include building geometry: floor plans, elevations, dimensions, orientation, and shading devices.
Thermal Properties	Thermal conductivity, specific heat, density, and thickness of building materials.
Fenestration Properties	Window characteristics: glazing type, glass properties (U-value, solar heat gain coefficient), and frame material.
Internal Loads	Occupancy schedules, lighting power density, equipment loads, and internal heat gains from appliances and occupants.
HVAC Systems	Details of HVAC systems: equipment efficiency, capacity, control strategies, schedules, and setpoints.
Weather Data	Local weather data includes temperature, solar radiation, wind speed, humidity, and cloud cover. Typical files are EPW (Energy Plus Weather).
Occupant Behavior	Consider occupant behavior, thermostat settings, window schedules, and other factors affecting energy.
Simulation Settings	Set simulation parameters: period (hourly, monthly), time-step resolution, convergence criteria, and output preferences (energy consumption, thermal comfort).

Simulation Outputs for Passive Cooling Strategy Selection

The table below outlines the relationship between performance indicators and the respective simulation outputs obtained from the analysis.

Table 5: Simulation outputs for passive cooling design strategy selection

Outputs from Energy Simulation	**Performance Indicators**
Annual Thermal load (kWh/year) of the building	Building cooling load
kWh/m^2 of the total envelope area & floor area	Building envelope thermal performance
kWh/m^2 of the cooling in the building	Cooling energy use intensity,
	unmet hours of comfort

Output Data Interpretation

Table 6: Output data interpretation

Output Data	**Analysis**	**Importance**

Total Energy Consumption	Evaluate energy consumption patterns to understand daily and seasonal variations and identify anomalies indicating inefficiencies or malfunctions.	Identifies high energy usage areas for targeted improvements and allows comparison with benchmarks or past data to track progress.
Heating and Cooling Loads	Determine heating and cooling load distribution by zone and time, identify peak demand periods, and assess HVAC system sizing.	Ensure HVAC systems are designed to maintain comfort efficiently, avoiding oversizing or under sizing issues.
Fenestration Analysis	Evaluate window and glazing options for energy efficiency, daylighting, and comfort, considering solar heat gain, daylight, glare control, and insulation.	Optimal fenestration design improves energy use, comfort, and indoor quality by balancing efficiency with daylighting and views.
HVAC System Performance	Evaluate HVAC efficiency by assessing performance curves, part-load efficiencies, and temperature control under various conditions.	Optimal HVAC performance is essential for indoor comfort, energy efficiency, and cost. Understanding system behavior improves equipment, control, and maintenance.
Indoor Comfort	Collect occupant feedback on thermal comfort, including temperature, humidity, air quality, and drafts, to identify comfort issues.	Ensuring indoor comfort boosts occupant health, productivity, and satisfaction, improving building performance and user experience.
Carbon Emissions	Quantify the carbon footprint from construction, operation, and material emissions. Assess design impacts and explore reduction opportunities.	Understanding and mitigating a building's carbon footprint is essential for sustainability and reducing environmental impact.

4.2.2 Key Performance Indicators

KPIs are metrics that evaluate the accuracy, reliability, and performance of a simulation model. They help assess design strategies, identify improvement areas, and ensure energy efficiency goals are met.

Table 7: Key performance indicators

Key Performance Indicators (KPI)	**Unit**
Total Energy Consumption	kWh/m^2/year
Heating and Cooling Loads	M^{2}tonne
Indoor Thermal Comfort	PMV/PPD
Cooling Energy Performance	Kwh/m^2
Fenestration Performance	u-value
	SHGC
	VLT

5 Application Methods to Implement and Manage Passive Cooling Strategies

5.1 Insulation

5.1.1 Wall Insulation

5.1.1.1 Solid block & Cavity wall

Passive cooling strategies reduce energy use by using natural elements to regulate indoor temperatures. Integrating wall types such as cavity, concrete hollow, hollow brick, and terracotta walls enhances thermal performance through insulation, ventilation, and thermal mass. These approaches provide efficient, climate-specific cooling solutions.

Design Consideration

In the context of PCS in building design, various wall types play a crucial role in maintaining thermal comfort and energy efficiency. Here are the general design considerations for cavity walls, concrete hollow walls, hollow brick walls, and terracotta walls:

Table 8: Design consideration of cavity wall, concrete hollow wall, hollow brick wall, terracotta wall

Cavity Wall	Concrete Hollow Wall	Hollow Brick Wall	Terracotta Wall
Key Function in Passive Cooling Strategies			
Dual-layer wall with air gap improves insulation, reduces heat transfer, and enhances indoor comfort.	Lightweight wall with high thermal resistance; provides thermal mass and reduces cooling/heating load.	Provides thermal mass with slow heat release; stabilizes indoor temperature; ideal for ventilated wall cooling.	High thermal mass & low conductivity; effective in hot–arid climates; supports natural ventilation for cooling.
Design Considerations			
Ensure cavity remains dry; prevent insect/pest ingress; maintain vertical/horizontal ties; inner leaf bears structural load.	Maintain dry, clean blocks; add insulation in warm climates; capitalize on thermal inertia for energy savings.	Use ventilated or non-ventilated designs; provide time lag & phase shift; ensure proper alignment and tie placement.	Ideal for hot–dry climates; promote natural airflow; low maintenance; ensure proper sealing and alignment.
Thermal / Physical Properties			
Thermal Conductivity: 0.3–0.7 W/m.K *Density:* 1500–2200 kg/m³ *R-Value:* 0.462–1.154 m²·K/W	*Thermal Conductivity:* 0.7–1.2 W/m.K *Density:* 1200–1800 kg/m³ *R-Value:* 0.367–0.578 m²·K/W	*Thermal Conductivity:* 0.7–1.2 W/m.K *Density:* 1200–1800 kg/m³ *R-Value:* 0.367–0.578 m²·K/W	*Thermal Conductivity:* 0.9–1.3 W/m.K *Density:* 1800–2200 kg/m³ *R-Value:* 0.405–0.578 m²·K/W
Construction Process			

<table>
<tr><td>
Prepare layout → Install ties → Drill holes → Inject insulation (mineral wool, beads, PU foam) → Seal holes → post-inspection.</td><td colspan="3">
Mortar Preparation → Laying Blocks → Interlocking → Levelling → Wall Tie Fitting.</td></tr>
<tr><td colspan="4">Insulation Approach</td></tr>
<tr><td>Insulation blown into cavity using equipment; must remain dry for efficiency.</td><td>Additional insulation recommended in hot climates; voids may be filled with sand/grout for performance.</td><td>Air gaps contribute to insulation; ventilated design uses airflow to enhance cooling.</td><td>Ventilated hollows enhance thermal performance; insulation rarely needed due to high thermal mass.</td></tr>
</table>

Maintenance at Operational Stage

Regular maintenance is crucial for preserving wall conditions. Routine inspections address issues like cracks and water damage. Basic upkeep includes surface cleaning, repairing damage, and checking sealants and drainage. For materials like terracotta, seek professional advice to ensure proper care and longevity.

Maintenance of Cavity wall

Inspect cavity walls regularly for deterioration and moisture. Repair cracks and gaps and replace damaged insulation to maintain efficiency. Maintain external cladding to prevent water ingress and protect insulation. Ensure proper sealing to prevent pest damage (One Insulation Ltd, n.d.).

Maintenance Procedures for Concrete Hollow Wall, Hollow Brick Wall, and Terracotta Wall

Regular wall maintenance is crucial for longevity and structural integrity. Conduct visual inspections for cracks and damage, clean surfaces, and remove stains promptly. Repair cracks and damages, maintain coatings, and check for water damage, leaks, or mold. Inspect sealants, wall ties, and drainage systems, and consult professionals for specialized care, especially for unique materials like terracotta.

The case study on "Energy Savings by Cavity Wall" can be accessed through the following link:https://www.cewales.org.uk/files/3014/7671/0110/Post_Installation_Performance_of_Cavity_Wall__External_Wall_Insulation.pdf

The case study on "Energy Savings by Hollow Brick Wall" can be accessed through the following link: http://data.conferenceworld.in/DHRUV_10JULY17/P806-813.pdf

The case study on "Energy Savings by Concrete Hollow Wall" can be accessed through the following link: https://www.ijmer.com/papers/Vol5_Issue5/Version-1/C0505_01-1926.pdf

The case study on "Energy Savings by Terracotta Wall" can be accessed through the following link: https://www.buildingconservation.com/articles/terracottabuild/terracottabuild.html

Insulated Wall

Description

Wall insulation is crucial for energy efficiency and comfort, with materials like cellulose, fiberglass, polyurethane foam, polystyrene, polyisocyanurate, mineral wool, and phenolic foam offering various benefits. Factors such as thermal resistance, vapor absorption, installation ease, durability, and cost vary among these options. Choosing the right insulation depends on building needs, budget, environmental impact, and performance goals. Consulting professionals can help select the best material for a project.

Types of Insulated Wall

The various types of insulation materials used in walls as part of passive cooling strategies are as follows:

- **Cellulose:** Made from 75–85% recycled newsprint, it has low embodied energy, emits few VOCs, and provides good acoustic and thermal insulation. Suitable for wall, ceiling, and floor cavities (Emery, 2021).
- **Cementitious:** Cement-based insulation (using magnesium oxide and ceramic talc) is VOC-free, fireproof, mold- and pest-resistant, with good thermal resistance and durability. (Homedit, 2024).
- **Fiberglass:** Made from recycled glass, it's used in roofs, walls, and ceilings. Provides thermal and sound insulation via glass wool, formed by spinning molten glass into fibers. (Designing Buildings Ltd, 2024).
- **PUF Board:** A rigid foam with high strength and flexibility at low temperatures. Non-toxic, VOC-free, and resistant to fire, mold, pests, and chemicals. Used in walls, roofs, and floors (Warm International, n.d.).
- **Polystyrene:** Lightweight foam insulation in EPS, XPS, and GPS forms, used for improving energy efficiency and thermal comfort.
- **Polyisocyanurate:** Rigid foam board with high thermal resistance, typically foil-faced. It's lightweight, moisture-resistant, and suitable for both new and retrofit projects (Buy Insulation Online, n.d.).
- **Mineral Wool:** Made from spun molten stone or silica, offering strong fire, thermal, and acoustic insulation. (Mineral Wool Insulation Manufacturers Association, 2024).

- **Phenolic Foam:** A rigid foam with superior fire resistance, minimal smoke, and good thermal/sound insulation. Made from phenolic resin and additives (W.T. Insulation, n.d.).

Design Considerations

The properties of all the insulation materials provided are as follows:

Table 9 Properties of Wall Materials

Parameter	Cellulose Foam	Cementitious Foam Board	PUF Board	Fiber Glass Board	Mineral Wool Board	Phenolic Foam Board	Polysocyanurate (PIR)	Polystyrene (EPS / XPS)
Specific Heat (J/kg·K)	2020	N/A	1215	840	N/A	1100	N/A	1100
Thermal Conductivity (W/m·K)	0.038–0.040	0.08–0.30	≤ 0.020 @ 23 °C	0.030	0.032–0.044	0.017	0.023–0.026	EPS = 0.025–0.032 / XPS = 0.028–0.035
Density (kg/m³)	27–65	300–1200	40 ± 2	20	100 ± 10 %	35	30–40	1050
Water Absorption (% by weight)	3–8 (Medium)	≤ 3 (Low)	≤ 3 (Low)	3–8 (Medium)	3–10 (Medium)	≤ 3 (Low)	≤ 3 (Low)	EPS ≤ 3 (Low) / XPS ≤ 2 (Low)
Temperature Range (°C)	up to 120 (Medium)	up to 150 (Med–High)	up to 140 (High)	up to 130 (Med–High)	up to 350 (High)	up to 150 (High)	up to 150 (High)	EPS up to 80 (Low–Med) / XPS up to 120 (Med–High)
Compressive Strength (kPa)	100–150 (Medium)	200–400 (High)	150–300 (Med–High)	≤ 100 (Low)	150–250 (Medium)	200–300 (Med–High)	200–400 (High)	EPS 70–200 (Low–Med) / XPS 250–500 (High)
R-Value (per inch)	22.18–27.68	N/A	45.06	15.25–26.34	20.80–22.88	46.45–52.01	48.55–55.47	EPS = 4 / XPS = 5

Strategy Application (Construction)

Insulated wall materials (mineral wool, PUF, fiberglass, phenolic foam, polyisocyanurate, and polystyrene boards) share general construction guidelines but differ based on material specifics. For insulated roofs, follow manufacturer-specific installation guidelines.

