TYPOLOGY TECHNICAL ANALYSIS REPORT

ENERGY SAVINGS AND EMISSIONS MITIGATION POTENTIAL OF PASSIVE COOLING STRATEGIES ACROSS BUILDING TYPOLOGIES IN CAMBODIA

November 2024

Technical and financial support was provided by:

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1 Introduction

Building typology refers to the broader categorisation of a group of buildings based on their function and form. Functional typology classifies buildings based on their similarity in use, activities, and/or purpose, while form typology focuses on morphology derived from spatial zoning, envelope geometry, and/or site spatial configuration. The building typology is further subcategorised as "Building Types" based on their specific functional purposes, such as residential, office, hotel, retail and hospital.

Examining the diversity in building design and construction within different building typologies establishes the foundation for understanding the heat and mass flows into and out of the buildings. This understanding is crucial for comprehending the thermal performance of building construction in Cambodia and for estimating the efficacy of various passive cooling strategies (PCS) within these building typologies. The report places emphasis on the design and construction performance of different building types, as well as the efficacy of individual and the combined PCS within these building types, particularly in terms of energy and emissions savings potential. The insights derived from this study will lead to the development of guidelines for building design and construction professionals in the country.

1.1 Building Typologies in Cambodia

The construction industry in Cambodia has experienced strong growth since the country opened its doors to foreign investment in the 1990s. Alongside garments, rice, and tourism, the construction sector stands as one of the four pillars of the country's economy. As of 2022, the annual GDP growth of Cambodian construction sector is 5.2%, amounting to 8.7 million USD[1].

In recent years, there has been a notable shift in Cambodian architecture, transitioning from Khmer architecture to modern architecture. This evolution in architecture has brought about changes in building usage and patterns to meet the evolving needs of the region. Notably, the Royal Government of Cambodia, under the Law of Construction, has documented a limited number of building typologies.

Drawing on information from the National Energy Efficiency Policy[2] (hereinafter referred to as "NEEP"), the Roadmap for Low Carbon and Climate-Resilient Buildings and Construction in Cambodia Vision 2050[3] (hereinafter referred to as "RLCCRB"), and stakeholder consultations[4], the forthcoming building thermal and energy performance analysis will consider the following building typologies:

- Residential buildings – Mid & high-income group housing (Borey & Condominiums)
- Residential buildings – Affordable housing (Borey & Condominiums)
- Office buildings
- Institutional buildings
    - Schools (elementary, middle and high schools)

[1] Updated data collected from the https://data.worldbank.org/indicator/NY.GDP.MKTP.CD
[2] Guided by the vision of transforming Cambodia into a high-income country, this policy serves as a comprehensive framework to enhance energy efficiency. It defines roles, sets targets, and prioritizes capacity building for sustainable development, aiming for a 19% reduction in total energy consumption by 2030 and sector-specific reductions in major energy-consuming sectors.
[3] Cambodia's construction sector, responsible for 45% of primary energy demand and significant greenhouse gas emissions, aims to shift towards sustainable, efficient, and low-carbon building practices under the NDC Roadmap to support its Paris Agreement commitments.
[4] Stakeholder consultation meetings conducted in the project team visit in March 2023

    - Universities and colleges
    - Educational research centres and laboratories
    - Vocational and trade schools
- Hotel buildings
- Hospital buildings
- Retail buildings

The information extracted from the draft documents of the NEEP and RLCCRB, alongside market research documents from facility management firms such as CBRE and Knight Frank, has been employed to establish a comprehensive understanding of the Cambodian real estate market. This understanding includes the categorisation of buildings to be analysed for each building type. The primary determinants for selecting the building typology include the following parameters:

- Expected growth in the floor space, cooling demand, and energy consumption under each typology and their sub-categories.
- Scope and extent of passive cooling strategies implemented in existing buildings within each typology and their respective building types.
- Potential for decarbonisation, reduction in cooling demand, and energy consumption through the implementation of PCS in each typology and their sub-categories.

This report utilises the aforementioned typologies to assess the effectiveness of PCS through parametric energy simulation. The insights gained from this evaluation will contribute to the development of guidelines for implementing potential PCS.

1.2 Representative Buildings for Technical Analysis

The selection of buildings for typology analysis is determined through desk research, site visits, and consultation with the project team, national consultants, and local architects and developers. The focus is on:

- The architectural concept (modern and Khmer) of the building types under each typology.
- The significance of the building, considering the typology definition from stakeholders.
- The availability of information and support from the building design/operation team to conduct the analysis.

For each building typology defined based on the above criteria, three to four different building types were identified. Mapping was facilitated using the “Cambodia Construction” mobile application and through site visits conducted by technical experts during the mission. Two representative building types per typology were then chosen for parametric simulation analysis, based on data availability and utilising tools like detailed surface maps from OpenStreetMap™. The information collected for the analysis of these building types included:

- Building architectural drawings, including site layout, floor plans, elevation, and sections.
- Construction materials and their properties for walls, roofs, windows, and paved surfaces.
- Site and building photographs.
- Building operational schedules.

Table 1 presents the researched information on energy modelling for the identified building types, assessed by the project team and national consultants to ensure their suitability for the implementation of the PCS within the national context.

Table 1 Representative Buildings in Cambodia for Typology Analysis

Building Name	Location	Type	Source of Data Collection	Availability of Documents			Potential for Successful Modelling
				Floor Plan	Elevation	Section	
Residential – Condominiums							
Representative Building 1 (Oxley World Bridge)	No 14 National Assembly Street	1 BHK & 3 BHK	Site Visit & Website	Yes	No	No	Yes
Representative Building 2 (Booyoung Town)	Russian Blvd, Sangkat Teuk Tla, Khan Sensok	1 BHK, 2 BHK (MIG)	Online	No	Yes	Yes	Yes
Residential – Borey (Landed Dwelling)							
Representative Building 1 (Borey Chankiri)	Thmey Village, Chroy Changvar	1 BHK, 3 BHK	Site Visit & Website	Yes	Yes	No	Yes
Residential – Affordable Housing							
Representative Building 1 (Borey Maha Boeng Trea)	Kandal Stueng	1 BHK, 2 BHK (Affordable housing)	Site Visit & Website	Yes	Yes	No	Yes
Representative Building 2 (bun ches flats)	Thmey Village, 12110, Chroy Changvar,	1 BHK, 2 BHK (Affordable & MIG)	Site Visit & Website	Yes	No	No	Yes
Offices							
Representative Building 1 (Sathapana bank tower)	#63 Preah Norodom Blvd (41), Penh 12210	High rise building	Site Visit & Website	Yes	No	No	Yes
Representative Building 2 (emerald tower)	No, 64 Preah Norodom Blvd (41),	High rise building	Site Visit & Website	Yes	Yes	Yes	Yes
Educational Institutional							
Representative Building 1 (Department of Information Technology)	HW7G+WCV	Low-rise building with a variety of PCS	Site Visit & Website	Yes	No	No	Yes
Representative Building 2 (Institute of Foreign Language)	Russian Federation Blvd (110)	Low rise with a variety of PCS	Site Visit & Website	Yes	Yes	Yes	Yes
Hotels							
Representative Building 1 (hotel Emion)	No.192 Preah Sisowath Quay	High rise building	Site Visit & Website	Yes	No	No	Yes
Representative Building 2 (Penh House)	JWX2+GX4	Low rise	Website	No	No	No	No
Hospitals							
Representative Building 1 (National Paediatric Hospital)	HV9W+FX3, St 253	Low rise	Site Visit & Website	No	No	No	No
Retail: Shopping Malls							

Building Name	Location	Type	Source of Data Collection	Availability of Documents			Potential for Successful Modelling
				Floor Plan	Elevation	Section	
Representative Building 1 (noro mall)	#199 Preah Norodom Blvd (41)	Low rise	Site Visit & Website	Yes	Yes	Yes	Yes
Representative Building 2 (central market)	Kamet St. (53)	Low rise	Website	Yes	Yes	Yes	Yes

2 Methodology for Typologies Technical Analysis

The parametric simulation of building types, both with and without PCS, was conducted while considering the desired indoor thermal comfort criteria as per the ASHRAE 55 standard (*ASHRAE - iWrapper*). This allowed for the estimation of the energy savings potential and associated GHG mitigation potential in Cambodia. Parametric simulation is a computational approach where various input parameters are systematically changed to analyse their impact on a system's behaviour or performance. It helps optimise designs and understand complex systems efficiently. The figure below illustrates the steps involved in the simulation analysis methodology:

Figure 1 Steps in Building Performance Analysis for Typologies

The subsequent sections below provide a comprehensive account of the data collected by the technical analysis team during the data collection mission.

2.1 Standards Used

In estimating the cooling energy performance of the building types, reference was made to the following international standards and protocols. These standards outline the methodology and input specifications for defining the energy simulation model.

Table 2 Standards Referred to Outline the Methodology and Input Specifications for the Energy Simulation Model

Standard	Description	Application for Energy Modelling
ANSI/ASHRAE Standard 209-2018: Energy Simulation Aided Design for Buildings Except Low-Rise	ASHRAE Standard 209-2018, Energy Simulation Aided Design for Buildings Except Low Rise Residential Buildings, defines minimum requirements for providing energy design assistance using building energy simulation and analysis. The standard defines consistent energy modelling procedures to quantify the impact of design decisions when they are being made.	**Inputs:** Modelling cycle numbers 2 & 10 – Air-conditioning equipment baseline efficiency, parametric energy modelling methodology **Outputs:** Performance indicators for cooling demand and energy Referred to Appendix C of the standard
California Code of Regulations Title 24	The regulation provides the minimum performance requirements	**Inputs:** Occupant load factor (m^2/person), occupant schedule, HVAC

	of the buildings to minimise wasteful use of energy using calculation methodology and input definitions for comparison with the designed building.	schedule, lighting schedule, equipment power rate (W/m^2) Referred to Section 150.0 (k) of the standard
ANSI/ASHRAE/IES Standard 90.1-2022: Energy Standard for Buildings Except for Low-Rise Residential Buildings	This standard provides the minimum requirements for energy-efficient design of most sites and buildings, except low-rise residential buildings. It offers, in detail, the minimum energy efficiency requirements for the design and construction of new sites and buildings and their systems, new portions of buildings and their systems, and new systems and equipment in existing buildings, as well as criteria for determining compliance with these requirements.	**Inputs:** Baseline building envelope requirements **Outputs:** Unmet hours of comfort Referred to Appendix G of the standard
ANSI/ASHRAE 55:2020: Thermal Environmental Conditions for Human Occupancy	This standard specifies conditions for acceptable thermal environments and is intended for use in the design, operation, and commissioning of buildings and other occupied spaces.	**Inputs:** Temperature and humidity setpoint for air-conditioned and naturally ventilated spaces

2.2 Definition of Simulation Inputs

The simulation inputs considered for parametric analysis include:

- Weather data for the location chosen for simulation
- Definition of building envelope inputs
- Definition of occupancy, metabolic rate, clothing, and comfort setpoints inputs
- Definition of infiltration, natural ventilation, and air-conditioning systems inputs
- Definition of equipment and lighting inputs
- Definition of operational schedules inputs

2.2.1 Weather Data

For the base case analysis, the EPW (Energy Plus Weather data) climate data from EnergyPlus was utilised. The available EPW data for Cambodia is for Phnom Penh, Battambang, Sihanouk, Kompong Cham, Kampot, Pursat, Siem Reap – Angkor, Svay Rieng, and Stung Treng.For the estimation of the energy and emissions potential in this report, the weather data of Phnom Penh is considered. Climate analysis of Phnom Penh is included in Annexure 1.

2.2.2 Definition of Building Envelope Inputs

The selection of construction materials for the various building typologies was determined through consultation with local architects and key stakeholders in the building sector during the data collection mission. Other data were collected by referencing standards such as California Title 24 (California Building Standards Commission., International Code Council. 2010) and ASHRAE. Presented below is a comprehensive inventory of conventional construction materials considered for the building envelope components such as walls, roofs, and windows in Cambodia.