- **Surface Preparation:** Clean, repair, and smooth the surface; prime if needed.
- **Apply Adhesive:** Use adhesive; follow manufacturer's application and drying guidelines.
- **Attach Insulation Board:** Align and press the board onto the adhesive for full contact.
- **Secure Insulation Board:** Fasten with nails, or clips; ensure the board is flat and level.
- **Seal Gaps and Joints:** Use caulk or foam sealant to fill gaps and prevent air leakage.
- **Verify Coverage:** Ensure even insulation coverage without gaps.

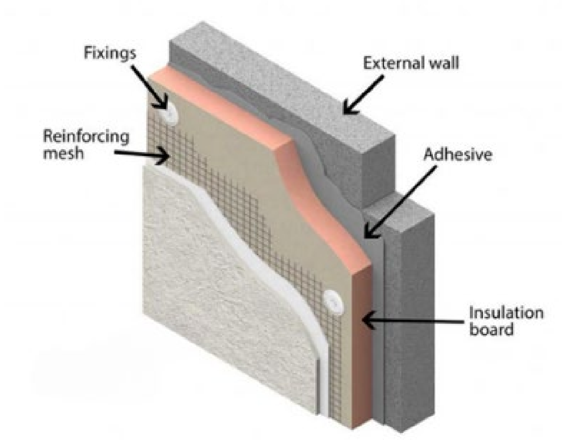


Figure 73 Cross-Section of an External Wall with Insulation

- **Preparation:** Clean the area and install mesh on open sides if needed.
- **Drilling:** Create access holes for hose entry.
- **Application:** Blow cellulose insulation into cavities using a specialized machine.
- **Finishing:** Patch holes and paint as needed.
- **Post-Installation Checks:** Ensure insulation fills all cavities without gaps and perform regular checks for long-term performance (Ardor Construction, n.d.).

Figure 74 Cellulose Insulation Installation

- **Preparation:** Ensure surfaces are dry, clean, and structurally sound; repair concrete or prime steel with a cement-based primer.
- **Installation:** Drill small holes between bricks, fill with cementitious foam insulation, power wash, and patch holes with matching mortar.

Figure 75: Exterior wall insulation

Interior Wall Installation: Drill dustless holes between studs and inject cementitious foam insulation (Brand Insulation Inc., 2024).

Figure 76: Interior wall insulation

Setting: Allow foam to set for about one hour. Remove excess foam and smooth the surface.

Drying: Let foam dry over several days.

Post-Installation Checks: Ensure foam fills all cavities without voids for optimal insulation.

Maintenance at Operational Stage

To maintain an insulated wall's effectiveness, follow the manufacturer's guidelines. Avoid surface impacts, minimize render penetration, and protect walls from creeping plants unless supported by a trellis. Inspect weathertightness annually, and check guttering and rainwater pipes for blockages or leaks. Address any issues promptly and use qualified tradesmen for repairs. Clean gently with water or mild detergent if necessary. (Urbane Eco Ltd, 2017).

The case study on each of the can be accessed through the following link:

Cellulose insulation - Potential Pitfalls of Green Building Material A Case Study of Cellulose Insulation.

Cementitious foam - Sustainable Wall Solutions Using Foam Concrete and Hemp Composites.
Polyisocyanurate- Building Technologies Office Peer Review.

Fibreglass - Insulation for Non-Combustible Walls.

Mineral Wool - The Big Build.

Polystyrene - Fenland Council, Cambridgeshire, Delivering on the Social Housing Decarbonisation Fund.

Phenolic Foam - Internal insulation of solid masonry walls.

5.1.1.2 Green Wall

Green walls, or living walls, provide multiple benefits including air purification, increased biodiversity, reduced urban heat island effect, stormwater mitigation, passive thermal performance, noise reduction, and protection against weather and temperature fluctuations. In hot-arid climates such as New Cairo, Egypt, green wall systems have been shown to reduce annual building energy consumption by up to 75% while maintaining acceptable thermal comfort levels (Ramadhan, 2023).

Description

Figure 77: Green wall

Green walls are an effective, sustainable passive design strategy that uses vegetation to insulate buildings, lower interior temperatures, enhance thermal comfort, and reduce energy consumption for heating and cooling (Aliwi, 2022). Green walls are nature-based solutions (NbS) that integrate vegetation into building façades to enhance thermal and environmental performance. In hot-humid climates such as Cambodia's, they help lower surface temperatures through evapotranspiration and shading, improving indoor comfort and reducing cooling energy demand.

Studies in tropical Asian cities show that green walls can reduce exterior wall temperatures by 8–12 °C and indoor cooling loads by up to 25 %, depending on plant density and wall type. Beyond thermal benefits, they also support stormwater retention, air-quality improvement, and urban heat-island mitigation, making them a quantifiable and multifunctional passive cooling strategy.

Types of Green Walls

There are two types of green walls: climbing facades and modular living walls, each offering unique benefits tailored to design and environmental needs.

Climbing facades: Create green walls by using structures like steel cables, trellises, or wire mesh to support climbing plants, directing their growth and creating a green cover.	 *Figure 78: Climbing facade*

Modular Living Walls: Modular living walls provide flexible aesthetic and functional options, available as hydroponic systems with specialized mediums or soil-based systems using typical gardening substrates.	
Hydroponics (soil-less): Hydroponic systems grow plants without soil, using panels with a growing medium mounted vertically. Plants spread out to cover the structure, relying on atmospheric minerals, carbon dioxide, and water.	 *Figure 79: Hydroponic green wall*
Substrate/Soil-Based: Substrate/soil-based systems use pre-molded troughs or containers on walls, supported by soil-based substrates with free-draining and lightweight materials. While they simplify irrigation and reduce costs, their weight is a drawback, though newer lightweight materials are emerging (Urban Greening, n.d.).	 *Figure 80: Substrate/soil based green wall*

The case studies can be accessed through the following links:

1. [Green Wall Systems]
2. [Living wall UK]
3. [Green Walls in High-Rise Buildings]

Design Considerations

- **Light and Shade:** Position the green wall to maximize natural light, considering intensity, reflection, and shading from nearby structures, as these affect plant growth.
- **Temperature:** Choose plants suited to local climate, as wall layers experience more heat.
- **Rainfall:** Evaluate local rainfall to determine irrigation needs; alternative water sources may be required in low-rainfall areas.
- **Wind:** Account for wind effects, particularly from nearby tall structures, which can impact wall maintenance and plant health (Green Walls, 2020) (MMA Architectural Systems, n.d.).
- **Plant Selection:** Select plants based on wall placement, light conditions, and desired function. Consider indoor lighting needs and plant tolerance to sun or shade (Urban Greening, n.d.).
- **Irrigation:** Use appropriate irrigation systems; simpler setups for climbing walls and automated systems for modular. Typical usage is 1-3 liters per square meter per day (Urban Greening, n.d.).
- **Vegetation:** Choose plants like ferns, herbs, and succulents based on temperature, climate, and sunlight exposure to enhance biodiversity and air quality (State of Victoria, Department of Environment and Primary Industries, 2014).

Application Strategy (Construction)

Consult manufacturer guidelines and experienced architects for green wall construction, as procedures vary by wall type.

Consider the available space, lighting, and proximity to water sources for a wall garden. Choose the wall's size and design, select plants based on light requirements and maintenance, such as ferns or succulents, and decide whether to hire a professional, use a pre-made modular system, or create a DIY setup with fabric pockets.

Construct a sturdy frame from metal, PVC, or wood to support plants and soil. Line with waterproof material, like weed cloth, and use felt or prefabricated planters with proper drainage. Install an automatic drip irrigation system for efficient watering or opt for manual watering. Use a lightweight, well-draining soil mix and plant species based on their light and moisture needs (HGTV, 2024).

The installation video can be viewed at the following links

Installation Part 1

Installation Part 2

Installation Part 3

Installation Part 4

Maintenance at Operational Stage

Maintenance procedures may vary by green wall system. Refer to the manufacturer's guidelines for precise instructions.

Table 10: Maintenance

Maintenance Objective	Task
Maintain plant growth	Remove plant waste and inspect for pests or disease; treat as needed. Adjust irrigation and nutrition based on seasonal needs. Inspect plants after severe weather events.
Maintain climbing plants	Perform annually or biannually to maintain density and cover. Remove growth from windows and drains. Renovate for renewed habit and growth.
Maintain substrate	Add growing substrate as needed to counteract loss from wind, rain, or animals. Check depth to avoid exceeding weight limits.
Monitor plant nutrition	Log fertilizer additions and record pH and electrical conductivity values before and after application.
Maintain drainage	Ensure roof drains are clear and functioning; remove debris from inspection chambers, check plumbing hardware, and inspect filter sheets and deeper layers if needed.
Maintain waterproofing	Inspect flashings at waterproofing terminations. Check wall fabric for damage from water, fertilizer, or plants. Conduct leak detection on green roofs if possible.
Maintain other hardscapes	Clean or oil decking/furniture and inspect green wall/facade supports for loose fittings.

5.1.1.3 Cool Wall

Cool walls reduce heat gain and cooling loads by reflecting sunlight, saving energy and mitigating the urban heat island effect. A UC Davis study found potential annual savings of up to $45,000 in energy costs, 3.1 TJ of energy, and 86 tCO_2e in emissions from cool paint on 49 buildings. For details, see the case study "Targeting buildings for energy-saving cool-wall retrofits: A case study at the University of California".

Description

In hot climates, reflective walls, or "cool" walls, use high emittance and albedo to reflect sunlight and emit thermal infrared radiation, like cool roofs (Heat Island Group - Berkley Lab, 2023).

Figure 81: Bright white color coated building

Types of Cool Wall

The types of cool wall coatings listed are as follows:

- **Acrylic Coating:** Water-based, low-VOC, good adhesion, and durability; protects against moisture and stains.
- **Epoxy Coating:** Two-component, highly resistant to physical and chemical abrasion; ideal for commercial use.
- **Urethane Coating:** Solvent-based, resists chemicals and abrasion, and UV rays; suitable for outdoor use.
- **Polyurea Coating:** Two-component, elastic, resists chemicals and water; flexible for commercial applications.
- **Fluoropolymer Coating:** Solvent-based, excellent UV protection, adhesion, durability, and corrosion resistance; ideal for outdoor walls (Valcourt Group, 2022).

The installation video can be viewed at the following link:

Installation Video

Design Considerations

Design Considerations: Cool walls are effective for sunlight-exposed structures; their minimal drawbacks are manageable.

Increased Reflectivity: Cool walls reflect more sunlight, potentially affecting nearby buildings' heat transfer and cooling loads, depending on reflectance, proximity, and sky view.

Thermal Comfort for Pedestrians: Cool walls impact pedestrian comfort by altering solar and thermal infrared radiation. Increased wall reflectance has minimal impact on comfort (Rosado & Levinson, 2019).

Color-Albedo: Wall color affects reflectivity, with varying albedo values for conventional to high cool colors impacting surface reflectivity.

Design cool walls for structures exposed to sunlight. Their minor drawbacks are typically easy to address.

Table 11: Estimated color-albedo relationship for wall products: Broad guidelines based on solar near-infrared penetration

Color	**Albedo with conventional Pigmentation**	**Albedo with intermediate performance "cool color" pigmentation[b]**	**Albedo with high performance "cool color" pigmentation[c]**
Black	0.05	0.28	0.40
Dark	0.10 to 0.20	0.30 to 0.35	0.43 to 0.48
Dark-to-medium	0.20 to 0.40	0.35 to 0.45	0.48 to 0.58
Medium-to-light	0.40 to 0.50	0.45 to 0.50	0.58 to 0.63
Light (off white or dull white)	0.60	NA[d]	0.68
Bright white	0.80	NA	NA

Notes: Estimated color-albedo values assume half of solar light enters the near-infrared region. Values are approximate and should not be quoted beyond one decimal place.

a. Assumes broadband reflectance N in the near-infrared spectrum (0.7 – 2.5 µm) is equal to broadband reflectance V in the visible spectrum (0.4 – 0.7 µm), b. Assumes $N = 0.50$, c. Assumes $N = 0.80$ for bright-white and $N = 0.75$ for all other colors, d. Not applicable (NA) because the near-infrared reflectance in the conventional formulation exceeds that in the cool color formulation.