Table 3 Baseline Inputs for Construction Materials

Typologies	Walls	Roofs	Windows & Shading Systems	Window-to-Wall Ratio (WWR)
Mid & High-Income Group Housing: Condominiums	External cement plaster + 230 mm hollow red brick + internal cement plaster	50 mm Plain Cement Concrete (PCC) + 100 mm RCC slab + 10 mm plaster	Single clear glass with minimal or no shading	30-40%
Mid & High-Income Group Housing: Landed Dwelling (Borey)	External cement plaster+230 mm hollow red brick + internal cement plaster	50 mm PCC + 100 mm RCC slab + 10 mm plaster[5]	Single clear glass and projected wall shading	20-35%
Affordable Housing: Borey & Condominiums	External cement plaster+230 mm hollow red brick + internal cement plaster	50 mm PCC + 100 mm RCC slab + 10 mm plaster	Single clear glass and projected wall shading	20-30%
Office	Option 1: External cement plaster+230 mm hollow red brick + internal cement plaster Option 2: Steel & Glass structure for the high-rise office building	50 mm PCC + 150 mm RCC slab + 10 mm plaster	Single glass with reflective coating or tint	20-30% 80-100%
Institutional	External cement plaster+230 mm hollow red brick + internal cement plaster	50 mm PCC + 150 mm RCC slab + 10 mm plaster	Openings without glazing; External louvre and projected shading	30-50%
Hotel	External cement plaster+230 mm hollow red brick + internal cement plaster	50 mm PCC + 150 mm RCC slab + 10 mm plaster	Single clear glass and projected wall shading	30-40%
Hospital	External cement plaster+230 mm hollow red brick + internal cement plaster	50 mm PCC + 150 mm RCC slab + 10 mm plaster	Single clear glass and projected wall shading	25-40%
Retail	External cement plaster+230 mm hollow red brick + internal cement plaster	50 mm PCC + 150 mm RCC slab + 10 mm plaster	Single clear glass with a partially exposed window area and partially shaded	20-30%

2.2.3 Definition of Occupancy, Metabolic Rate, Clothing, and Comfort Setpoint Inputs

Following is the compilation of the inputs considered for occupant load factor, metabolic rate, clothing insulation and comfort set-points considered for the baseline model definition.

Table 4 Simulation Inputs for Occupancy, Metabolism, and Comfort Setpoints

Typology	Occupant Load Factor (m^2/person)	Metabolic Rate per Person (W/person)	Clothing Insulation	Comfort Setpoints
Mid & High-Income Group	25	108	0.5 clo (typical summer indoor clothing)	Cooling operative temperature (OT): twenty-five ºC

[5] In this typology, one of the buildings (Borey Cahngkiri) has used foam concrete as the roof insulation material. The material thickness are properties to be collected by national consultant team.

Housing: Condominiums				Relative Humidity (RH): fifty%
Mid & High-Income Group Housing: Landed Dwelling (Borey)	30	108	0.5 clo (typical summer indoor clothing)	Cooling OT: 25 ºC; RH: 50%
Affordable Housing: Borey & Condominiums	12.5	108	0.5 clo (typical summer indoor clothing)	Cooling OT: 25 ºC; RH: 50%
Office	10	127	0.61 clo (trousers and long sleeve shirt)	Cooling OT: 25 ºC; RH: 50%
Institutional	4	127	0.61 clo (trousers and long sleeve shirt)	Cooling OT: 25 ºC; RH: 50%
Hotel	15	108	0.61 clo (trousers and long sleeve shirt)	Cooling OT: 25 ºC; RH: 50%
Hospital	Indoor patient area: 15; Outdoor patient area: 10	127	0.61 clo (trousers and long sleeve shirt)	Cooling OT: 25 ºC; RH: 50%
Retail	6	160	0.61 clo (trousers and long sleeve shirt)	Cooling OT: 25 ºC; RH: 50%

2.2.4 Definition of Infiltration, Natural Ventilation, and Air-Conditioning System Inputs

The ventilation requirements for the area and occupancy are defined by the ASHRAE 62.1-2019 standards, while the air infiltration rates adhere to the ASHRAE 90.1-2022 standard. The selection of ventilation system types and the utilisation of air conditioning systems are established through on-site visits and extensive consultations with architects during the assessment in Cambodia. For residential building typologies, the air-conditioning system model incorporates Direct Expansion (DX) Room Air Conditioners, whereas Packaged DX systems are considered for commercial building typologies.

Table 5 Ventilation, Air-Conditioning, and Infiltration Inputs

Typology	Ventilation Rate per Area (L/s-m²)	Ventilation Rate per occupancy (L/s.person)	Air-Conditioning COP	Natural Ventilation	Air Infiltration Rate (ACH)[6]
Mid & High-Income Group Housing: Condominiums	0.3	2.5	3	Yes. Natural ventilation is activated whenever the space temperature exceeds 25°C, and the outside temperature	1
Mid & High-Income Group Housing: Landed Dwelling (Borey)	0.3	2.5	3		

[6] Source- ASHRAE 90.1-2022

Affordable Housing: Borey & Condominiums	0.3	2.5	3	is 3°C lower than the room temperature. If the zone temperature does not reach or fall below 25 °C through natural ventilation, the air-conditioner gets activated.	
Office	0.3	2.5	3.1	No	1
Institutional	0.6	5	3.1	Yes. Same logic as mentioned above.	0.7
Hotel	0.3	2.5	3.1	No	0.7
Hospital	0.9	5	3.1	No	0.7
Retail	0.6	3.8	3.1	Yes. Same logic as mentioned above.	0.7

2.2.5 Definition of Equipment and Lighting Inputs

The building's internal loads considered in the analysis include the lighting and equipment loads, which contribute to thermal loads in the building. The lighting and equipment power densities for the building typologies are defined as per ASHRAE 90.1-2022 and California Code of Regulations Title 24, respectively, as shown in Table 6 below:

Table 6 Lighting and Equipment Power Densities

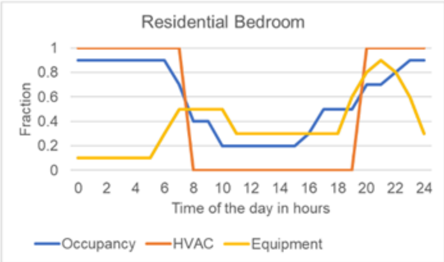
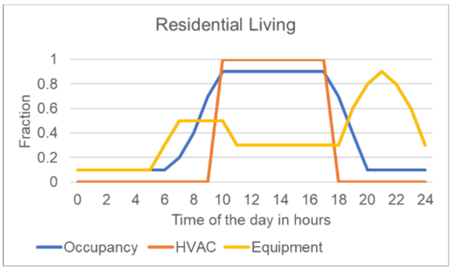
Typology	Lighting (W/m²)	Equipment (W/m²)
Mid & High-Income Group Housing: Condominiums	5	10.8
Mid & High-Income Group Housing: Landed Dwelling (Borey)	5	10.8
Affordable Housing: Borey & Condominiums	5	10.8
Office	6.6	14.4
Institutional	7.5	10.8
Hotel	5.7	5.4
Hospital	9.9	12.7
Retail	8.4	10.1

2.2.6 Lighting, Equipment, and Operational Schedule

The following schedules, adapted from California Code of Regulations Title 24, are utilised for occupancy, lighting, HVAC, and equipment operation.

Table 7 Lighting, Equipment & HVAC Operational Schedule

Typologies	Schedules for occupancy, HVAC, lighting and equipment	
Mid & High-Income Group Housing: Landed Dwelling		

<table>
<tr><td>(Borey) & Condominiums
Affordable Housing: Landed Dwelling Borey & Condominiums</td><td>
</td><td>
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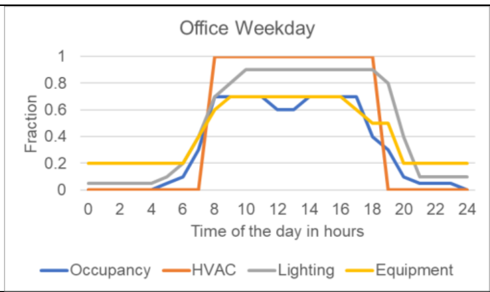
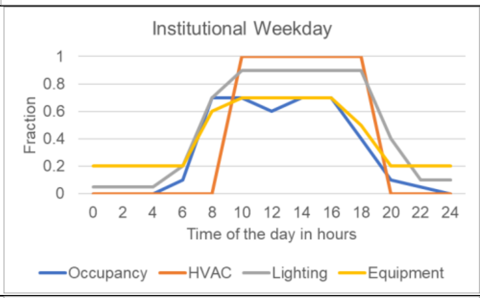
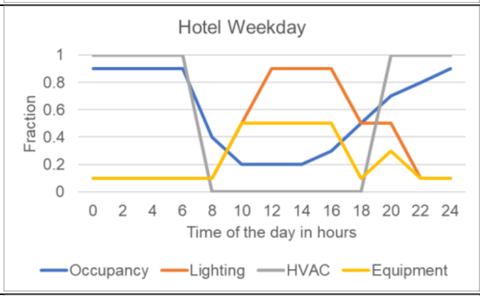
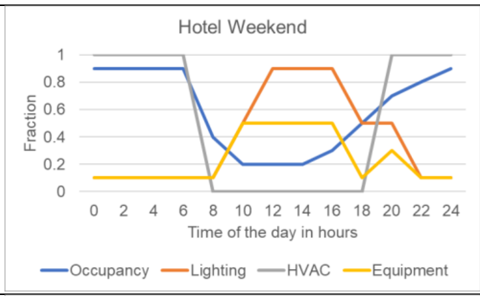
<tr><td>Office</td><td>
</td><td>No operation</td></tr>
<tr><td>Institutional</td><td>
</td><td>No operation</td></tr>
<tr><td>Hotel</td><td>
</td><td>
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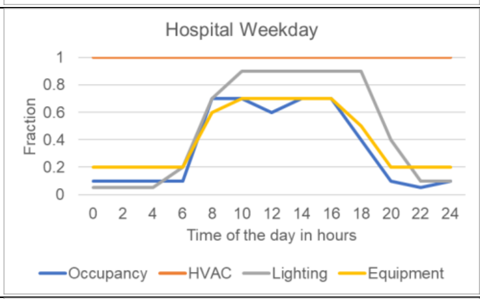
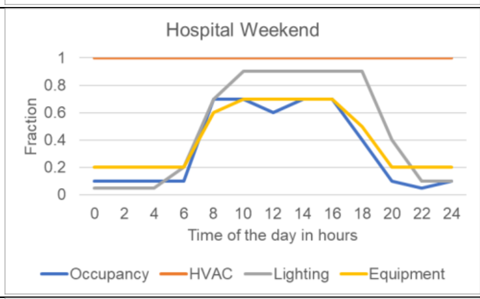
<tr><td>Hospital</td><td>
</td><td>
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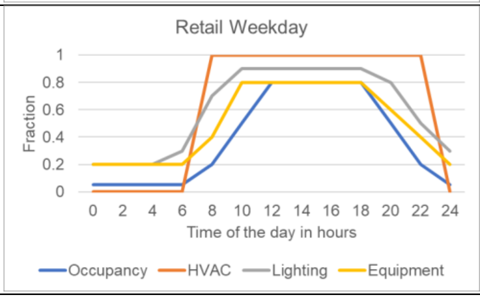
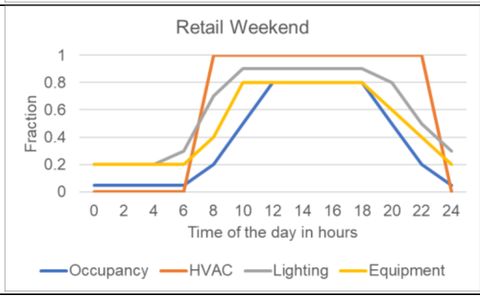
<tr><td>Retail</td><td>
</td><td>
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</table>

2.3 Modelling of Passive Cooling Strategies

The efficacy of the listed PCS was assessed for all typologies through energy simulation analysis and parametric runs.

Table 8 PCS Strategies for Individual Typologies

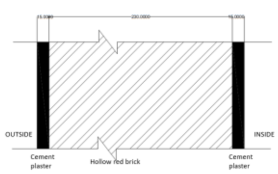
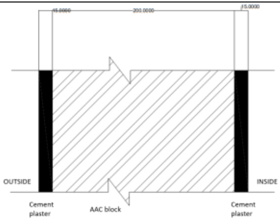
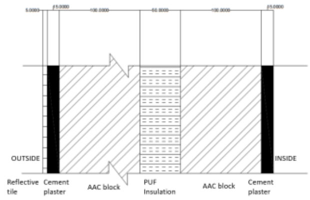
Typology	PCS Strategies Analysed Through Simulation
Mid & High-Income Group Housing: Condominiums	• Roof insulation • Wall insulation • Window performance: glazing and frames • Natural and cross ventilation • Night cooling • Orientation • Window-to-Wall Ratio • Static Shading (façade or fitting component on the outside of the walls)
Mid & High-Income Group Housing: Landed Dwelling (Borey)	
Affordable Housing: Borey & Condominiums	
Office	
Institutional	
Hotel	
Hospital	
Retail	

To structure the evaluation of the PCS mentioned in Table 8, three options for building envelope composition were outlined, taking into account their gradual improvement in thermal performance. These options are as follows:

- Option 1: Baseline envelope performance case
- Option 2: Intermediate envelope performance case
- Option 3: Best envelope performance case

Table 9 provides a summary of the composition of these three envelope cases along with their corresponding thermal performance parameters. The mapping of envelope cases and their parameters, including u-value improvements, was conducted through intensive discussion with architects, consultants and technical experts.

Table 9 Envelope Performance Options

<table>
<tr><th rowspan="2">Component</th><th>Option 1</th><th>Option 2</th><th>Option 3</th></tr>
<tr><th>Baseline Envelope Case</th><th>Intermediate Envelope Case</th><th>Best Performance Envelope Case</th></tr>
<tr><td rowspan="3">Wall</td><td>External cement plaster + 230 mm hollow red brick + internal cement plaster</td><td>(Outer) 15mm cement plaster + 200mm AAC block + 15mm cement plaster (INNER)</td><td>(Outer) 5mm reflective paint + 15mm cement plaster + 100mm AAC block + 50mm PUF insulation + 100mm AAC block + 15mm cement plaster (INNER)</td></tr>
<tr><td>U-Value: 1.07 W/m^2. K</td><td>U-Value: 0.77 W/m^2. K</td><td>U-Value: 0.33 W/m^2. K</td></tr>
<tr><td>
</td><td>
</td><td>
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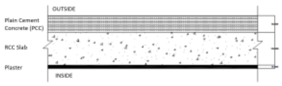
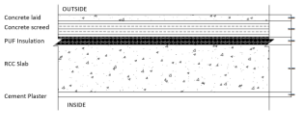
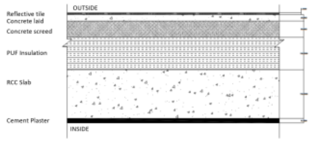
</table>

Roof	(OUTER) 50 mm plain cement concrete (PCC) + 100 mm RCC slab + 10 mm plaster (INNER)	(OUTER) 20mm concrete laid + 50mm concrete screed + 25mm PUF over deck insulation + 150mm RCC slab + 15mm cement plaster (INNER)	(OUTER) 5mm reflective tile + 20mm concrete laid + 50mm concrete screed + 100mm PUF over deck insulation + 150mm RCC slab + 15mm cement plaster (INNER)
	U-Value: 2.46 W/m^2. K	U-Value: 0.74W/m^2. K	U-Value: 0.23 W/m^2. K
			
Glazing and Frame	Single clear glass and aluminium frame	Double clear glass with 6mm air gap and aluminium frame with thermal break	Double clear glass with 13mm argon fill and low e coat and UPVC frame
	U-value: 7.1 W/m^2. K	U-value: 5.1 W/m^2. K	U-value: 3.1 W/m^2. K
	SHGC: 0.8	SHGC: 0.7	SHGC: 0.25
Ventilation and Night Cooling	Natural ventilation is activated whenever the indoor temperature exceeds 25°C, and the outside temperature is 3°C lower than the room temperature.		

The parametric models assume that all regularly occupied zones in the building are air-conditioned during the occupied hours when thermal comfort is not met, excluding the periods when natural ventilation meets the requirements of indoor thermal comfort

Through the parametric simulation iterations, the potential of the PCS was evaluated by considering the following performance steps (in Table 10) in combination with the building envelope options mentioned in Table 9.

Table 10 Parametric Performance Steps Considered for PCS Evaluation

S. No.	PCS	Step 1	Step 2	Step 3	Step 4
1	Shading depth	0	0.5 m	1 m	-
2	WWR	0.3	0.4	0.5	0.6
3	WoR	0.3	0.45	0.6	-
4	Orientation	0^0	90^0	180^0	270^0

2.4 Estimation of the Potential of Individual and Combination of Passive Cooling Strategies

Outputs from the parametric simulation analysis provided the performance potential for both individual and combination of PCS for each building type. This potential was assessed based on indicators such as variations in the achievement of thermal comfort indices, reduction in cooling demand, and energy savings.

To assess the performance potential of PCS, parametric simulations were conducted in the Rhino Grasshopper environment, employing EnergyPlus version 9.6 as the underlying engine. Each building type was modelled within the Rhino environment, considering inputs mentioned in section 2.2. The software generated outputs, including total energy use intensity (EUI) and cooling load intensities. To facilitate analysis and comparison, multiple simulation results for each building typology were saved in the CSV file format. These files were then imported into Design Explorer, a web-based result viewer. Within this platform, the results were further evaluated to identify optimal combinations or solutions based on their cooling energy performance index (CEPI).

2.5 Energy Simulation Outputs

The table below illustrates the mapping of performance indicators and the corresponding simulation outputs from the simulation analysis.

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

3 Results of the Typology Analysis

Cooling Energy Performance Index (CEPI) is a metric used to quantify cooling performance, measured in annual cooling energy consumption per gross floor area (kWh/m^2.year). A lower CEPI value indicates a lower building envelope load and cooling demand. For the analysis of the parametric simulation for individual typologies, the outputs were categorised into four performance levels of CEPI.

- **Near-zero Scenario**: CEPI range below and equal to 25 percentiles of the results
- **High-performance Scenario**: CEPI range between the 26th percentile and 50 percentiles of the results
- **Code Compliance Scenario**: CEPI range between 51st percentile and 75 percentiles of the results
- **Business-as-usual (BAU) Scenario**: CEPI range between 76th percentile and 100 percentiles of the results

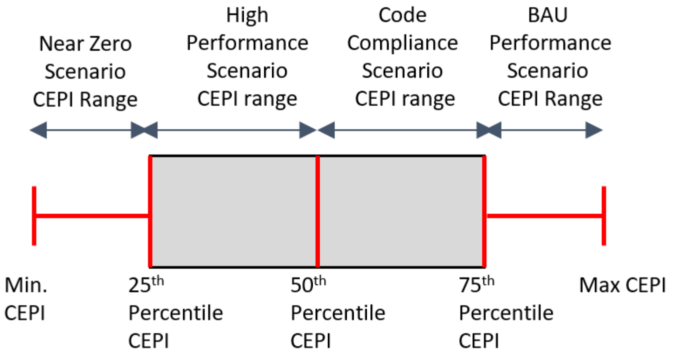


Figure 2 CEPI Performance Scenarios

The baseline CEPI is estimated by averaging the maximum CEPI and the 75th percentile CEPI values. The BAU performance scenario includes a range of energy savings, representing the difference between the 75th percentile and the baseline CEPI values. The summary of the CEPI range for all the building typologies is shown in the figure below.

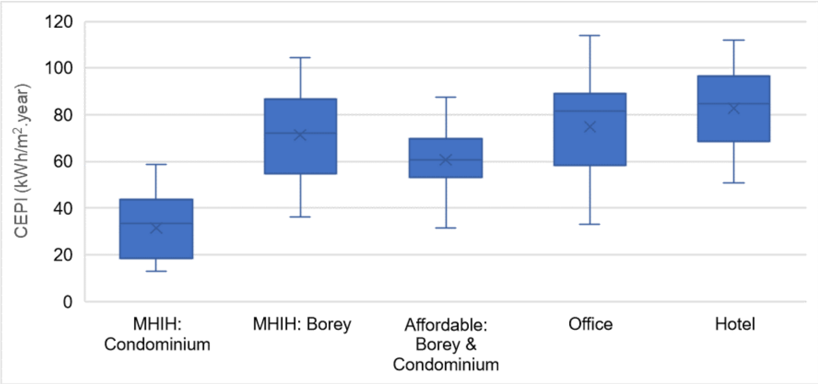


Figure 3 Summary of CEPI Range for all the Typologies

The outputs form the parametric analysis of each typology were visualised and assessed using the "Design Explorer 2" tool (available at https://tt-acm.github.io/DesignExplorer/), as depicted in Figure 4.

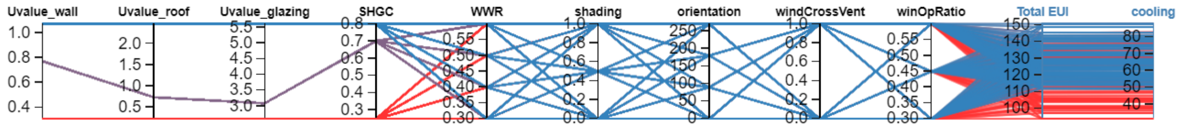


Figure 4 Parametric Simulation Output View – Design Explorer 2

Sections 3.1 to 3.4 elaborate on the energy model description and the results of the parametric analysis for all typologies.

3.1 Residential Building: Affordable Housing

Affordable housing projects in Cambodia take two different forms: traditional borey-type houses, typically having two floors per household, and modern condominiums with a single dwelling (flat) per household. In comparison to a conventional dwelling unit, affordable housing units have smaller floor area (up to 60 m^2). The results for both design prototypes considered for parametric analysis are presented in the sections below.

3.1.1 Affordable Housing: Borey-Type

3.1.1.1 Description of the Representative Building

In the parametric energy simulation, a representative building of affordable housing — a borey-type unit in Phnom Penh — is considered. The building comprises 8 dwelling units, with each dwelling having 2 floors (Ground +1) and a built-up area of 60 m^2.

The structure includes a living room, dining room, kitchen, and a toilet on the ground floor. On the first floor, there are two bedrooms and a toilet, connected through a staircase. The bedrooms in this building typology are air-conditioned, while the rest of the rooms are naturally ventilated, based on the outdoor conditions defined in the natural ventilation calculation inputs in section 2.2.4.

A snapshot of the energy model of the building is presented in the figure below.

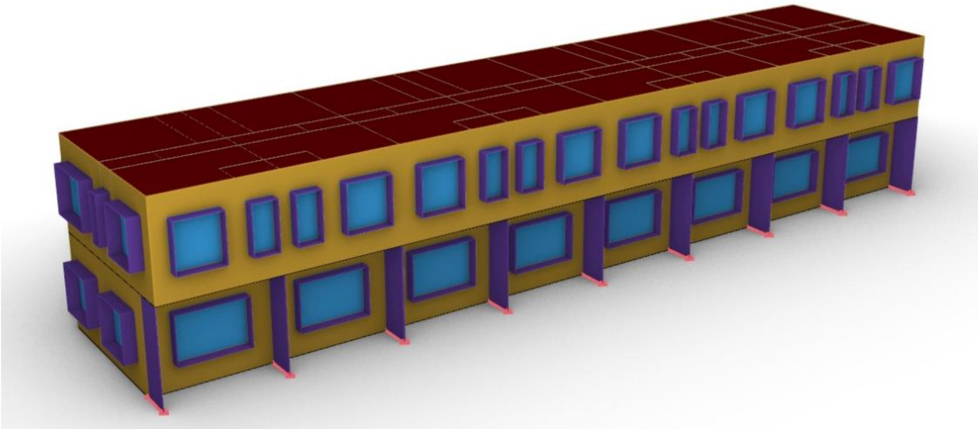


Figure 5 Building Energy Model: Affordable Housing Borey-Type

The floor plans of the individual dwellings are shown in the figures below:

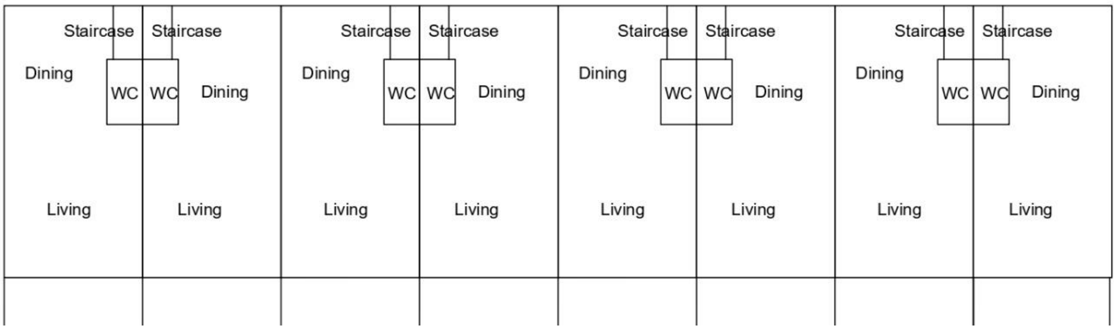


Figure 6 Ground Floor Plan: Affordable Housing Borey-Type

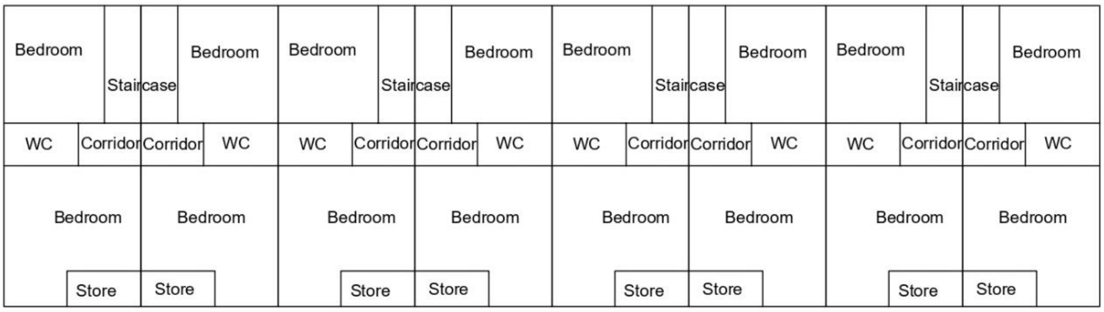


Figure 7 First Floor Plan: Affordable Housing Borey-Type

The passive design strategies considered in the parametric energy simulation for this typology include the orientation of the building at the site with respect to true North, Window-to-Wall Ratio (WWR), shading (box type), Window Opening Ratio (WoR), and the Window Cross Ventilation.