Application Strategy (Construction)

Follow manufacturer's guidelines and consult professionals for installing cool walls.

Inspection: Check for stucco damage, wood rot, peeling, chipping, and step cracking.,
Trenching: Excavate around the foundation to prevent deterioration; apply primer and cool wall below the surface to limit moisture.
Pressure Washing: Remove debris to prepare the surface, revealing repair needs and cracks.
Repair and Patch: Seal joints and repair deteriorated areas, focusing on water entry points.
Cover and Protective Cover: Shield openings and other surfaces not intended for coating.
Primer Application: Apply primer to protect wood, stucco, and masonry from water damage.
Inspection: Inspect the entire house after primer application to ensure uniform preparedness.
Finish: Apply a thick coat using heavy-duty equipment for optimal adhesion.
Clean and Inspect: Remove masking and inspect surfaces for correct thickness and uniform appearance. (SunBelt Home Solutions, 2023).

Figure 82: Peeling of exterior wall

Figure 83: Application of primer on the wall surface

Figure 84: Spraying of final coat

The installation video can be viewed at the following links:
Installation Link 1
Installation Link 2

Maintenance at Operational Stage

- Physical Inspections: Inspect every 6-12 months for damage to wall coating. Check for holes, cuts, abrasions, and sealant integrity.
- Wall Coating System Cleaning: Clean every 2-4 years based on conditions. Use water, bleach, detergent, and trisodium phosphate at 1,500 PSI. Rinse thoroughly with water.
- Wall Coating Fixes: Clean and prime damaged areas. Reapply two coats of coating.
- Structural Fixes: Hire a structural engineer for comprehensive repairs. Follow their recommendations and recoating guidelines (Neogard Wall Coating Systems, 2023).

5.1.2 Roof

5.1.2.1 Insulated Roof

All buildings benefit from passive cooling techniques for roofs, enhancing energy efficiency and thermal performance in hot climates. Materials such as glass wool, PUF spray, PUF board, rockwool, and XPS reduce heat absorption and maintain comfortable interior temperatures.

Figure 85: Roof insulation types and materials

Description

Effective roof insulation enhances energy efficiency and comfort. Materials like glass wool, PUF spray, rockwool, and XPS offer varied thermal and sound insulation. Choice depends on location, climate, budget, and needs. Proper insulation regulates temperature, reduces energy use, and minimizes noise.

Types of Insulated Roof

The commonly used roof insulation materials include:

Glass Wool: Glass wool, produced from glass fibers bound together, features numerous tiny air pockets for excellent thermal insulation. It is commonly used in boards and rolls for insulation (Hossain, n.d.).

Polyurethane Foam (PUF) Board/Spray: Polyurethane is a thermoset foam insulation with low-conductivity gas. Closed-cell foam has high-density, sealed cells, expanding well into spaces. Open-cell foam has less dense cells filled with air, resulting in a spongy texture and lower R-value (U.S. Department of Energy, n.d.-b).

- **Rockwool:** Rockwool is made from melted volcanic rock minerals, used in buildings for heat, sound, and fire insulation. It is valued for its durability and versatile insulation applications (CelluBOR, n.d.).
- **XPS (Extruded Polystyrene):** Polystyrene is a translucent thermoplastic used in foam board, beadboard, and loose-fill insulation. With 95-98% air, it's effective for thermal insulation in structural panels and concrete forms (Thermal Engineering, n.d.).

Design Considerations

- **Moisture Content:** Insulation's thermal performance can drop by up to 55% with 20% moisture. Closed-cell PUF resists water absorption, while rockwool and glass wool suffer increased thermal conductivity with even 1% moisture (Stassi, 2018).
- **Energy Efficiency:** High R-value materials like PUF boards, glass wool, and rockwool improve energy efficiency (U.S. Department of Energy, n.d.-b)
- **Load-bearing Capacity:** Choose insulation with sufficient compressive strength to support expected loads without compression.
- **UV Exposure:** UV can degrade PUF and XPS. Use UV-resistant coatings or opt for more UV-resistant materials like glass wool.
- **Fire Resistance:** Fire-resistant materials like rockwool, rigid polyurethane insulation withstand high temperatures and slow fire spread (Myreal Energy Saving, 2025).
- **R-value:** Higher R-value indicates better insulation effectiveness against heat flow.
- **Durability:** Assess and ensure the durability of insulation materials annually.

Consider roofing material properties before installing an insulated roof. Assess the factors in below table for optimal thermal and energy efficiency.

Table 12: Properties of insulated roof materials

Parameter	Glass Wool	PUF Board	PUF Spray	Rock Wool	XPS Board
Specific Heat (J/kg·K)	840	1400 – 1500	1470	1030	1712
Thermal Conductivity (W/m·K)	0.030	0.022 – 0.035	0.026 – 0.042	0.039	0.026 – 0.035
Density (kg/m³)	20	30 – 45	6 – 55	40 – 150	35 – 45
Water Absorption (% by weight)	≤ 3 % (**Low**)	≤ 3 % (**Low**)	≤ 3 % (**Low**)	> 10 % (**High**)	≤ 3 % (**Low**)
Temperature Range (°C)	up to 350 (**High**)	up to 140 (**High**)	up to 140 (**High**)	up to 350 (**High**)	up to 120 (**Medium–High**)
Compressive Strength (kPa)	100 – 150 (**Medium**)	200 – 300 (**High**)	200 – 300 (**High**)	200 – 400 (**High**)	70 – 150 (**Low–Med**)
R-Value (per inch)	2.9 – 3.8	3.8 – 6.3	3.8 – 6.3	3.0 – 4.0	5.5

Note: All values are presented in their respective units

Application Strategy (Construction)

Construction procedures for insulated roof materials differ among various materials; therefore, it is advisable to refer to the manufacturer's guidelines before installing the insulated roof material.

PUF Spray Insulation

Roof Preparation: Prepare the roof surface; mix components A and B using spray foam equipment.
Waterproof Foam Application: Spray closed-cell SPF in the middle of the roof; let it rise and cure; ensure a seamless barrier; trim edges; adjust thickness for drainage.
Protective Coat Application: Apply two layers of acrylic elastomeric coating, then a reflective Cool Roof coating. (Eric, 2024).

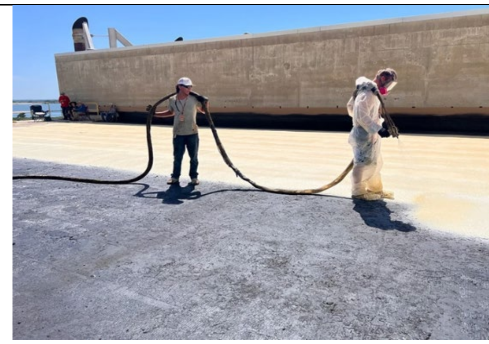


Figure 86: PUF sprayed on roof

Construction Procedure of Glass Wool, PUF Board, Rockwool and XPS

Surface Preparation: Ensure the roof is dry and clean; repair any damage. Remove old insulation if needed.
Install Insulation: Measure the roof; fill gaps between joists with insulation.
Install Vapor Barrier: Place above insulation to prevent moisture entry.
Install Roof Covering: Add a waterproof membrane or roofing tiles (Composite Roof Supplies, 2024).

Figure 87 Installation of Board Type Insulation

Maintenance at Post Construction Stage

To maximize an insulated roof's lifespan and performance, conduct annual inspections, especially after severe weather, and promptly address issues like debris buildup, discoloration, and small damages. Remove items from the roof, fix minor problems immediately, and repair punctures and leaks swiftly. Ensure careful maintenance to prevent puncturing the membrane.

The case study on "Energy Savings by PUF Board" can be accessed through the following link: construction of st. Paul school: a success story with pronto's puf panels - pronto panels

The case study on "Energy Savings by PUF Spray" can be accessed through the following link: Case Study: Poliuretan Spray S-403 HFO and Urespray P-500 (synthesia.com)

The case study on "Energy Savings by Glass Wool" can be accessed through the following link: Glasswool

The case study on "Energy Savings by Rockwool" can be accessed through the following link: Wayne State University Case Study (rockwool.com)

The case study on "Energy Savings by XPS" can be accessed through the following link: DuPont™ Larkin Case Study

5.1.2.2 Green Roofs

Green roofs are key in passive cooling, reducing heat infiltration, and improving energy efficiency across various structures. They combat theUHIE, enhance air quality, manage stormwater, and extend roof lifespan. A case study in Egypt's New Cairo City shows green roofs cut energy use by 12% and lower outdoor temperatures by 3°C (Goda et al, 2023)

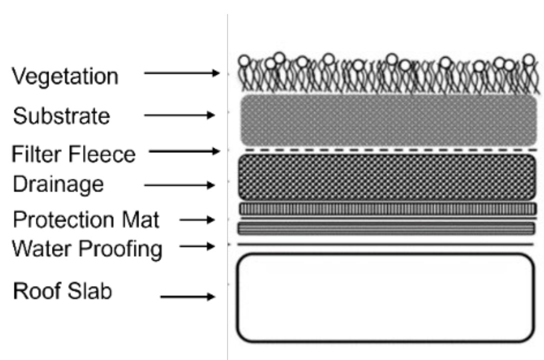
Figure 88: Green roof on building of World Bank Group Office, Accra, Ghana

Part-C of Cambodia's 2019 Green Infrastructure Guide highlights green roofs as a key feature for environmental improvement. These systems use vegetation to enhance ecosystems and public projects. Initial strategies for integrating green roofs into guidelines are presented. Despite early-stage research in ASEAN, their benefits are significant. For further details, please refer to the Green Infrastructure Guide 2019.

Description

Green rooftops are living systems on rooftops, including water-sealing layers, root barriers, drainage, growing mediums, and plants. They can be modular or installed individually. The commonly used green roof types include:

Extensive Green Roofs: An Extensive Green Roof (EGR) is a minimalist, lightweight system for functional roofs, consisting of a waterproof membrane, vegetation, and growing substrate. It includes additional layers like a protection mat and drainage layer. Single-layer systems suit roofs with at least a 2% slope. EGRs are low maintenance, typically requiring irrigation only during establishment or droughts. It offers low-



cost, low-maintenance green space for buildings.

The case study on "Energy Savings by Extensive Green Roof" can be accessed through the following link: *An Integrative Analysis of an Extensive Green Roof System*

Figure 89: Extensive green roof

Semi-Intensive Green Roofs: A semi-intensive green roof has deeper soil than extensive roofs, supporting a wider range of plants. It can be layered or installed in trays and requires moderate maintenance, including pruning and watering.

The case study on "Energy Savings by Semi Intensive Green Roof" can be accessed through the following link: Semi Intensive Green Roof

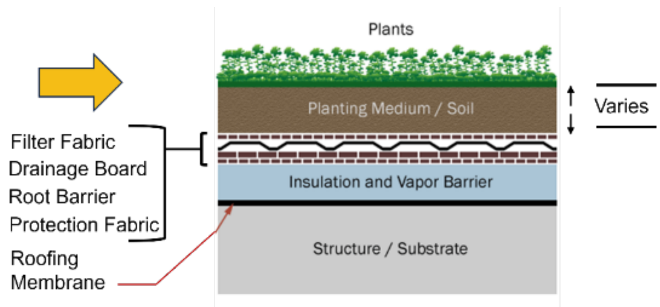


Figure 90: Layers of semi- intensive green roof

Intensive Green Roofs: Intensive green roofs, requiring more maintenance, support diverse plantings like shrubs and trees. They need deep soil and impact structural layout, making tray systems impractical. They are ideal for creating park-like environments but demand careful waterproofing and root barrier considerations.