3.1.1.2 Results of Affordable Housing: Borey-Type

The simulation analysis provides the annual cooling demand, associated energy consumption, and thermal comfort with natural ventilation. The parametric analysis, considering all the envelope construction and passive cooling strategies, indicates that the Cooling Energy Performance Index (CEPI) for affordable housing: borey-type ranges between 31 to 88 kWh/m^2.year. Comparative results from the four CEPI performance levels are presented in the table below:

Table 11 CEPI Performance Levels For Affordable Housing: Borey-Type

Indicator	Near-Zero Scenario	High-Performance Scenario	Code Compliance Scenario	BAU Scenario	Unit
Annual Cooling Demand	94-160	161-182	183-208	209-235	kWh$_{thermal}$/m^2.year
Annual Baseline CEPI	31-53	54-61	62-69	70-78	kWh/m^2.year
Annual Cooling Energy Savings	25-47	18-24	9-17	8	kWh/m^2.year
% Cooling Energy Savings compared with baseline	32-60%	22-31%	12-21%	0-11%	

3.1.1.2.1 PCS Selection Matrix to Achieve the Near-Zero Scenario

The CEPI range for near-zero scenario is between 31 and 53 kWh/m^2.year. The table below illustrates the PCS selection matrix for achieving a near-zero scenario for borey-type affordable housing.

Table 12 PCS Selection Matrix for Achieving Near-Zero Scenario in Affordable Housing: Borey-Type

Building Envelope Configuration	WWR	Shading Depth	Orientation	Window Opening Ratio	Window Cross Ventilation	CEPI Range (kWh/m^2.year)
Baseline envelope performance case	0.3	0.5 m, 1 m	0, 180	0.3 to 0.6	0 & 1	31-53
	0.4	1 m	0, 180	0.3 to 0.6	0 & 1	
Intermediate envelope performance case	0.3	0.5 m, 1 m	0, 180	0.3 to 0.6	0 & 1	
	0.4	0.5 m	0, 180	0.3 to 0.6	0 & 1	
Best envelope performance case	0.3	No shading	0, 180	0.3 to 0.6	0 & 1	
		0.5 m	All orientations	0.3 to 0.6	0 & 1	
		1 m		0.3 to 0.6	0 & 1	
	0.4	0.5 m, 1 m		0.3 to 0.6	0 & 1	
	0.5	0.5 m, 1 m		0.3 to 0.6	0 & 1	
	0.6	0.5 m, 1 m		0.3 to 0.6	0 & 1	

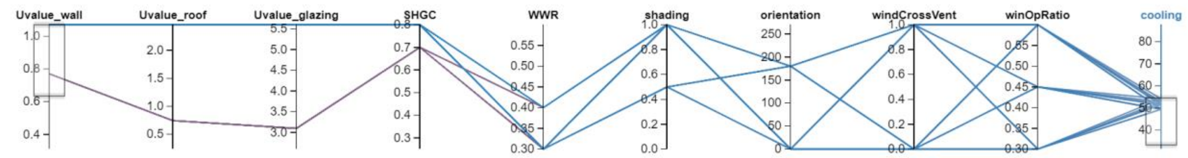


Figure 8 Results with Baseline & Intermediate Envelope Configurations to Achieve Near-Zero Scenario in Affordable Housing: Borey-Type

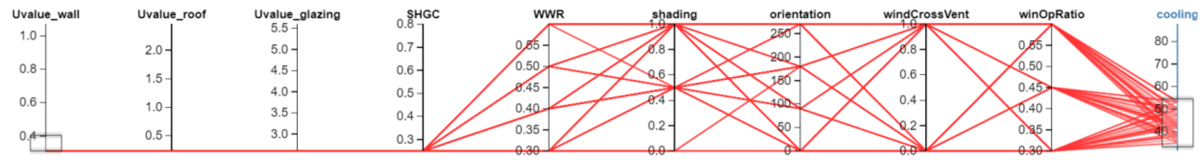


Figure 9 Results with Best-Performance Envelope Configuration to Achieve Near-Zero Scenario in Affordable Housing: Borey-Type

The results in Table 12 indicate that achieving the CEPI range under a near-zero scenario is only possible with baseline and intermediate envelope configurations by minimising the WWR to 0.3 - 0.4, requiring shading depth between 0.5 m and 1 m. Regardless of WWR or shading variation, optimal outcomes are observed when the building's longer façade faces North-South.

The best-performance building envelope configuration allows maximum flexibility for incorporating all PCS strategies. The WWR serves as the key design parameter, guiding the selection of a suitable shading depth. Unshaded windows result in a limited adoption, restricted to orientations of 0 and 180 degrees.

The order of significance of the PCS strategies is depicted in the figure below:

Figure 10 Order of Significance of PCS for Achieving Near-Zero Scenario in Affordable Housing: Borey-Type

3.1.1.2.2 PCS Selection Matrix to Achieve the High-Performance Scenario

The CEPI range for high-performance scenario is between 54 and 61 kWh/m^2.year. Table 13 presents the PCS selection matrix for achieving high-performance scenario in borey-type affordable housing.

Table 13 PCS Selection Matrix for Achieving High-Performance Scenario in Affordable Housing: Borey-Type

Building Envelope Configuration	WWR	Shading Depth	Orientation	Window Opening Ratio	Window Cross Ventilation	CEPI Range (kWh/m^2.year)
Baseline envelope performance case	0.3	0.5 m	90, 180, 270	0.3 to 0.6	0 & 1	54-61
	0.3	1 m	90, 270	0.3 to 0.6	0 & 1	
	0.4	0.5 m	0, 180	0.3 to 0.6	0 & 1	
	0.4	1 m	90, 270	0.3 to 0.6	0 & 1	
	0.5	0.5 m	0	0.3 to 0.6	0 & 1	
	0.5	1 m	0, 90, 180	0.3 to 0.6	0 & 1	
	0.6	1 m	0, 180	0.3 to 0.6	0 & 1	
Intermediate envelope performance case	0.3	0.5 m	90, 180, 270	0.3 to 0.6	0 & 1	
	0.3	1 m	90, 270	0.3 to 0.6	0 & 1	
	0.4	0.5 m	0, 180	0.3 to 0.6	0 & 1	
	0.4	1 m	90, 270	0.3 to 0.6	0 & 1	
	0.5	0.5 m	0	0.3 to 0.6	0 & 1	
	0.5	1 m	0, 90, 180	0.3 to 0.6	0 & 1	
	0.6	1 m	0, 180	0.3 to 0.6	0 & 1	
Best envelope performance case	0.3	No shading	90, 270	0.3 to 0.6	0 & 1	
	0.4	No shading	0, 180	0.3 to 0.6	0 & 1	
	0.4	0.5 m	270	0.3 to 0.6	0 & 1	
	0.5	0.5 m	90, 270	0.3 to 0.6	0 & 1	
	0.6	0.5 m	0, 180	0.3 to 0.6	0 & 1	
	0.6	1 m	90, 270	0.3 to 0.6	0 & 1	

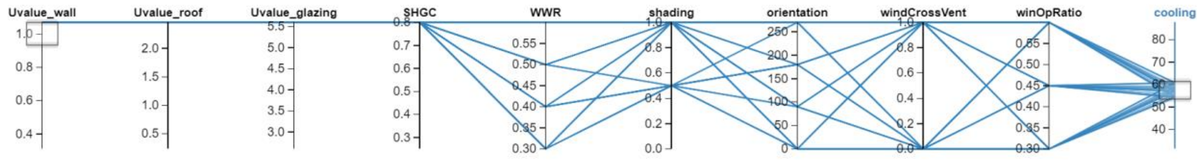


Figure 11 Results with Baseline Envelope Configuration to Achieve High-Performance Scenario in Affordable Housing: Borey-Type

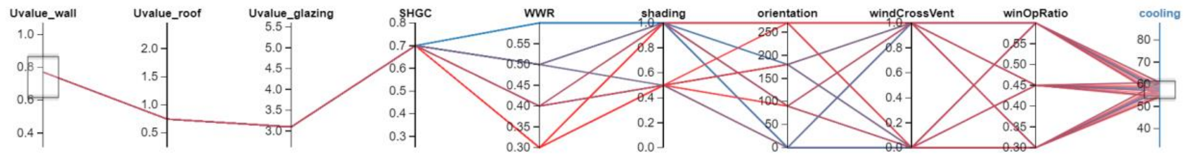


Figure 12 Results with Intermediate Envelope Configuration to Achieve High-Performance Scenario in Affordable Housing: Borey-Type

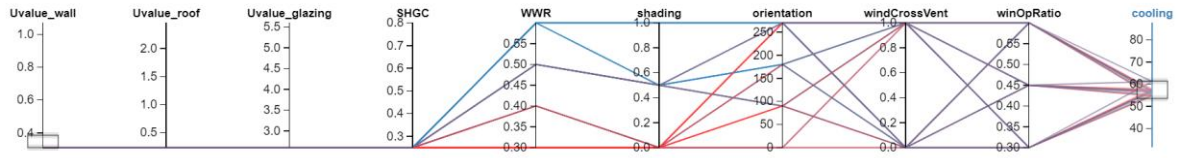


Figure 13 Results with Best-Performance Envelope Configuration to Achieve High-Performance Scenario in Affordable Housing: Borey-Type

To attain the high-performance scenario, multiple design options are available within the baseline, intermediate and best-performance envelope configurations. Despite the best-performance envelope configuration offering flexibility in shading design, the desired energy performance can be easily achieved through baseline and intermediate materials, with adjustments in WWR and orientation of the building.

The order of significance of the PCS strategies is illustrated in the figure below:

Figure 14 Order of Significance of PCS for Achieving High-Performance Scenario in Affordable Housing: Borey-Type

3.1.1.2.3 PCS Selection Matrix to Achieve Code Compliance Scenario

The CEPI range for the code compliance scenario falls between 62 and 69 kWh/m^2.year. Table 14 presents the PCS selection matrix for achieving code compliance scenario in borey-type affordable housing.

Table 14 PCS Selection Matrix for Achieving Code Compliance Scenario in Borey-Type Affordable Housing

Building Envelope Configuration	WWR	Shading Depth	Orientation	Window Opening Ratio	Window Cross Ventilation	CEPI Range (kWh/m^2.year)
Baseline envelope	0.3	No shading	0, 90, 180	0.3 to 0.6	0 & 1	62-69
	0.4	0.5 m	90, 270	0.3 to 0.6	0 & 1	

performance case	0.5	0.5 m	90, 180	0.3 to 0.6	0 & 1	
	0.5	1 m	270	0.3 to 0.6	0 & 1	
	0.6	0.5 m	0, 180	0.3 to 0.6	0 & 1	
	0.6	1 m	90, 270	0.3 to 0.6	0 & 1	
Intermediate envelope performance case	0.3	No shading	0, 90, 180	0.3 to 0.6	0 & 1	
	0.4	0.5 m	90, 270	0.3 to 0.6	0 & 1	
	0.4	0.5 m	90, 180	0.3 to 0.6	0 & 1	
	0.4	1 m	90, 270	0.3 to 0.6	0 & 1	
	0.5	0.5 m	90, 180	0.3 to 0.6	0 & 1	
	0.5	1 m	270	0.3 to 0.6	0 & 1	
	0.6	0.5 m	0, 180	0.3 to 0.6	0 & 1	
	0.6	1 m	90, 270	0.3 to 0.6	0 & 1	
Best envelope performance case	0.4	No shading	90, 270	0.3 to 0.6	0 & 1	
	0.5	No shading	0, 180	0.3 to 0.6	0 & 1	
	0.6	No shading	0, 180	0.3 to 0.6	0 & 1	
	0.5	0.5 m	90, 270	0.3 to 0.6	0 & 1	

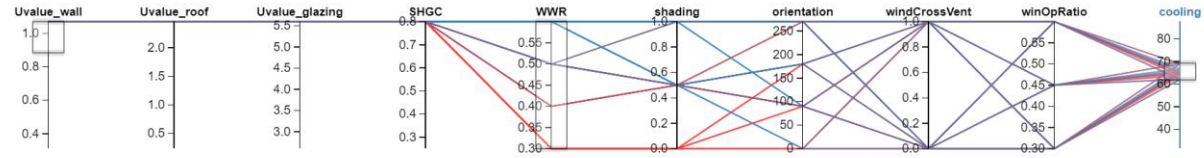


Figure 15 Results with Baseline Envelope Configuration to Achieve Code Compliance Scenario in Affordable Housing: Borey-Type

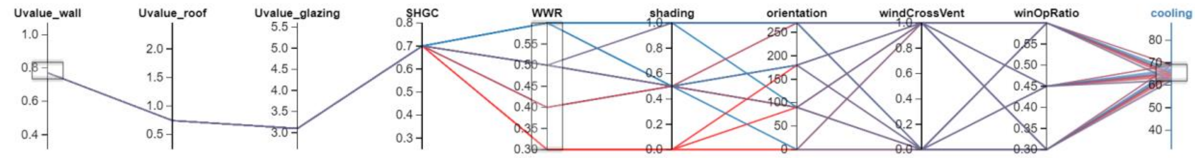


Figure 16 Results with Intermediate Envelope Configuration to Achieve Code Compliance Scenario in Affordable Housing: Borey-Type

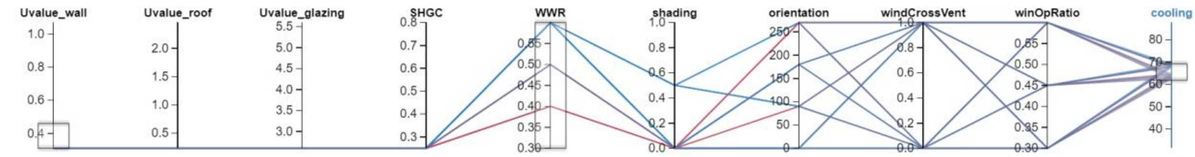


Figure 17 Results with Best-Performance Envelope Configuration to Achieve Code Compliance Scenario in Affordable Housing: Borey-Type

In achieving the performance code compliance scenario, the building design can exhibit extensive flexibility concerning the selection of the building envelope and the PCS design outlined in the preceding table and figures. At this level, no parameters demonstrate a strong relationship with the CEPI, with the building orientation providing the most significant correlation with changes in building envelope configurations.

The order of significance of the PCS strategies is illustrated in the figure below:

Figure 18 Order of Significance of PCS for Achieving Code Compliance Scenario in Affordable Housing: Borey-Type

3.1.1.3 Summary of the Results of Affordable Housing: Borey-Type

To achieve optimal CEPI targets for affordable housing, specifically borey-type units, the emphasis should be on the building design parameters such as WWR and shading, followed by the selection of construction materials. This approach can result in enhanced energy savings with lower associated costs. Shading emerges as a crucial factor in achieving higher energy savings (up to 11%), particularly in scenarios where a higher WWR is essential in the dwelling's design, even when conventional construction materials are employed.

3.1.2 Affordable Housing: Condominium-Type

This typology refers to affordable housing units with a built-up area of up to 60 m^2, structured in the form of towers, featuring one dwelling or flat per household. To conduct parametric energy simulations, a representative building of affordable housing ─ a condominium-type unit in Phnom Penh ─ is taken into consideration.

The building comprises five dwelling units, each with two floors (Ground+1), resulting in a total built-up area of 360 m^2. The layout includes a living room, dining room, kitchen, and a toilet on the ground floor. The first floor accommodates two bedrooms and another toilet, connected by a staircase. Notably, the bedrooms in this building typology are air-conditioned, while the remaining rooms rely on naturally ventilation, guided by the outdoor conditions specified in the inputs for natural ventilation calculation in Section 2.2.4.

Refer to the figure below for a snapshot of the energy model and the floor plans of the building.

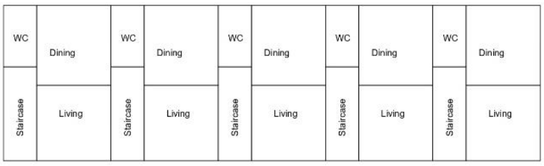


Figure 19 Ground Floor Plan: Affordable Housing Condominium-Type

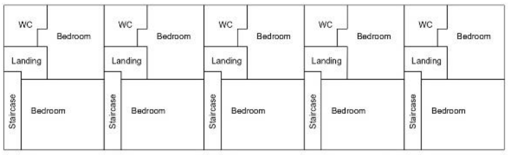


Figure 20 First Floor Plan: Affordable Housing Condominium-Type

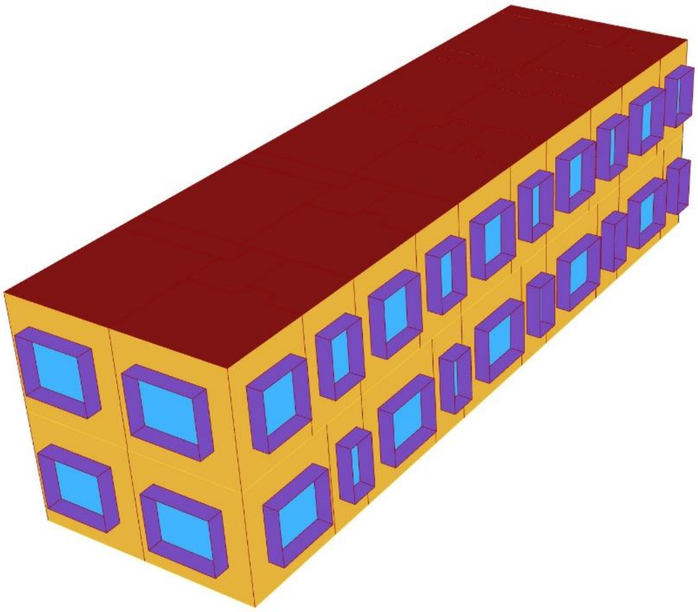


Figure 21 Building Energy Model of Affordable Housing: Condominium-Type

3.1.2.1 Results of Affordable Housing: Condominium-Type

Across various construction materials and passive cooling design strategies, the CEPI for affordable housing of the condominium-type falls between the range of 26 to 87 kWh/m^2.year. The comparative results from the four CEPI performance levels are illustrated in the table below.

Table 15 Energy Savings Potential Results for Affordable Housing: Condominium-Type

Indicator	Near-Zero Scenario	High-Performance Scenario	Code Compliance Scenario	BAU Scenario	Unit
Annual cooling demand	77-141	142-169	170-194	195-227	kWh$_{thermal}$/m^2.year
Annual baseline cooling energy performance index	26-47	48-56	57-65	66-76	kWh/m^2.year
Annual Cooling Energy Savings	29-20	19-28	11-18	10	kWh/m^2.year
% Cooling Energy Savings compared with baseline	38-66%	26-36%	16-24%	13%	

3.1.2.1.1 PCS Selection Matrix to Achieve the Near-Zero Scenario

The PCS selection matrix for achieving the near-zero scenario for affordable housing condominium-type is presented in the table below.

Table 16 PCS Selection Matrix to Achieve Near-Zero Scenario in Affordable Housing: Condominium-Type

Building Envelope Configuration	WWR	Shading Depth	Orientation	Window Opening Ratio	Window Cross Ventilation	CEPI Range (kWh/m^2.year)
Baseline Envelope Performance	0.3	1m	90,270	0.3 to 0.6	0 & 1	26-47
	0.4	1m	270	0.3 to 0.6	0 & 1	

Building Envelope Configuration	WWR	Shading Depth	Orientation	Window Opening Ratio	Window Cross Ventilation	CEPI Range (kWh/m^2.year)
Case & Intermediate Envelope Performance Case						
Best Envelope Performance Case	0.3	No shading	270	0.3	0	
		0.5 m	0,90,180,270	0.3	0	
		1 m	0,90,180	0.3	0	
	0.4	No shading	270	0.3	0	
		0.5 m	0,90,270	0.3	0	
		1 m	0,90,180	0.3	0	
	0.5	0.5 m	270	0.3	0	
		1 m	0,90,180	0.3	0	
	0.6	1 m	90	0.3	0	

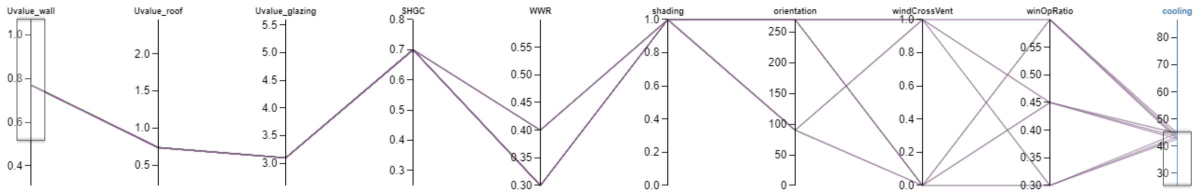


Figure 22 Results with Baseline & Intermediate Envelope Configurations to Achieve Near-Zero Scenario in Affordable Housing: Condominium

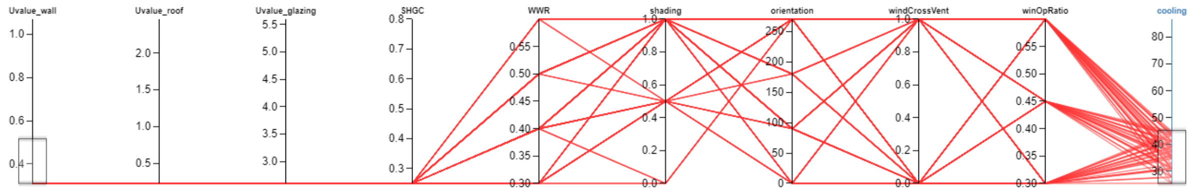


Figure 23 Results with Best-Performance Envelope Configuration to Achieve Near-Zero Scenario in Affordable Housing: Condominium

3.1.2.1.2 PCS Selection Matrix to Achieve the High-Performance Scenario

The CEPI range for high-performance scenario falls between 48 and 56 kWh/m^2.year. The PCS selection matrix for achieving the high-performance scenario for affordable housing of the condominium-type is presented in the table below.