The case study on "Energy Savings by Intensive Green Roof" can be accessed through the following link: Intensive Green Roof, Roofdrain, Education City, Qatar

Design Guide: Intensive Green Roof Design & Installation Manual

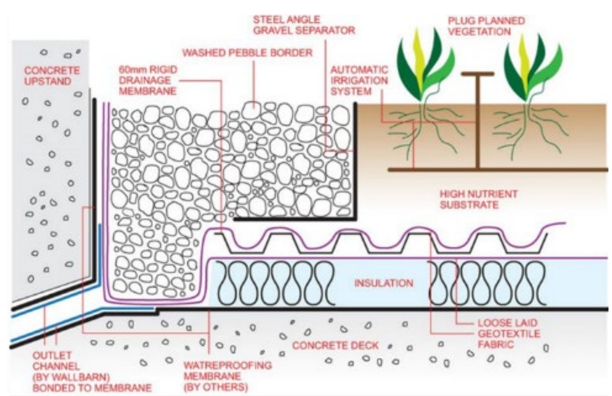


Figure 91: Layers of intensive system layers

Table 13: Three main contemporary green roof classifications

Characteristic	**Extensive**	**Semi-Intensive**	**Intensive**
Substrate Depth	40-100 mm	80-120 mm	150 mm and above.
Substrate Composition	Lightweight, low organic matter (0-20%)	Lightweight, low organic matter (10-20%)	Higher density, higher organic matter (20-40%)
Maintenance	Low (annual)	Medium (bi-annual with some vegetation clearance)	High (regular weeding and vegetation cutting required)
Weight Loading	Low (60–150 kg/m^2)	150 kg/m^2 - >300 kg/m^2	High (>300 kg/m^2)
Irrigation Requirement	No irrigation required	Irrigation is required	Irrigation required depending on species selection

Suitable Plant Variety	Mixture of Sedum species, some drought-tolerant perennials and grasses. Mat-forming species of Sedum, Sempervivum, moss, Sedum acre, S. rupestre, S. album, Delosperma Ferns (Polypodium vulgare, Asplenium trichomanes), Bidens alba, Tulbaghia violacea, Nephrolepis multiflora, Paspalum paniculatum, Euphorbia graminea, Cymbopogon ambiguous, Kalanchoes x houghtonii	Mixture of Sedum species, dry meadow species, drought-tolerant perennials, grasses and alpines. Dry habitat perennials, Ornamental grasses, Rudbeckia, Achillea, Potentilla, Armeria, Dianthus, Helictotrichon sempervirens, Stipa tenuissima, Bulbs (Muscari, Allium flavum, A. pulchellum)	Mixture of Sedum species, dry meadow species, drought-tolerant perennials, grasses, alpines, turf grass, sub shrubs, shrubs, edible plants, small trees. Alopecurus pratensis, Aurinia saxatilis (syn. Alyssum saxatile), Campanula rotundifolia, Chrysopsis mariana, Dianthus species, Gaillardia grandiflora, Lobelia cardinalis, Monarda punctata.

Note: The three main classifications are based on data sources in table 14 are: (Young,), (Fairfax County Public Works and Environmental Services, n.d.), (Green Roof Organisation, 2023)

Design Considerations

Effective green roof selection and installation require careful consideration of roof type, climate, water availability, thermal performance, surface reflectivity, and soil depth.

Roof Type: Choose based on roof type, soil depth, irrigation needs, and vegetation.

Table 14: Suitable green roof types

Roof Type	**Suitable Green Roof Type**
Flat Roof	Extensive, Semi-Intensive & Intensive
Sloped Roof	Extensive & Semi-Intensive

Climate: Choose green roof types based on climate, soil depth, and plant variety.

Extensive Green Roof: Effective in temperate climates; struggles in hot, tropical, and subtropical regions (Simmons, 2015).

Water Availability: Water capacity of the growing medium affects plant health and growth, measured as a percentage of weight or volume. Challenge on sloped roof for water retention

Thermal Performance: Green roofs improve thermal performance, cooling buildings more effectively where ceiling insulation is absent. They can reduce summer cooling demand by up to 48%, but benefits lessen with roof thickness over 10 cm and insulation over 5 cm (Young,) (Ahmad, 2015).

U-Value Limits: Affected by green roof type, substrate thickness, soil moisture, and insulation layers. U-values vary with soil moisture content.

Table 15: Green roof U-values based on the soil moisture content and type

Moisture Level	U-Value (W/(m².K) for Vegetated Roof	U-Value (W/m².K) for Vegetated Roof with Water Retention
0%	0.42	0.38
20%	0.46	0.41
80%	0.53	0.48

Green Roof Type	Typical Soil Depth	R-Value (m²·K/W)	U-Value (W/m²·K)
Extensive	40–100 mm	0.3 – 0.6	1.7 – 3.3
Semi-Intensive	80–120 mm	0.6 – 1.2	0.8 – 1.7
Intensive	≥150 mm	1.2 – 2.5	0.4 – 0.8

Green roofs' cooling effect is influenced by plant species, leaf textures, and albedo, with temperature reductions ranging from 0.5 K to 3.5 K and albedo increasing from 0.05 to 0.61 (Li & Yeung, 2014). Higher plant cover enhances albedo and reduces thermal loading. Soil depth is crucial, impacting insulation, sound absorption, and water filtering. Typically, soil mixes include compost, crushed bricks, and clay, affecting green roof performance (Grullón-Penkova, 2017).

Table 16: Range of soil depth – Min to Max for different types of green roof systems.

Type of GR System	Limit	Value (in mm)
Extensive	Min	40
	Max	100
Semi-Intensive	Min	80
	Max	120
Intensive	Min	150
	Max	>150

Performance Evaluation Methods

DesignBuilder software allows architects to simulate and analyze green roof performance by inputting data on building location, climate, roof materials, and plant species, enabling accurate long-term behavior replication. (Green Roof using DesignBuilder).

Application Strategy (Construction)

Constructing a green roof involves layering a waterproof membrane, root barrier, drainage system, and lightweight growing media, topped with selected plants. This approach ensures structural integrity, effective water management, and a thriving green area.

Structural Support: Use methods like FRP composites or post-tensioning to support green roof weight. Analyze existing structure for load capacity.

Waterproof Membrane: Provides leak protection. Types: single-ply, fluid-applied, bitumen/asphalt.

Root-proof Barrier: Protects waterproofing from roots and microbes. Typical PVC (0.8-1 mm thick).

Drainage Layer: Ensures effective water drainage. Common types: plastic modules, porous mats, granular materials.

Filter Membrane: Keeps drainage layer free from substrate particles. Made from semi-permeable polypropylene mat.

Substrate: Lightweight, well-draining mix of 80% mineral matter and 20% organic matter for plant growth.

Vegetation: Provides cooling, pollution absorption, and aesthetic value. Plant types vary by depth:

0–50 mm: Moss, sedum, 50-100 mm: Sedum, drought-tolerant grasses, perennials, 100-200 mm: Perennials, grasses, small shrubs, 200-500 mm: Medium shrubs, edible plants.

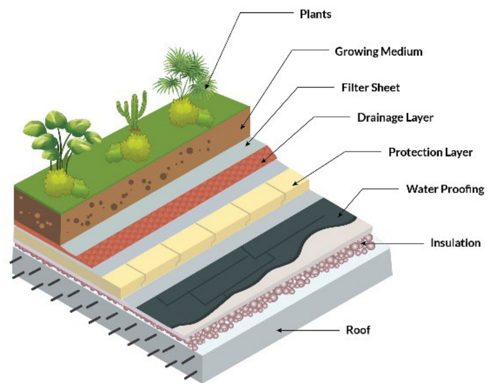


Figure 92 Layers in a Green Roof

Green Roof layer explanation can be viewed at the following link:
https://www.youtube.com/watch?v=tEouAa6J5Fk

The installation video can be viewed at the following link:
Installation Video

Maintenance at Operational Stage

Maintaining green roofs involves managing plants, general upkeep, fire safety, organic matter, irrigation, and fertilization to ensure sustainability and safety.

Table 17: Maintenance of green roofs

Parameter	**Extensive**	**Semi-Intensive**	**Intensive**
General Maintenance	Remove wind-blown seeds or cuttings to prevent rooting. Manage dominant species and habitat for ecology and aesthetics. Trim taller blooming plants to 150 mm in autumn or winter.		
Fire Hazards	Maintain green roofs for health and fire safety by controlling vegetation and upkeeping fire buffers.		
Dry organic Matter	Regularly remove leaves, trash, dead flowers, and seed heads to minimize dry organic matter risk.		
Irrigation	Large green roofs usually need no post-installation irrigation. Assess water storage capacity and plant needs.	Irrigate periodically per plant needs and roof climate.	Irrigate as needed based on plant specs and roof climate.

Fertilization	Requires minimal nutrients, are usually fertilized annually in spring with slow release fertilizer.	More frequent fertilization is necessary with a fertile growing medium and diverse planting.	
Plant Management	Remove unwanted plant types and leaves twice a year.	Remove unwanted plants from the green space twice a year.	Regularly upkeep grass and borders for aesthetics. Remove unwanted plants from green spaces twice yearly. Replace plants if over 5% are failing.

Data Reference: (The GRO Green Roof Code, 2023)

The maintenance video can be viewed at the following link:
Maintenance Video Link-1
Maintenance Video Link-2

Vendor information:
Website: https://www.ecooutdoor.com.my/
Contact Number: 855 17 273 185 Address: #32A Street 480, Phnom Penh
Products: 1. Green roof 2. Green wall 3. Architectural facades

5.1.2.3 Cool Roofs

Cool roofs reflect more sunlight and absorb less heat, enhancing thermal comfort and energy efficiency. They reduce air conditioning needs, mitigate urban heat islands, slow smog formation, lower peak electricity demand, cut emissions, and aid in global warming reduction. Research by Mohan Rawat and R. N. Singh shows cool roofs save 8.4% to 30.4% in energy and lower indoor temperatures by 2.0°C to 7.0°C across different Indian climates. For case study, please refer to: "Energy saving opportunities in buildings using cool roofs for India: A review"

Description

A cool roof reflects most sunlight and redirects absorbed radiation, keeping buildings cooler with lower surface temperatures. Its outer layer, with higher solar reflectance than standard roofs, minimizes heat absorption (Shakti Foundation, 2023).

The case study on "Energy Savings by Cool Roof" can be accessed through the following link: "Cool Reflective Roof Coating: Technology in Practice"

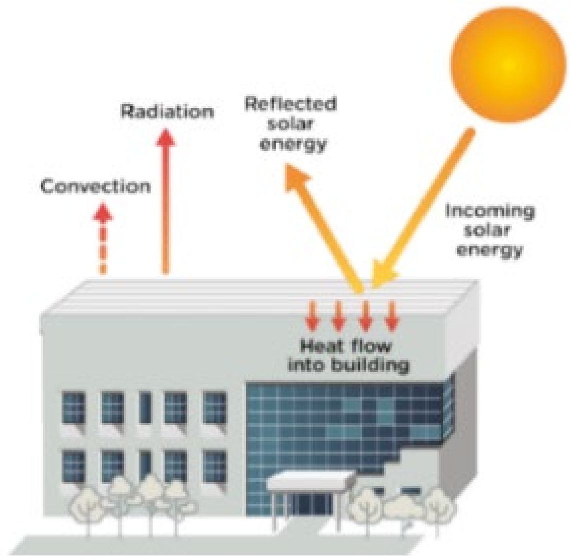


Figure 93: Illustration of a cool roof

Cool roof materials come in various types, with the following being among the most frequently used options:

Roof Coatings: Roof coatings are either factory-applied (e.g., glazes on tiles, metal coatings) or field-applied, which may require priming.

Broken China Mosaic Terracing: Use broken glossy tiles, ideally white, embedded in wet mortar for cool roofing. Fill joints with waterproofed cement mortar.

Modified Bitumen: Modified bitumen is asphalt altered with plastics and reinforced, then coated to improve solar reflectance and radiative qualities.

RCC Roofs: Used in low- and high-rise buildings; can be enhanced with elastomeric cool coatings or white glazed tiles.

Slate & Tile Roofs: Reflect sunlight; white concrete and clay tiles have ~70% reflectance; red tiles reflect 20–30%.

Metal Roofs: Often white, have a solar reflectance of about 65%. Unpainted metal should be coated white to boost emittance. These roofs can mimic tiles or fit specific curves, with factory-applied textures and colors, including dark cool hues with infrared-reflective pigments.

Cool-Colored Roofing: Uses infrared-reflecting pigments to keep dark roofs cool. They save more energy than standard dark roofs but less than white or light-colored roofs. (Shakti Foundation, 2023).

Figure 94: Types of cool roofs

Design Considerations

Solar Reflectance Changes: Roof reflectance declines over time due to aging and environmental factors, potentially increasing heat transfer. Initial losses can be up to 25% within three years.