Table 17 PCS Selection Matrix to Achieve High-Performance Scenario in Affordable Housing: Condominium

Building Envelope Configuration	WWR	Shading Depth	Orientation	Window Opening Ratio	Window Cross Ventilation	CEPI Range (kWh/m^2.year)
Baseline envelope performance case	0.3	0.5 m	90,270	0.3	0 &1	48-56
		1 m	0,180,270	0.3	0 &1	
	0.4	0.5 m	270	0.3	0 &1	
		1 m	90, 270	0.3	0 &1	
	0.5	1 m	90, 270	0.3	0 &1	
Intermediate envelope performance case	0.3	0.5 m	0,90,180,270	0.3	0 &1	
		1 m	0,180	0.3	0 &1	
	0.4	0.5 m	90,270	0.3	0	
		1 m	0,90,180	0.3	0	

Building Envelope Configuration	WWR	Shading Depth	Orientation	Window Opening Ratio	Window Cross Ventilation	CEPI Range (kWh/m^2.year)
	0.5	1 m	0,90,180,270	0.3	0	
Best envelope performance case	0.3	No shading	0,90, 180	0.3	0&1	
	0.4	No shading	90	0.3	0&1	
		0.5 m	180	0.3	0	
	0.5	0.5 m	0,90, 180	0.3	0&1	
	0.6	0.5 m	90, 270	0.3	0	
	0.6	1 m	0,180	0.3	0&1	

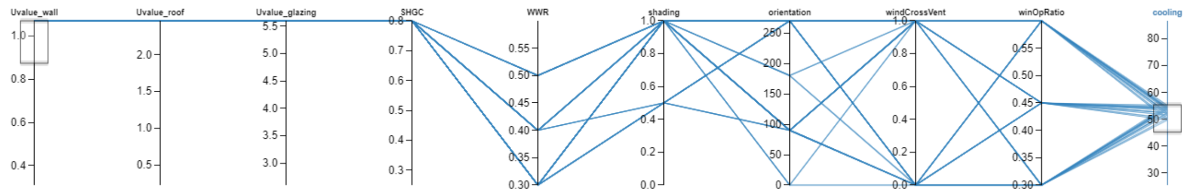


Figure 24 Results with Baseline Envelope Configuration to Achieve High-Performance Scenario in Affordable Housing: Condominium

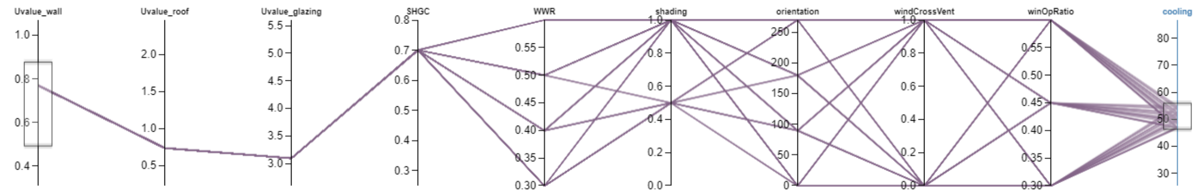


Figure 25 Results with Intermediate Envelope Configuration to Achieve High-Performance Scenario in Affordable Housing: Condominium

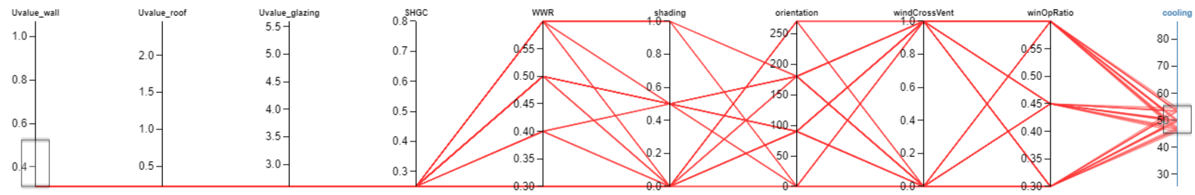


Figure 26 Results with Best-Performance Envelope Configuration to Achieve High-Performance Scenario in Affordable Housing: Condominium

3.1.2.1.3 PCS Selection Matrix to Achieve Code Compliance Scenario

The CEPI range for the code compliance scenario falls between 57 and 65 kWh/m^2.year. The table below presents the PCS selection matrix for achieving the code compliance scenario in affordable housing of the condominium-type.

Table 18 PCS Selection Matrix To Achieve Code Compliance Scenario In Affordable Housing: Condominium

Building Envelope Configuration	WWR	Shading Depth	Orientation	Window Opening Ratio	Window Cross Ventilation	CEPI Range (kWh/m^2.year)
Baseline envelope performance case	0.3	No shading	90,270	0.3	0	57-65
		0.5 m	0,180	0.3	0 &1	
	0.4	No shading	270	0.3	0	
	0.4	0.5 m	0, 90, 180	0.3	0 & 1	
	0.4	1 m	0,180	0.3	0	
	0.5	0.5 m	90	0.3	0	
	0.5	1 m	0,180	0.3	0	

Building Envelope Configuration	WWR	Shading Depth	Orientation	Window Opening Ratio	Window Cross Ventilation	CEPI Range (kWh/m^2.year)
	0.6	No shading	0, 90, 180	0.3	0	
		0.5 m	0, 90, 270	0.3	0	
		1 m	90, 270	0.3	0	
Intermediate envelope performance case	0.3	No shading	0, 90, 180,270	0.3	0 & 1	
	0.4	No shading	0,180	0.3	0	
		0.5 m	0,180	0.3 to 0.45	0 & 1	
	0.5	0.5 m	0,90, 180	0.3	0 & 1	
	0.6	0.5 m	90, 270	0.3	0	
		1 m	90, 180	0.3	0 & 1	
Best envelope performance case	0.4	No shading	0,180	0.3 to 0.45	0 & 1	
	0.5	No shading	0,90	0.3 to 0.45	0 & 1	
	0.6	No shading	90	0.3 to 0.45	0 & 1	
		0.5 m	0,180	0.3 to 0.45	0 & 1	

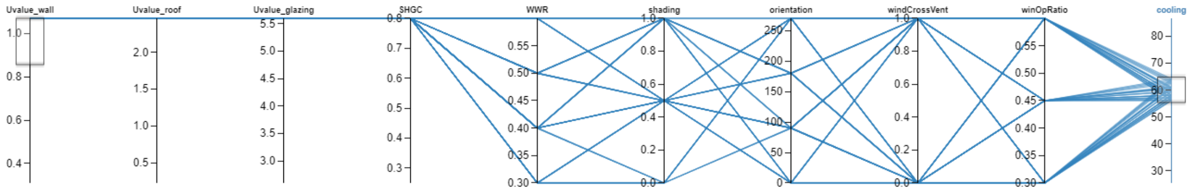


Figure 27 Results with Baseline Envelope Configuration to Achieve Code Compliance Scenario in Affordable Housing: Condominium

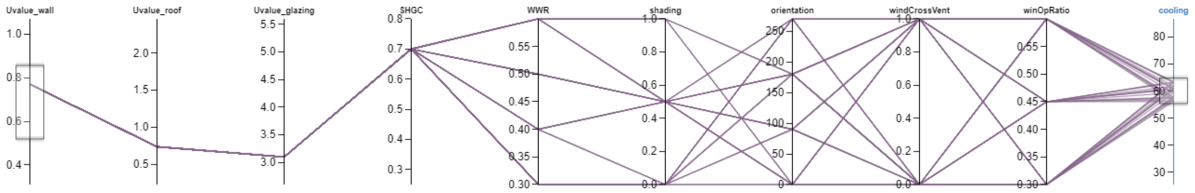


Figure 28 Results with Intermediate Envelope Configuration to Achieve Code Compliance Scenario in Affordable Housing: Condominium

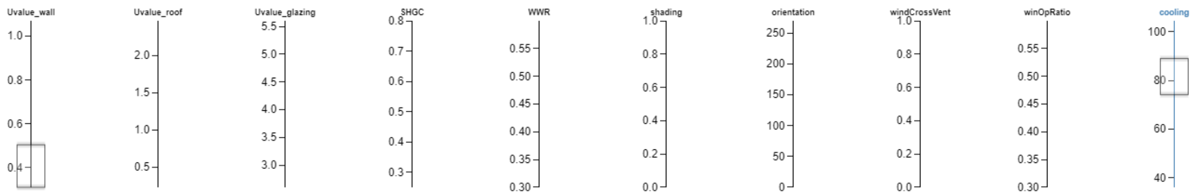


Figure 29 Results with Best-Performance Envelope Configuration to Achieve Code Compliance Scenario in Affordable Housing: Condominium

3.1.2.2 Summary of the Results of Affordable Housing: Condominium-Type

To attain the optimal CEPI targets for affordable housing of the condominium-type, priority should be placed on the selection of building construction materials. Subsequently, attention should be given to design parameters such as WWR, shading, and the building orientation at the site. Insulation of the building plays a major role in achieving higher energy savings (9 to 22%), followed by shading (3 to 13%), even in cases where a higher WWR is essential in the design of the dwelling.

3.2 Residential Buildings: Middle & High-Income Housing

This typology comprises buildings with a higher floor area per occupant in comparison to the affordable housing units in Cambodia, with the built-up area per dwelling unit ranging from 80 m^2 to 200 m^2. The Middle & High-Income Housing (MHIH) isconstructed in two types in Cambodia, namely, the borey-type and the condominium type.

3.2.1 MHIH: Borey-Type

3.2.1.1 Building Description

A representative building of the borey-type (landed dwelling) housing unit in Phnom Penh is considered in the parametric energy simulation. The building consists of 2 floors (Ground +1) with a built-up area of 148 m^2. The structure includes a living room, dining room, kitchen, and a toilet on the ground floor, and 3 bedrooms and 2 toilets on the first floor, connected by a staircase. The bedrooms and living rooms in this building typology are air-conditioned, while the rest of the rooms are naturally ventilated, based on the outdoor conditions defined in the natural ventilation calculation inputs in Section 2.2.4.

A snapshot of the energy model and floor plan of the building is presented in the figure below.

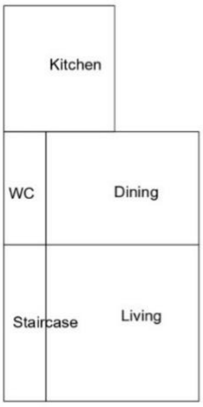


Figure 30 Ground Floor Plan

Figure 31 First Floor Plan

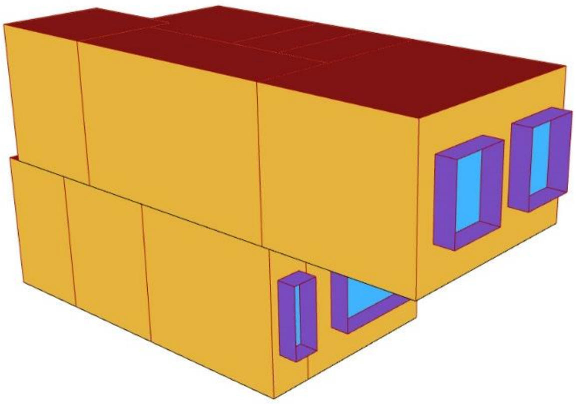


Figure 32 Snapshot of the Energy Model - MHIH: Borey-Type

The passive design strategies considered in the parametric energy simulation for this typology include the orientation of the building at the site with respect to True North, Window-to-Wall Ratio (WWR), shading (box type), Window Opening Ratio (WoR), and the Window Cross Ventilation.

3.2.1.2 Results of MHIH: Borey-Type

Across various construction materials and passive cooling design strategies, the CEPI for borey housing ranges from of 36 to 104 kWh/m^2.year. The comparative results for the four CEPI performance levels are presented in the table below

Table 19 Energy Savings Potential Results for MHIH: Borey-Type

Indicator	Near-Zero Scenario	High-Performance Scenario	Code Compliance Scenario	BAU Scenario	Unit
Annual Cooling Demand	109-165	166-217	218-260	261-286	kWh$_{thermal}$/m^2.year
Annual Baseline Cooling Energy Performance Index	36-55	56-72	73-87	88-95	kWh/m^2.year
Annual Cooling Energy Savings	40-59	23-39	9-22	8	kWh/m^2.year
% Cooling Energy Savings Compared with Baseline	42-62%	24-41%	9-23%	0-8%	

3.2.1.2.1 PCS Selection Matrix to Achieve Near-Zero Scenario

The table below illustrates the PCS selection matrix for achieving the near-zero scenario for MHIH borey-type affordable housing.

Table 20 PCS Selection Matrix to Achieve Near-Zero Scenario in MHIH: Borey-Type

Building Envelope Configuration	WWR	Shading Depth	Orientation	Window Opening Ratio	Window Cross Ventilation	CEPI Range (kWh/m^2.year)
Baseline envelope performance case & Intermediate envelope performance case	If the baseline and intermediate envelope performance values are selected, the estimated CEPI range exceeds the CEPI range specified for the near-zero compliance scenario.					36-55
Best envelope performance case	0.3	No shading	0	0.3 to 0.6	0	
		0.5 m	0,90,180	0.3 to 0.6	0	
		1 m	0,90,180	0.3 to 0.6	0	
	0.4	0.5 m	0,90,180	0.3 to 0.6	0	
	0.4	1 m	0,90	0.3 to 0.6	0	
	0.5	0.5 m	0,180	0.3 to 0.6	0	
	0.5	1 m	0,90	0.3 to 0.6	0	
	0.6	0.5 m	180	0.3 to 0.6	0	
	0.6	1 m	0	0.3 to 0.6	0	

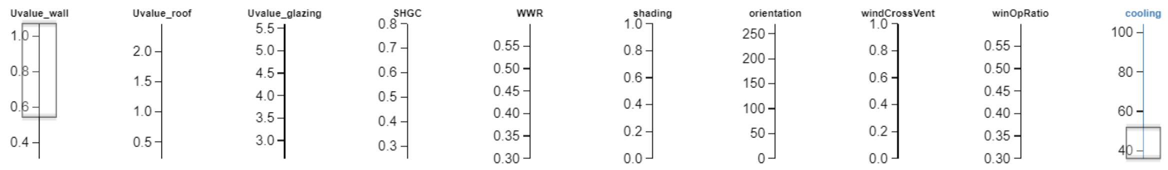


Figure 33 Results with Baseline & Intermediate Envelope Configurations to Achieve Near-Zero Scenario in MHIH: Borey-Type

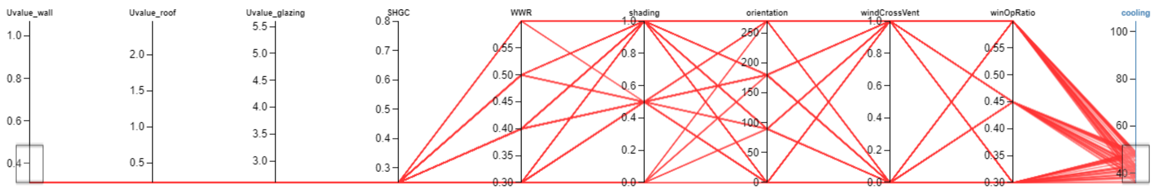


Figure 34 Results with Best-Performance Envelope Configuration to Achieve Near-Zero Scenario in MHIH: Borey-Type

The results in the table indicate that, with the baseline and intermediate envelope configurations, there is no combination available to achieve the CEPI range under a near-zero scenario. The use of best-performance building envelope configuration offers several site and design options, shown in the table above. The dictating design parameter is the WWR, guiding the selection of suitable shading depth and the orientation of the façade. The higher the WWR, the more the requirement for shading, and all orientations become feasible with shading depths above 0.5 m.

The order of significance of the PCS strategies is illustrated in the figure below:

Figure 35 Order of Significance of PCS to Achieve Near-Zero Scenario in MHIH: Borey-Type

3.2.1.2.2 PCS Selection Matrix to Achieve the High-Performance Scenario

The CEPI range for the high-performance scenario falls between 56 and 72 kWh/m^2.year. Table 21 presents the PCS selection matrix for achieving high-performance scenario in MHIH borey type affordable housing.

Table 21 PCS Selection Matrix to Achieve High-Performance Scenario in MHIH: Borey-Type

Building Envelope Configuration	WWR	Shading Depth	Orientation	Window Opening Ratio	Window Cross Ventilation	CEPI Range (kWh/m^2.year)
Baseline Envelope Performance Case	If the baseline envelope performance values are selected, the estimated CEPI range exceeds the CEPI range specified for the near-zero compliance scenario.					56-72
Intermediate Envelope Performance Case	0.3	No Shading	0,90,180	0.3	0	
	0.3	0.5 m	0,90,180	0.3	0	
	0.3	1 m	0,90,180	0.3	0	
	0.4	0.5 m	0,90,180	0.3	0	

	0.4	1 m	0,90	0.3	0	
	0.5	0.5 m	0,180	0.3	0	
	0.5	1 m	0, 90	0.3	0	
	0.6	0.5 m	180	0.3	0	
	0.6	1 m	0	0.3	0	
Best Envelope Performance Case	0.4	No shading	0,90, 270	0.3	0&1	
	0.5	No shading	0, 90, 180, 270	0.3	0&1	
	0.5	0.5 m	90, 270	0.3	0	
	0.6	No shading	0, 90, 180, 270	0.3	0&1	
	0.6	0.5 m	90, 270	0.3	0	
	0.6	1 m	90	0.3	0	

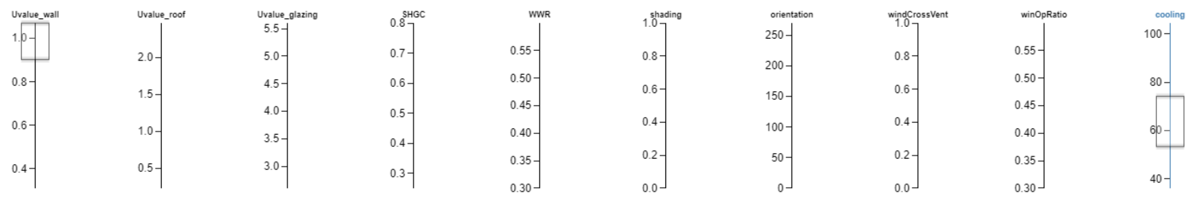


Figure 36 Results with Baseline Envelope Configuration to Achieve High-Performance Scenario in MHIH: Borey-Type

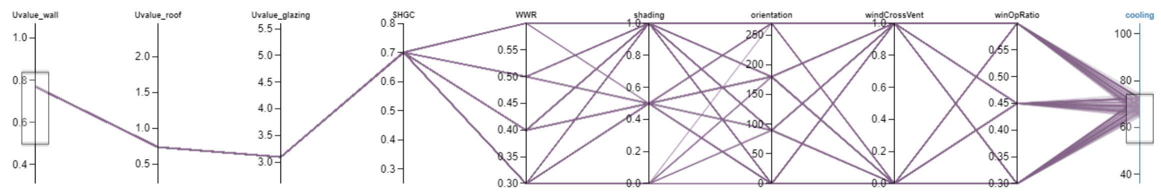


Figure 37 Results with Intermediate Envelope Configuration to Achieve High-Performance Scenario in MHIH: Borey-Type

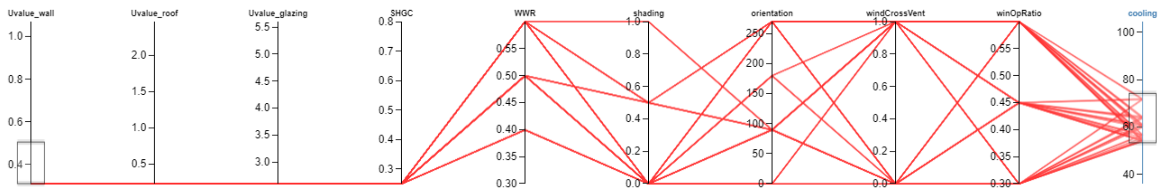


Figure 38 Results with Best-Performance Envelope Configuration to Achieve High-Performance Scenario in MHIH: Borey-Type

3.2.1.2.3 PCS Selection Matrix to Achieve Code Compliance Scenario

The CEPI range for the code compliance scenario falls between 73 and 87 kWh/m^2.year. Table 14 illustrates the PCS selection matrix for achieving the code compliance scenario in MHIH borey-type affordable housing.

Table 22 PCS Selection Matrix to Achieve Code Compliance Scenario in MHIH: Borey-Type

Building Envelope Configuration	WWR	Shading Depth	Orientation	Window Opening Ratio	Window Cross Ventilation	CEPI Range (kWh/m^2.year)
Baseline Envelope Performance Case	0.3	No shading	180	0.3	0	73-87
	0.3	0.5 m	0, 90, 180, 270	0.3	0	
	0.3	1 m	0, 90, 180, 270	0.3	0	
	0.4	0.5 m	0,180	0.3	0	
	0.4	1 m	0, 90, 180, 270	0.3	0	
	0.5	0.5 m	180	0.3	0	
	0.5	1 m	0, 180	0.3	0	

	0.6	1 m	0, 180	0.3	0	
Intermediate Envelope Performance Case	0.3	No shading	270	0.3	0	
	0.4	No shading	0, 90, 180,270	0.3	0 & 1	
	0.5	No shading	0, 90, 180,270	0.3	0	
	0.5	0.5 m	90, 270	0.3	0	
	0.6	No shading	0, 90, 180	0.3	0	
	0.6	0.5 m	0, 90, 270	0.3	0	
	0.6	1 m	90, 270	0.3	0	
Best Envelope Performance Case	If the best envelope performance values are selected, the estimated CEPI range is better than the code compliance scenario CEPI range.					

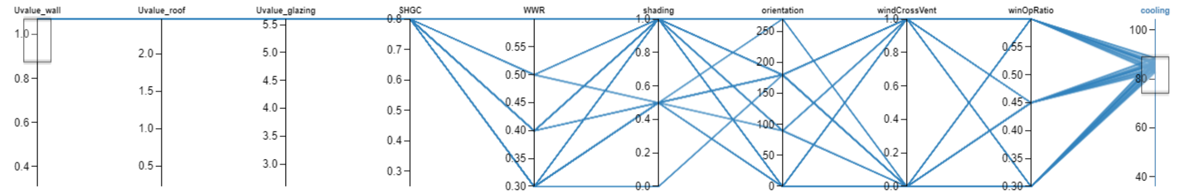


Figure 39 Results with Baseline Envelope Configuration to Achieve Code Compliance Scenario in MHIH: Borey-Type

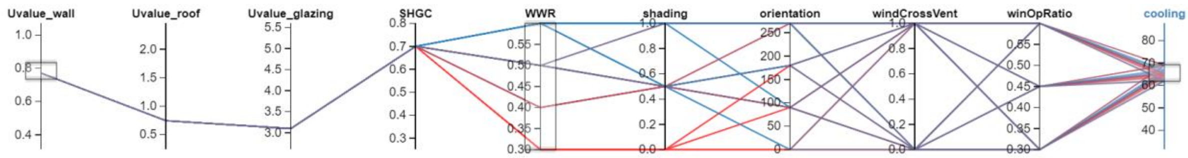


Figure 40 Results with Intermediate Envelope Configuration to Achieve Code Compliance Scenario in MHIH: Borey-Type

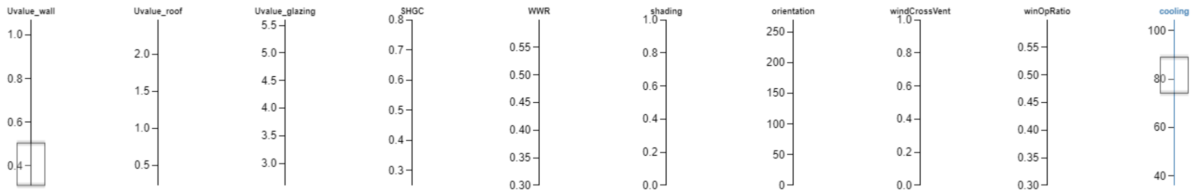


Figure 41 Results with Best-Performance Envelope Configuration to Achieve Code Compliance Scenario in MHIH: Borey-Type

3.2.1.3 Summary of the Results of MHIH: Borey-Type

To achieve the best CEPI targets for MHIH: borey-type units, the emphasis should be on the selection of building construction materials. Subsequently, attention should be given to design parameters such as WWR and shading, followed by consideration of the building orientation at the site. Insulation of the building plays a significant role in achieving higher energy savings (11 to 19%), followed by shading (6 to 15%), even in the cases where a higher WWR is essential in the design of the dwelling.

3.2.2 MHIH: Condominium-Type

3.2.2.1 Building Description

A representative building of the residential condominium in Phnom Penh is considered in the parametric energy simulation. The building comprises 2 towers, each with 45 floors (Ground + 44 floors), resulting in a total built-up area of 8,516 m^2.

The structure includes units with varying configurations, such as 1 Bedroom, 2 Bedrooms + Study room, 3 Bedroom, Penthouses (2-4 Bedrooms) and Small Office Home Office (SOHO). In this building typology, the bedrooms are air-conditioned, while the rest of the rooms, corridors, and staircases are naturally ventilated. This ventilation is based on the outdoor conditions defined in the calculation inputs for natural ventilation in Section 2.2.4. For the parametric simulation runs, the ground, 23rd, and 45th floors are considered, with each floor having an area of 1,550 m².

A snapshot of the energy model of the building is presented in the figure below.

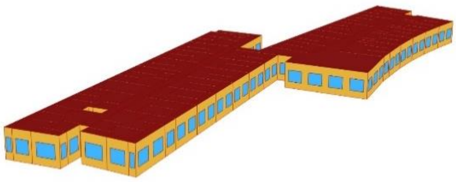


Figure 42 Building Energy Model of MHIH: Condominium-Type

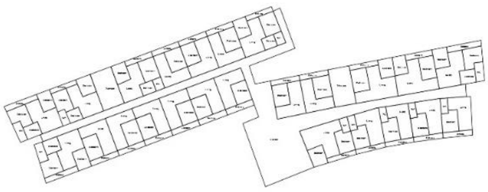


Figure 43 Floor Plan of MHIH: Condominium-Type

The passive design strategies considered in the parametric energy simulation for this typology include the orientation of the building at the site with respect to True North, Window-to-Wall Ratio (WWR), shading (box type), Window Opening Ratio (WoR), and the Window Cross Ventilation.

3.2.2.2 Results Of MHIH: Condominium-Type

Across various construction materials and passive cooling design strategies, the CEPI for residential building MHIH falls between the range of 13 to 59 kWh/m^2.year. The comparative results for the four CEPI performance levels are presented in the table below.