Condensation: Condensation risks can be mitigated through climate-appropriate vapor barriers, ventilated roof cavities, and self-drying roof assemblies. Air sealing and moisture control strategies—such as limiting vapor diffusion, controlling indoor humidity, and selecting permeable insulation materials are essential to prevent interstitial condensation and maintain long-term roof performance (Allana, 2018).

Insulation Effects: Effective insulation and roof reflectance reduce heat transfer, with roof color impacting summer heat and insulation affecting winter heat (World Bank, 2023).

Potential Glare Problems: Glare Issues: Cool roofs may cause glare and discomfort from reflected light, especially in high-rise areas (Santamouris et al, 2022).

Software: DesignBuilder simulates cool roof performance using location, climate data, and materials.

The case study on "Energy Savings by Cool Roof" can be accessed through the following link: Energy Savings by Cool Roof - A case study of two buildings in Hyderabad

Application Strategy (Construction)

The application of the preferred material varies depending on the specific type of material chosen. The construction of a cool roof involves following a set of steps outlined below.

Roof Coating: Clean the roof's surface using water to eliminate any dust. Mix the paint thoroughly after adding the required amount of water. Apply the paint using a brush or roller. Allow three to four hours for the initial coat to dry. After the first coat, let it dry for a period of 48 hours.

Figure 95: Roof coating

The installation video can be viewed at the following link:
[Installation Video-1]

Bitumen: Clear the roof's surface of dust and other debris. Lower the bitumen sheet onto the roof's surface. Use hot asphalt or cold glue to secure the bitumen sheet using the torch-down technique. Apply a white coating to increase the roof's reflectivity.

Figure 96: Installation of modified bitumen

The installation video can be viewed at the following link:
[Installation Video-2]

Slate or Tile: Prepare and apply mortar to the roof, maintaining a 1:4 cement to sand ratio. Spread cement slurry over the mortar layer for bonding. Prior to placement on mortar, dampen the back of each tile with water. Clean the tiles using a wet sponge and allow 48 hours for drying.

Figure 97: Installation of slate

The installation video can be viewed at the following link

[Installation Video-3]

The installation video can be viewed at the following link:

[Installation Video-4]

Metal Roofing: Clear the roof's surface of dust and other debris. Secure the metal sheet to the roof using mechanical fasteners. Enhance the reflectivity of the metal sheet by painting it in a cool shade (Rajasekar et al, 2014).

Figure 98: Installation of metal cool roof

The installation video can be viewed at the following link:

[Installation Video-5]

Broken China Mosaic Terracing: Clean and dry the roof surface. Mix sand and cement. Insert mosaic fragments into the mortar. Adjust pieces for a uniform level. Use white cement slurry to fill gaps. (Shakti Foundation, 2023).

The installation video can be viewed at the following link:

Installation Video-6

Figure 99: Installation of broken China mosaic

Maintenance at Operational Stage

Patching and Sealing: Fix punctures, cracks, or holes to prevent water damage.

Flashing Repair: Replace damaged flashing around roof penetrations for a watertight seal.

Leaks and Moisture Intrusion: Repair leaks and moisture issues to prevent damage and mold.

Shingle or Membrane Replacement: Replace damaged shingles or membrane sections to restore integrity.

Cleaning Drains and Gutters: Remove debris to ensure proper drainage and prevent accumulation.

Repairing Equipment Supports: Secure rooftop equipment supports and installations.

Coating and Sealant Application: Apply protective coatings or sealants for enhanced durability.

Skylight Maintenance: Repair or replace skylight seals and flashing to prevent leaks. (RJ Evans Flat Roofing Limited, 2023).

Maintenance video guide : https://cdn.jwplayer.com/previews/UmQqGieI

Vendor information:
Website: https://kh80574-cool-house-trading.contact.page/
Contact Number: 076 2222 187 *Address*: No 80C Street 310 corner St 217
Email: sccg.cambodia@gmail.com

5.1.3 Fenestration

Fenestration involves designing windows, doors, and openings in a building. It affects solar heat gain, energy efficiency, and indoor comfort. Proper design and materials optimize natural light, minimize heat gain in tropical climates, and enhance ventilation, reducing reliance on cooling systems.

Glazing - Glass or transparent materials used in windows, doors, and skylights.

- **Types:** Single-pane, double-pane, low-e coatings, laminated glass.
- **Parameters:**
  - U-value: Lower values indicate better insulation.
  - SHGC: Lower values reduce solar heat gain.
  - VLT: Higher values increase natural light.

Frames: Support glazing, insulate thermally, provide security, ensure water and air tightness, and enhance aesthetics. Available in various material types based on performance and requirements.

Design Methodology for Fenestration in Buildings

Incorporate weep holes for drainage to extend insulating glass lifespan and slope sill flashings outward with wet glazing seals for better water resistance. Adhere to safety standards with safety glazing for hazardous areas and protect laminated glass edges from water to prevent delamination. Ensure framing supports glass properly and allows for tolerances, use anti-walk pads at jambs to prevent movement, and design frames with substantial return legs for proper sealant bonding.

Thermal Performance Evaluation

Table 18: Glazing values

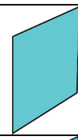
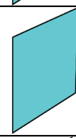
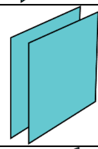
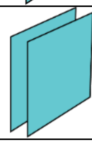
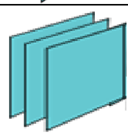
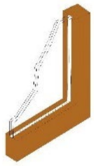
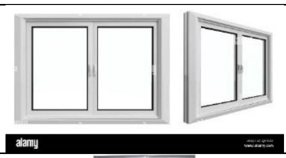
Glass Type	Image	U-Value	SHGC
Single glazing		5.6 W/(m^2.K)	0.9
Single glazing with low-e coating		5.6 W/(m^2.K)	0.75 to 0.61
Double Glazing		1.8 W/(m^2.K)	0.8 to 0.7
Double High-Performance Glazing (Low-e coating)		1.5 W/(m^2.K)	0.6 to 0.25
Triple glazing		0.5 to 0.8 W/(m^2.K)	0.6 to 0.1

Table 19: Frame values

Frame Type	Image	U-Value
Wooden frame		1.2 to2.4 W/(m^2.K)
Unplasticized Poly Vinyl Chloride (UPVC) frame		1.2 to 1.6 W/(m^2.K)
Aluminum frame		6.0 to 7.0 W/(m^2.K)

Selection of Glazing

Select glazing based on local climate, building orientation, and required SHGC and U-value. opt for double or triple-pane units with low-e coatings to enhance energy efficiency. Consider VLT, UV protection, sound transmission, and compliance with building codes and safety standards. Evaluate life-cycle costs to balance performance, aesthetics, and budget.

Application Strategy (Construction)

Preparation: Set up the work area with tools, materials, and safety gear.
Measurement and Planning: Measure window openings accurately and plan the installation considering access and conditions.
Removal: Carefully take out old windows without damaging surrounding structures.
Installation of Frames: Install frames level and square, following guidelines and codes.
Installation of Glass: Place glass panels, apply sealant, and ensure they are properly seated.
Sealing and Insulation: Add sealant or insulation around the frame to prevent leaks and improve efficiency.
Testing and Adjustment: Test windows for proper operation and adjust as needed.

Maintenance at Construction Stage

Inspect glass regularly for damage. Use protective films during construction. Train personnel in safe cleaning techniques. Provide soft cloths, squeegees, and mild solutions. Remove debris immediately to prevent scratches. Clean with water and soap; avoid harsh chemicals. Promptly remove concrete or mortar slurry. Check surfaces for damage after cleaning (*Glass Cleaning and Maintenance Recommendations*).

Maintenance at Operational Stage

Clean windows with a commercial solution or mild soap and water using a soft cloth or sponge. Rinse thoroughly and dry with a clean cloth or squeegee; avoid metal tools. Disinfect with 70% isopropyl alcohol using a clean cloth; ensure no pooling. Inspect periodically for leaks or damage; maintain sealants and lubricate hardware. Address any damage or issues promptly to prevent further deterioration (*Glass Cleaning and Maintenance Recommendations*).

5.2 Shading

The best way to keep a building cool is through shading, which blocks sunlight and reduces heat absorption, saving 10-40% on cooling. Methods include building recesses, external blinds, louvres, orientation, vegetation, and reflective roofing. In Cambodia's climate, year-round shading is beneficial, but ventilation must be maintained (Kamal, 2011).

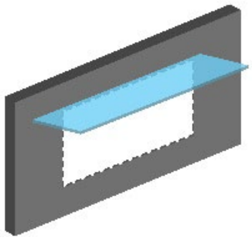
5.2.1 External Shading

Shading reduces solar heat absorption in buildings, with a focus on windows. External shading is more effective than internal shading and includes Static shading devices, Movable shading devices

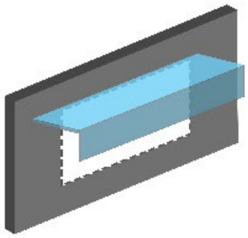
5.2.1.1 Static Shading

Static shading devices are fixed exterior elements that reduce solar heat gain and glare.

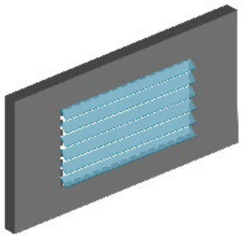
Overhang Horizontal Panel or Awning: Overhangs or awnings above windows block direct sunlight, reduce solar heat gain, and improve energy efficiency while allowing natural light.(Recommended for north and south-facing façades to block high-angle solar radiation during midday periods in tropical climates.)



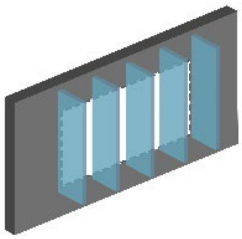
Overhang Horizontal Louvres: Overhang louvres are exterior shading devices with slanted slats that block direct sunlight, reducing heat gain while allowing light and airflow.



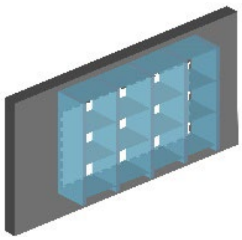
Overhang Vertical Panel: Overhang vertical panels block direct sunlight and reduce solar heat gain, improving energy efficiency. Ideal for all orientations, they enhance glass insulation and act as windbreaks for east and west exposures.



Vertical Fin: Vertical fins block direct sunlight, improve energy efficiency, and act as windbreaks, especially for east and west exposures.



Egg-crate: Egg-crate shading systems, oriented east and west, use vertical and horizontal elements to reduce solar glare and heat gain, enhancing comfort in hot climates. Ideal for walls, they are effective in high-sun areas



Design Methodology

For external shading devices, consider building orientation, solar exposure, and shading effectiveness. Use sun path and radiation analysis for optimal design. Materials should balance durability, cost, and code compliance. Iterative design, including simulations and prototypes, refines effectiveness in reducing solar heat gain while maximizing daylight and visual comfort.

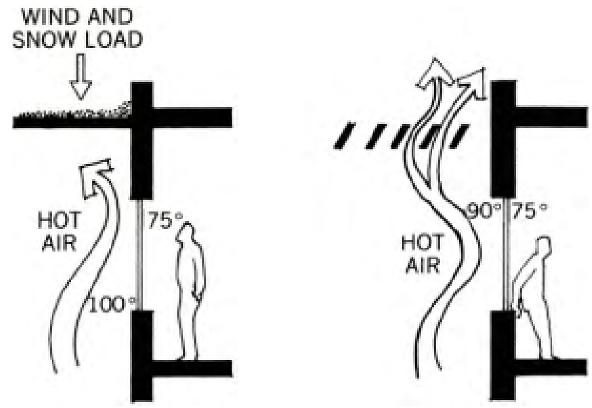


Figure 100: Overhangs

Figure 101 Overhangs

Overhang Horizontal Panel or Awning: Design with a 2-3 feet projection and a 45–60-degree angle for optimal shading. Ideal for east and west windows, and south facades. Effective for blocking high summer sun while permitting winter sunlight. Suitable for southeast, southwest, east, and west windows (Atzeri et al, 2013).

Overhang Horizontal Louvres: Position horizontally to reduce structural loads, allow airflow, and minimize hot air collection. For effective shading on south facades, calculate width based on sun's path. Consider durability and aesthetics in material choice (Atzeri et al, 2013).

Overhang Vertical Panel: Used for east and west windows to block direct sunlight and reduce heat gain while allowing natural light (Atzeri et al, 2013). Adjust orientation and dimensions for precise shading control (Iqbal et al, 2023).

Vertical Fin: Effective for east and west windows, and optionally southeast and southwest. Control sun penetration with vertical fins based on sun angles, balancing shading efficiency and view. Prioritize durable, weather-resistant materials.

Egg-Crate: Combines horizontal louvres and vertical fins for east and west windows, and optionally southeast and southwest. Provides efficient shading but can obstruct views. Modern versions are metal or masonry; adjust dimensions for optimal performance (Atzeri et al, 2013).

Evaluation of the Thermal Performance

- **Sun Control:** Proper shading can cut cooling needs by 5-15% and improve natural lighting (Sciences, 2024).
- **Horizontal Panels:** Can reduce thermal gain by up to 38.7% in summer, applicable to various building components (Evangelisti & Guattari, 2020).
- **Egg-Crate System:** Can lower solar heat gain by up to 80% through complete shading of glazed areas (Knaack et al, 2018).

Application Strategy

Assess building orientation, location, and surroundings for solar exposure and shading needs. Create initial design with shading device size, shape, materials, and integration in mind. Analyze sun angles, sunlight paths, and shading effectiveness throughout the day and year. Choose durable, weather-resistant, and thermally suitable materials for awnings. Determine optimal dimensions based on projection, angle, and louvre or fin size. Ensure walls or fenestration are clean and level. Verify the building can support shading device weight. Attach brackets or beams to support structure. Secure panels to the frame, ensuring alignment and anchoring. Seal edges with weatherproofing sealant to prevent water infiltration (USA, Building America Solution Center, 2024).

Maintenance Construction Stage

- **Construction Stage:** Cover panels or use scaffolding to prevent damage during construction. Regularly check for damage or misalignment and address issues promptly.
- **Operational Stage:** Regularly check for cracks, chips, warping, and loose hardware. Fix issues promptly. Examine sealant and flashing; repair or replace damaged materials to prevent water infiltration. Trim trees and shrubs obstructing panels to ensure effective shading and airflow. Tighten loose fasteners and replace damaged or corroded mounting hardware. Restore appearance and protection if paint or finish fades.

5.2.1.2 Movable Shading

For shading facades at high sun angles, use fixed components like chajjas and vertical fins. In sun-rich areas like Cambodia, dynamic shading is essential for eastern and western facades due to high diffused radiation. External movable shading systems (EMSyS), such as shutters and roller blinds, can reduce solar gain by up to 80% compared to fixed shading. (BEE, 2021).

Figure 102: Façade vertical folding shading system

Design Methodology

Optimize for reducing solar heat gain and enhancing daylight. Design considering building shape and window placement to control solar heat gain. Choose durable materials and consider maintenance needs for movable parts. Automated systems are typically more efficient than manual controls. Balance solar heat gain reduction with adequate natural light for occupant comfort (National Institute of Building Sciences, 2024), (Better Buildings Partnership, 2024), (Wulfinghoff, 1999), (Heidari et al, 2021).

Evaluation of the Thermal Performance

Select shading devices with suitable dimensions and shapes for optimal coverage (Atzeri et al, 2013). Position devices based on local sun angle and building orientation (Iqbal et al, 2023).Use materials with low thermal conductivity to reduce heat absorption (Heidari et al, 2021). Evaluate manual and automatic controls for efficiency. Consider maintenance costs and lifespan in design (Wulfinghoff, 1999). Use simulations and measurements to validate design (Yoon & Bae, 2020).

Application Strategy

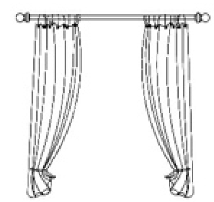
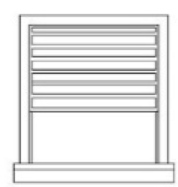
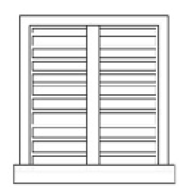
Analyze sun azimuth and altitude during cooling season. Assess sun impact on facades by season and time. Select shading devices like awnings or motorized shades based on effectiveness and aesthetics. Ensure shading strategies suit local weather and latitude. Integrate shading devices with building aesthetics. Measure shading performance with metrics like shading coefficient (SC) and projection factor (PF). Combine shading with other sustainable elements like BIPV systems (Whole Building Design Guide, 2024). Use simulations to predict indoor lighting levels with different shading scenarios (Gugliermetti & Bisegna, 2006).

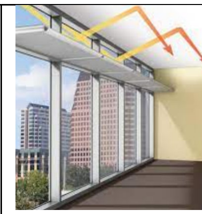
Maintenance at Operational Stage

Regularly check for wear, damage, or malfunction. Keep devices free from dirt and debris. Apply lubricant to moving parts. Adjust for optimal performance and seasonal changes. Address issues promptly to prevent further damage. Hire experts for thorough upkeep.

5.2.2 Internal Shading

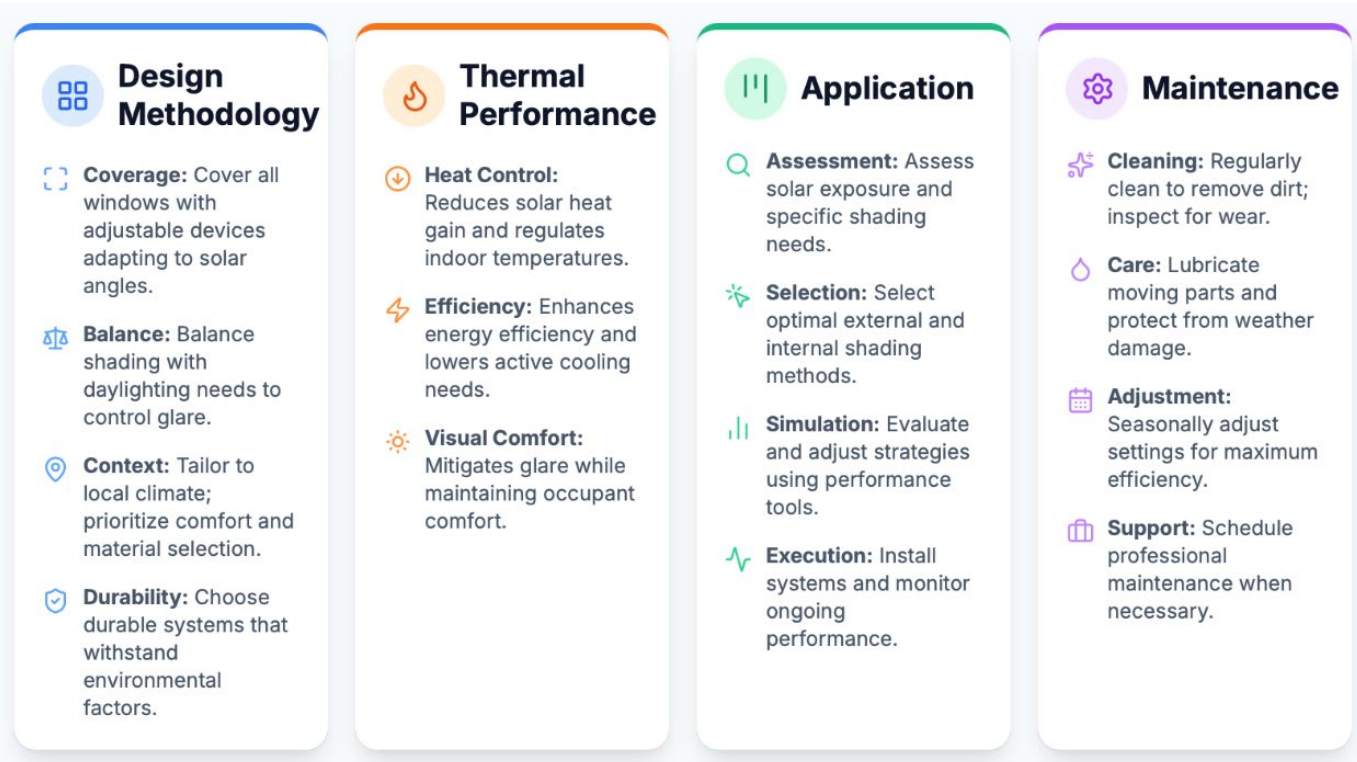
Interior shading devices like blinds, curtains, and louvres block or filter sunlight, reduce glare, and provide privacy. They offer cost-effective, adjustable light control but may trap heat indoors and can't block the sun while maintaining views like external shading. Ideal for use when the sun outflanks external shading or during exceptionally hot days.

Curtain: It is the most used shading device, often found in residential buildings due to its affordability and availability in various varieties, colors, and texture. Curtains also serve as decorative items.	
Roller Shades: Roller shades are made of stiffened polyester, mounted on an aluminum tube, and operated with a chain or spring. They come in block-out, sunscreen, and translucent options.	
Venetian Blinds: Venetian blinds have slats made of metal, plastic, wood, or bamboo, which can rotate up to 180 degrees. Slat widths range from 16 to 120mm, with 25mm being the most common.	

Light Shelf: A light shelf reflects natural light deeper into a room while shading direct sunlight, enhancing daylighting and reducing glare.	
Insulated glass with integrated blinds, also known as integral blinds, features blinds sealed within the airspace of an insulated glass unit (IGU). This design provides a dust-free, low-maintenance, and aesthetically pleasing solution for light and privacy control in windows and doors.	

5.2.3 Whole Building Shading

Whole building shading applies shading solutions to all windows and openings to minimize solar heat gain, reduce glare, and enhance energy efficiency, improving comfort and reducing cooling needs.



5.3 Ventilation

5.3.1 Stack Ventilation

The stack effect drives passive air movement by rising warm air creating negative pressure, pulling in cooler air through lower openings. Stack ventilation enhances this with longer stacks for increased airflow, offering passive cooling with low maintenance, cost, and energy use. In Tampa's Logan House case study, a stack airflow of 2,800 cfm can remove about 15,000 Btuh, shifting the comfort zone by 2°F (Sustainable Buildings Initiative, n.d.-a). To read further, refer to "The Logan House: Stack Effect EffectivenessThe Logan House: Stack Effect Effectiveness".

Stack ventilation uses tall vents to expel warm air, creating airflow for fresh air intake. It's simple, low-cost, and energy-efficient compared to mechanical systems.

Figure 102: Stack ventilation

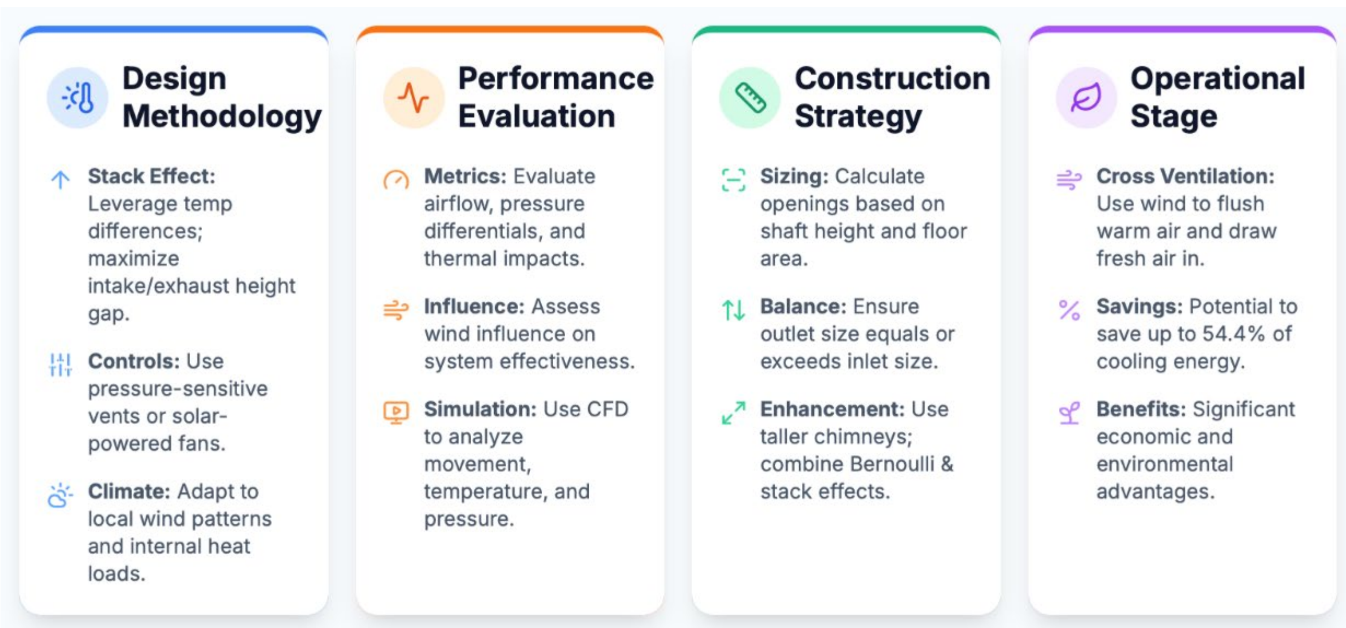
Principals of Stack Ventilation

Stack Ventilation: The primary concepts behind stack ventilation's operation are the pressure difference and system-wide air circulation.

Cross Ventilation (Wind Effect Ventilation): Cross ventilation uses wind to expel warm, humid air through inlets and outlets, optimizing air quality and circulation within a building.

Venturi Effect: Fresh air enters through leaks, vents, and windows, creating negative pressure that expels warm, stale air.

Warm Air's Buoyancy: Buoyancy and air density differences drive natural heat transfer: warm air near heat sources rises, dispersing energy (Linquip Technews, 2024).



The case studies on about stack ventilation can be accessed through the following link:
[The Logan House: Stack Effect Effectiveness]
[Sustainable approach for university clinic; a case study of stack effect system][Natural Ventilation Case Studies]

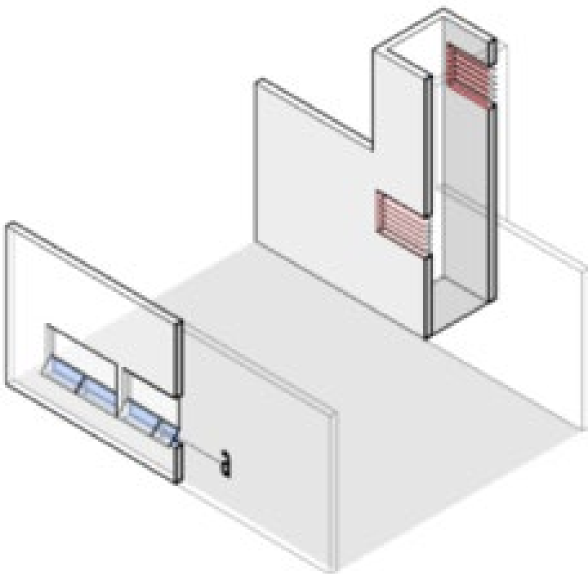


Figure 103: Inlet openings

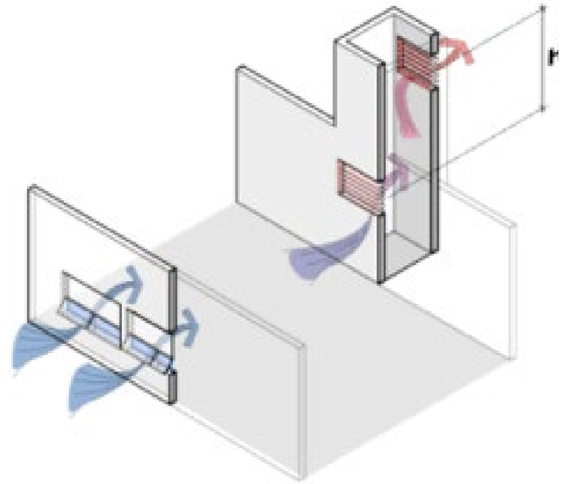


Figure 105: Ventilation shaft

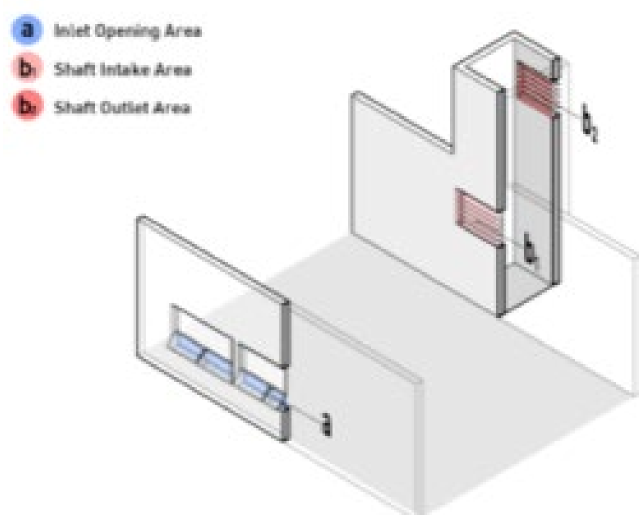


Figure 104 :Cross-section of stack ventilation

Description

Cross ventilation, or wind effect ventilation, uses wind to expel warm interior air through outlets like roof vents while drawing cooler outdoor air through inlets such as wall louvres or open windows. This technique enhances natural airflow and cooling within a building. (Moffitt Natural Ventilation Solutions, 2024).

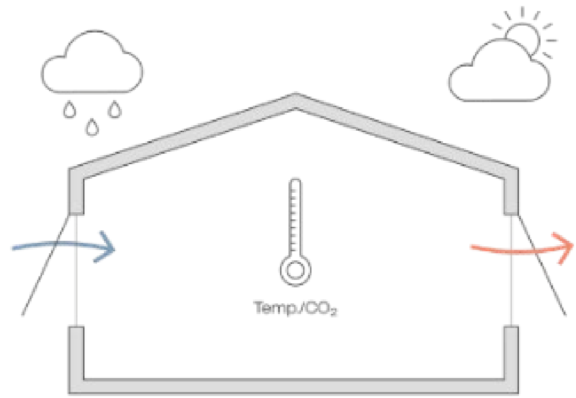


Figure 106: Cross ventilation

The case studies on about cross ventilation can be accessed through the following link: [Cross Ventilation, the Chimney Effect and Other Concepts of Natural Ventilation]

[Natural Ventilation and its Use in Different Contexts]

Design Methodology

To optimize cross ventilation, position the building perpendicular to prevailing winds and place windows on opposite sides to create a breeze. Ensure minimal spacing between openings for effective airflow. Airflow efficiency is influenced by wind pressure differentials and building layout. These strategies enhance natural cooling and thermal comfort (VentureWell, n.d.) (Energy5, 2024) (Cross Ventilation: Best Strategies and Benefits, 2024) (Sustainable Buildings Initiative, n.d.-a).

Evaluation of the Ventilation Performance

Evaluating cross ventilation involves several techniques:

- CFD simulations analyze airflow patterns and window configurations
- Field studies test real-world ventilation performance (Yuanyuan Wang, 2021).
- Wind tunnel experiments assess ventilation under various wind conditions
- Adaptive discharge coefficients refine airflow calculations (Hwang).
- Numerical simulations measure effectiveness including airflow rates and air change (Montazeri & Montazeri, 2017).
- Domain decomposition techniques provide detailed insights into ventilation performance under different conditions. These methods ensure optimal natural airflow and ventilation in buildings (Tsuruta et al, 2011).

Application Strategy (Construction)

Several important concepts and techniques must be followed for cross ventilation to work effectively. They are:

Two Openings Minimum: For effective cross ventilation, rooms need at least two openings, such as windows or doors, with one facing the prevailing wind and the other on the opposite side. This setup ensures proper airflow through the room. Position a door on the wall opposite a window facing the dominant wind direction to enhance airflow, especially in rooms with a single exterior wall. Ensure the door allows sufficient air entry.

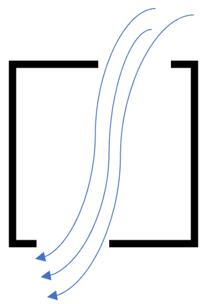


Figure 107: Cross ventilation with two openings

Minimal Space Between Openings: To enhance cross ventilation, minimize the distance between openings in a room, as shorter gaps allow better airflow. Deep rooms have slower airflow, so keep openings close together. For wide houses, include a courtyard to reduce wind travel distance and improve ventilation.

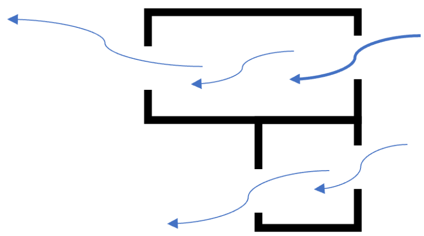


Figure 108 Minimal spaced openings

Unhindered Wind Routes: For optimal cross ventilation, ensure an open, unobstructed pathway for wind. Walls and partitions can block or slow airflow, reducing ventilation efficiency.
Placement of Doors or Windows: To enhance cross ventilation, place windows and doors to allow breezes to flow through high-traffic areas like the living room. Ensure efficient air circulation for better thermal comfort and fresh air and avoid placing openings in unused areas or corners to prevent ineffective airflow.
The Number and Size of Window or Door Openings: Larger window openings enhance cross-ventilation by allowing more air to pass through, while a mix of large and small apertures can further optimize airflow in a home (Architropics, n.d.).

Maintenance at Operational Stage

To ensure efficient cross ventilation, keep airflow unobstructed by removing obstacles, regularly clean and inspect fans and inlets, adjust fan speeds according to airflow needs, and maintain cooling pads with weekly and monthly checks. Monitor humidity levels and explore alternative ventilation if necessary and inspect other ventilation components like vents and curtains. Perform routine maintenance to sustain system efficiency and address issues promptly (Eadie, 2024).

5.3.2 Assisted Ventilation

Mechanical ventilation systems are crucial for modern buildings, enhancing indoor air quality by supporting natural ventilation, removing contaminants, and supplying fresh outdoor air through mechanical means.

Mechanical ventilation uses fans and ducts to expel stale air and introduce fresh air, ensuring continuous airflow, improved indoor air quality, and climate control. It can also filter, dehumidify, and condition incoming air for enhanced comfort (Kingspan, 2021); (Energy Star, 2024) .

Types of Mechanical Ventilation

The following are the four prominent types of mechanical ventilation commonly used:

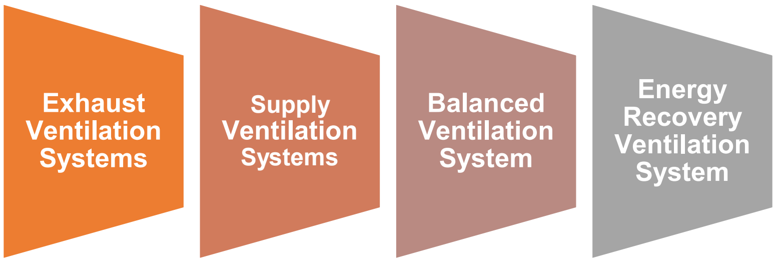


Figure 109 Types of Mechanical Ventilation

Exhaust Ventilation System: Exhaust ventilation systems use a central fan and ducts to expel air and draw in fresh air through passive vents, making them cost-effective and easy to install. Ideal for cooler climates, they prevent pollutants from areas like bathrooms and kitchens but may cause moisture damage and draw in contaminants. Unlike energy recovery systems, they don't condition or dehumidify incoming air, potentially increasing heating and cooling costs.

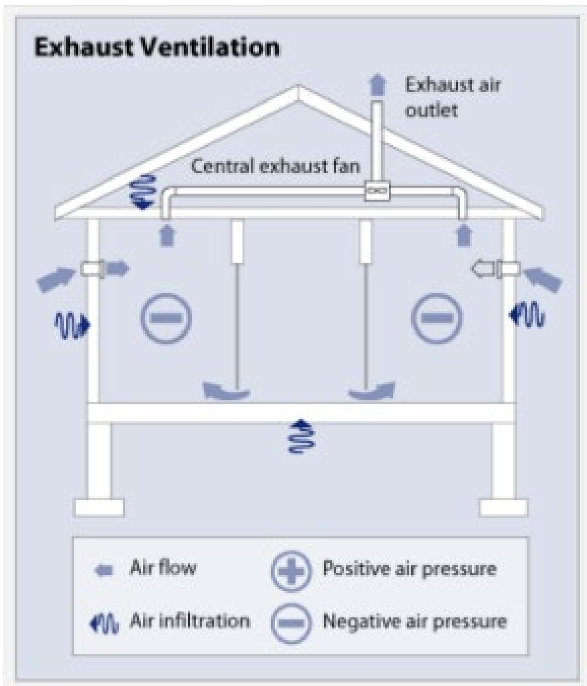


Figure 110: Exhaust ventilation system

Supply Ventilation System: Supply ventilation systems use fans to pressurize a building, bringing in fresh air while expelling stale air through ducts. They are cost-effective, enhance control over airflow, reduce pollutants, and allow air filtration and dehumidification. However, they may cause higher heating and cooling costs due to unconditioned incoming air and potential moisture issues in cold climates. Mixing outdoor and indoor air before delivery can help prevent drafts.

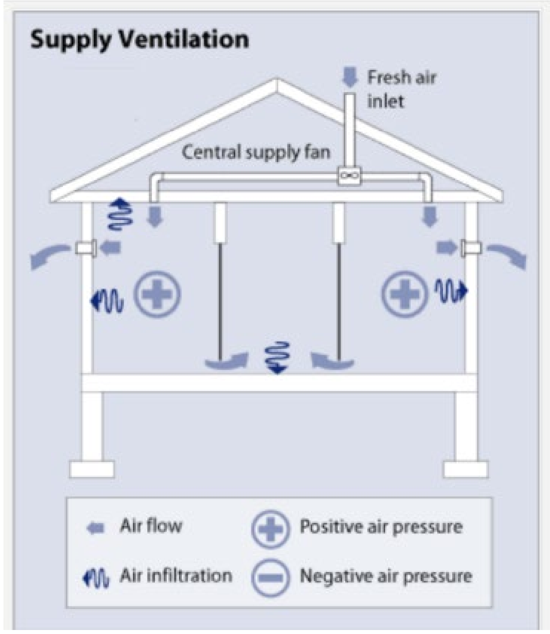


Figure 111: Supply ventilation system

Balanced Ventilation System: Balanced ventilation systems manage indoor air quality by introducing and expelling equal amounts of air, using two duct systems and fans. They ensure fresh air in high-occupancy areas and remove contaminants from moisture-prone zones. However, they don't condition or dehumidify incoming air, potentially raising energy costs, and can be more expensive to install and maintain due to the dual system requirements.

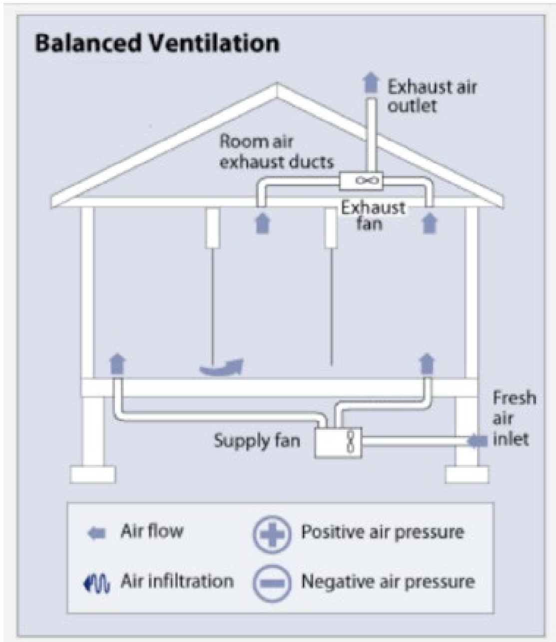


Figure 112: Balanced ventilation system

Energy Recovery Ventilation System: Energy Recovery Ventilation (ERV) systems efficiently manage ventilation by transferring heat in winter and cooling in summer, recovering 70-80% of energy from exhaust air and regulating humidity, particularly in summer. However, installation costs can be higher than conventional systems, and while simpler, economical installations use existing ducting, complex systems may require more maintenance and electricity (Home Ventilating Institute, 2024).

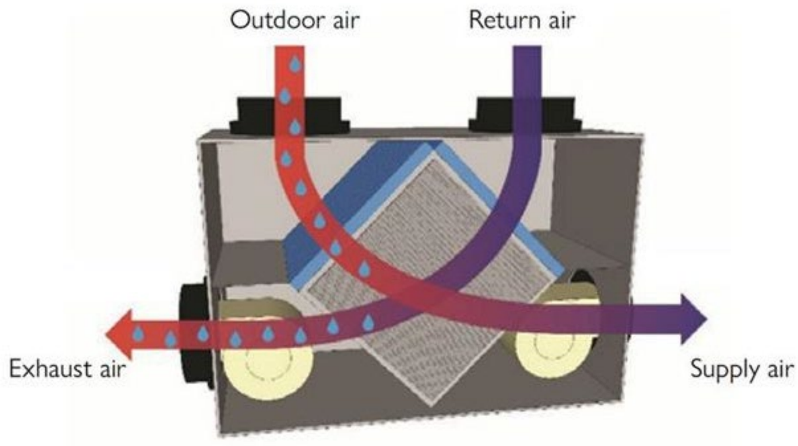


Figure 113: ERV ventilation airflow in summer

Design Methodology

Designing mechanical ventilation systems involves evaluating local environment, climate, and air quality to select appropriate techniques, ensuring efficient installation with minimal comfort issues. Airflow should move from clean to dirty areas, with equal distribution and integration with air conditioning systems. Include filtration systems to remove pollutants and ensure easy access for maintenance (Kingspan, 2021) (The Chartered Institution of Building Services Engineers (CIBSE), 2015).

Evaluation of the Ventilation Performance

To assess mechanical ventilation effectiveness, ensure the system meets required ventilation rates, verifies airflow moves from clean to dirty zones, and efficiently distributes outdoor air throughout the building. Additionally, evaluate the ratio of bulk airflow rate to effective airflow rate for performance insights (National Library of Medicine, n.d.), (Zhou et al, 2021).

Application Strategy (Construction)

To install mechanical ventilation effectively: ensure building airtightness to control air leakage; integrate systems with BAS or BMS; select appropriate ventilation types (balanced, supply, etc.); size and position AHUs to optimize air distribution; use HRV or ERV for energy recovery; optimize ductwork for efficiency; use high-efficiency filters (MERV 8+); and test the system to ensure it meets design specifications (MPW Engineering, 2021) (BEAMA, 2021).

Maintenance at Operational Stage

Assisted ventilation systems require careful design for easy access, regular inspections to check for wear and pollutants, and in-depth testing for hidden microbial issues. Cleaning schedules depend on system type and usage, with professional maintenance recommended. Safety protocols for maintenance staff are essential, and building owners should educate residents on efficient system use (Kingspan, 2021).

5.3.3 Mixed Mode Ventilation

Mixed-mode ventilation (MMV) combines natural and mechanical systems to optimize comfort and reduce energy use. The study "Evaluation of Mixed-Mode Ventilation Thermal Performance and Energy Saving Potential from Retrofitting a Beijing Office Building" found MMV cut cooling energy consumption and carbon emissions by about 45.4%, improved thermal comfort, and indoor air quality. Retrofitting with MMV is cost-effective, with a payback period of approximately 4.5 years. For further details, refer to "Evaluation of Mixed-Mode Ventilation Thermal Performance and Energy Saving Potential from Retrofitting a Beijing Office Building".

Description

Hybrid ventilation blends mechanical and natural methods to optimize fresh air and comfort, with a Building Automation System (BAS) selecting the most efficient approach based on conditions. These systems are often more cost-effective than fully mechanical ones. Their success depends on a holistic approach, supported by advanced design techniques like Integrated Project Delivery (IPD) and Building Information Modelling (BIM) (Solar Innovations, 2024).

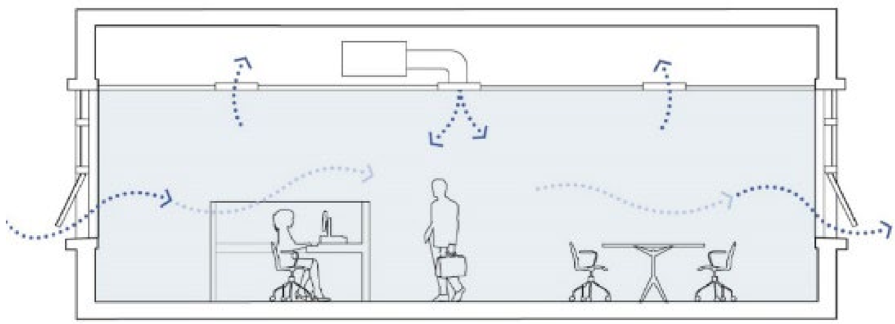


Figure 114: Illustration of mixed-mode ventilation

The case studies on about mixed-mode ventilation can be accessed through the following link:
A case study on residential mixed-mode ventilation using the Ventilation Controls Virtual Test Bed
Control strategies for mixed-mode buildings
Mixed-Mode Ventilation: HVAC Meets Mother Nature

Cambodia shares a similar tropical climate with Singapore, characterized by high temperatures and humidity. Hybrid cooling systems, which combine air conditioning with ceiling fans or evaporative cooling, can offer significant energy savings while maintaining comfortable temperatures, making them a viable option for Cambodian buildings (Department of Architecture, National University of Singapore., 2025)

Design Methodology

When designing buildings with mixed-mode ventilation, focus on minimizing mechanical ventilation needs through intelligent facade design and passive strategies. Understand natural ventilation methods like single-sided, crossflow, or stack ventilation. Ensure a well-designed control system for optimizing ventilation rates and maintain the system properly to avoid conflicts. Plan air inlet placement to avoid draughts, manage noise from equipment, and allocate adequate space for central plant components. Also, ensure fire safety with appropriate ductwork fire dampers and maintain accessibility for upkeep (Mitsubishi Electric Direct Air-Conditioning Systems, 2024) (CIBSE, 2015).

Evaluation of the Ventilation Performance

To evaluate MMV systems, key elements include analyzing thermal performance to identify energy savings, validating natural ventilation models for accurate temperature and airflow projections, comparing hybrid ventilation strategies like free cooling and night ventilation, and assessing economic and energy impacts to choose the best approach for the building .

Application Strategy (Construction)

The construction of mixed-mode ventilation relies on specific design principles.

Both Mechanical and Natural ventilation: This principle integrates two systems: one for extreme weather (e.g., mechanical ventilation) and one for milder conditions (e.g., natural ventilation). The control strategy switches between them based on environmental conditions.

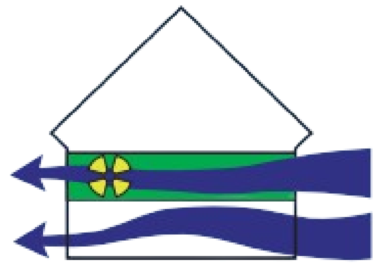


Figure 115: Mechanical & natural ventilation

Natural Airflow Aided by Fans: This principle uses fans to boost pressure differences in natural ventilation systems, enhancing airflow when natural forces are weak or demand is high, by combining mechanical assistance with natural ventilation.

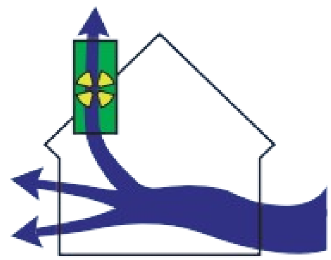


Figure 116: Fan aided natural airflow

Mechanical Ventilation with the Use of Stacks and Winds: This concept optimizes mechanical ventilation by leveraging natural forces like stacks and winds to enhance airflow, designing systems with minimal pressure losses to boost efficiency and reduce energy use.

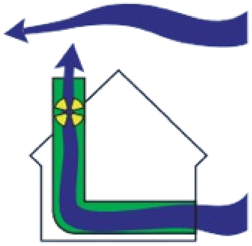


Figure 117: Mechanical ventilation aided by wind and stack

Maintenance at Operational Stage

Maintaining mixed-mode ventilation systems involves ensuring optimal performance and preventing issues like dust accumulation and mold growth. Key maintenance steps include: designing for easy access, conducting regular visual and in-depth inspections, adjusting inspection frequency based on system needs and building use, cleaning and replacing filters as required, ensuring safety protocols are followed, and educating building occupants on proper system use.

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Data Sources for Figures and Tables

Table 8	https://tinyurl.com/t9psf25f
Table 11	https://tinyurl.com/mv32jfkb
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