Table 23 Energy Savings Potential Results for MHIH: Condominium

Indicator	Near-Zero Scenario	High-Performance Scenario	Code Compliance Scenario	BAU Scenario	Unit
Annual Cooling Demand	39-56	57-90	91-130	131-153	$kWh_{thermal}/m^2$.year
Annual Baseline Cooling Energy Performance Index	13-19	20-30	31-43	44-51	kWh/m^2.year
Annual Cooling Energy Savings	33-38	21-32	8-20	7	kWh/m^2.year
% Cooling Energy Savings Compared With Baseline	64-75%	41-62%	15-39%	0-13%	

3.2.2.2.1 PCS Selection Matrix To Achieve The Near-Zero Scenario

The PCS selection matrix for achieving the near-zero scenario for MHIH condominium-type is presented in the table below.

Table 24 PCS Selection Matrix to Achieve Near-Zero Scenario in MHIH: Condominium-Type

Building Envelope Configuration	WWR	Shading Depth	Orientation	Window Opening Ratio	Window Cross Ventilation	CEPI Range (kWh/m^2.year)

Baseline Envelope Performance Case & Intermediate Envelope Performance Case	If the performance values for the baseline and intermediate envelope are selected, the estimated CEPI range exceeds the CEPI range specified for the near-zero compliance scenario.					13-19
Best Envelope Performance Case	0.3	No shading	0,90,180	0.3	0	
		0.5 m	0,90,180	0.3	0	
		1 m	0,90	0.3	0	
	0.6	0.5 m	0	0.3	0	
		1 m	0,90	0.3	0	

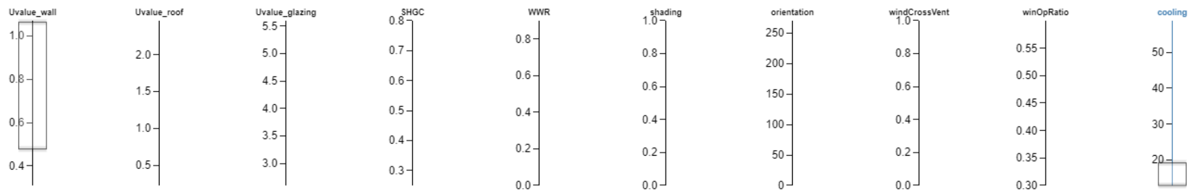


Figure 44 Results with Baseline & Intermediate Envelope Configurations to Achieve Near-Zero Scenario in MHIH: Condominium

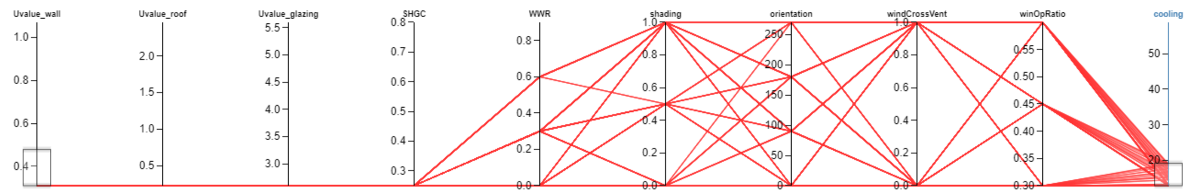


Figure 45 Results with Best-Performance Envelope Configuration to Achieve Near-Zero Scenario n MHIH: Condominium

3.2.2.2.2 PCS Selection Matrix to Achieve the High-Performance Scenario

The CEPI range for the high-performance scenario falls between 20 and 30 kWh/m^2.year. The PCS selection matrix for achieving the high-performance scenario for MHIH condominium-type is presented in the table below.

Table 25 PCS Selection Matrix For the High-Performance Scenario for Condominium-Type

Building Envelope Configuration	WWR	Shading Depth	Orientation	Window Opening Ratio	Window Cross Ventilation	CEPI Range (kWh/m^2.year)
Baseline Envelope Performance Case	If the performance values for the baseline envelope are selected, the estimated CEPI range exceeds the CEPI range specified for the near-zero compliance scenario.					20-30
Intermediate Envelope Performance Case	**0.3**	**1 m**	**0,90,180,270**	**0.3**	**0&1**	
	0.4	**1 m**	**0,180,270**	**0.3**	**0**	
	0.5	**1 m**	**0,180**	**0.3**	**0**	
Best Envelope Performance Case	0.6	No shading	0,90,180,270	0.3	0&1	
		0.5 m	90, 180, 270	0.3	0	
	0.9	No shading	0, 90, 180, 270			
	0.9	0.5 m	0, 90, 180, 270	0.3	0	
	0.9	1 m	90, 180, 270	0.3	0	

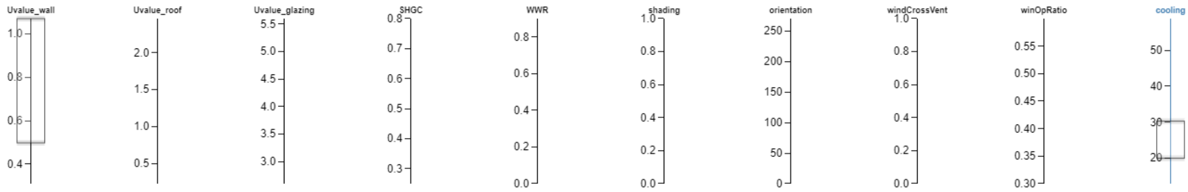


Figure 46 Results with Baseline Envelope Configuration to Achieve High-Performance Scenario in MHIH: Condominium

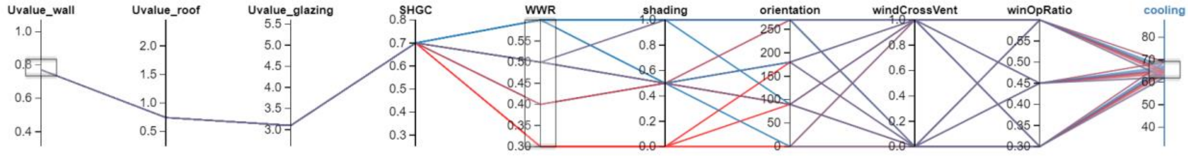


Figure 47 Results with Intermediate Material Configuration to Achieve High-Performance Scenario in MHIH: Condominium

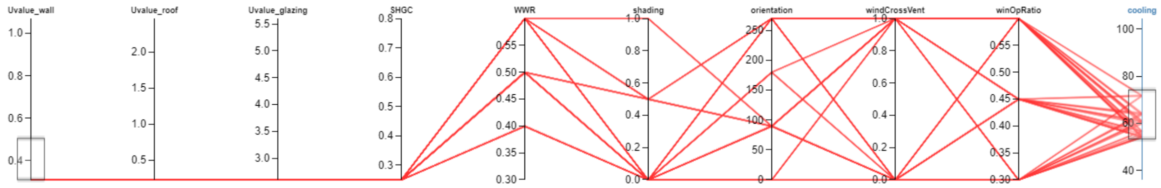


Figure 48 Results with Best-Performance Envelope Configuration to Achieve High-Performance Scenario in MHIH: Condominium

3.2.2.2.3 PCS Selection Matrix to Achieve Code Compliance Scenario

The CEPI range for the code compliance scenario falls between 31 and 43 kWh/m^2.year. Table 26 below presents the PCS selection matrix for achieving the code compliance scenario in MHIH condominium-type.

Table 26 PCS Selection Matrix to Achieve Code Compliance Scenario in MHIH: Condominium

Building Envelope Configuration	WWR	Shading Depth	Orientation	Window Opening Ratio	Window Cross Ventilation	CEPI Range (kWh/m^2.year)
Baseline Envelope Performance Case & Intermediate Envelope Performance Case	0.3	No shading	0	0.3	0	31-43
		0.5 m	0, 90, 180	0.3	0	
		1 m	0, 90, 180	0.3	0	
	0.6	1 m	0, 180	0.3	0	
Best Envelope Performance Case	If the best envelope performance values are selected, the estimated CEPI range surpasses the CEPI range specified for the code compliance scenario.					

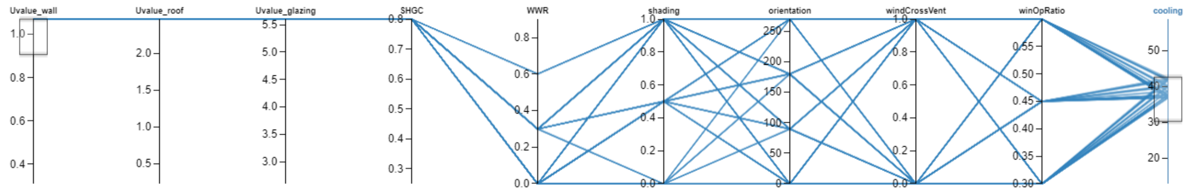


Figure 49 Results with Baseline and Intermediate Material Configuration to Achieve Code Compliance Scenario in MHIH: Condominium

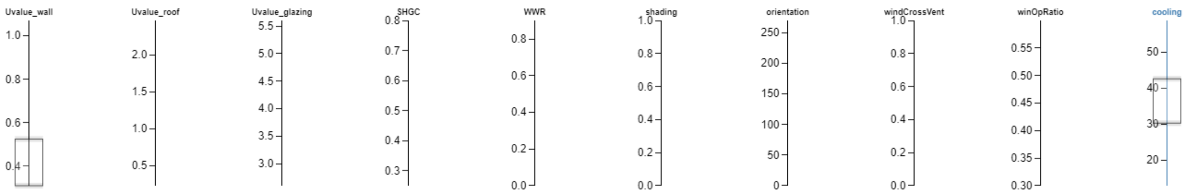


Figure 50 Results with Best-Performance Envelope Configuration to Achieve Code Compliance Scenario in MHIH: Condominium

3.2.2.3 Summary of the Results

To achieve the best CEPI targets for MHIH: condominium units, the emphasis should be on the selection of building construction materials, followed by attention to design parameters such as WWR and shading, and then considering the building orientation at the site. Insulation of the building plays a significant role in achieving higher energy savings (15 to 23%), followed by shading (7 to 18%), even in cases where a higher WWR is essential in the design of the dwelling.

3.3 Office Buildings

3.3.1 Building 1: High-Rise Modern Office

3.3.1.1 Building Description

In the parametric energy simulation, a representative high-rise modern office building in Phnom Penh is examined. This building comprises nineteen floors (Ground +18) with a total area of 20,415 m^2, featuring open office floors and resting spaces. The office spaces are air-conditioned, while the rest spaces, such as toilets, rely on natural ventilation based on outdoor conditions defined in the calculation inputs for natural ventilation (Section 2.2.4). The simulation focuses on the Ground, 9th, and 19th floors, each covering an area of 1,074 m^2. The energy model and floor plan snapshot of the building are presented in the figures below.

Figure 51 Typical Floor Plan: High-Rise Office Building

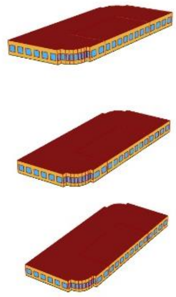


Figure 52 Snapshot of Energy Model: High-Rise Office Building

The parametric energy simulation for this typology considers passive design strategies like orientation with respect to True North, Window-to-Wall Ratio (WWR), shading (box type), Window Opening Ratio (WoR), and Window Cross Ventilation.

3.3.1.2 Results

The CEPI for high-rise office buildings, considering all construction materials and passive cooling strategies, ranges from 33 to 114 kWh/m^2.year. The table below provides a comparison of the results from the four performance scenarios.

Table 27 Energy Savings Potential Results for the High-Rise Office Building

Indicator	**Near-Zero Scenario**	**High-Performance Scenario**	**Code Compliance Scenario**	**BAU Scenario**	**Unit**
Annual Cooling Demand	99-176	177-244	245-267	268-342	kWh$_{thermal}$/m^2.year
Annual Baseline Cooling Energy Performance Index	33-59	60-81	82-89	90-114	kWh/m^2.year
Annual Cooling Energy Savings	26-69	22-42	7-19	12	kWh/m^2.year
% Cooling Energy Savings Compared With Baseline	42-68%	20-41%	12-19%	0-11%	

3.3.1.2.1 PCS Selection Matrix To Achieve The Near-Zero Scenario

The table below presents the PCS selection matrix for achieving near-zero scenario for high-rise office buildings.

Table 28 PCS Selection Matrix to Achieve Near-Zero Scenario in High-Rise Office Building Type

<table>
<tr><th>Building Envelope Configuration</th><th>WWR</th><th>Shading Depth</th><th>Orientation</th><th>Window Opening Ratio</th><th>Window Cross Ventilation</th><th>CEPI Range (kWh/m^2.year)</th></tr>
<tr><td>Baseline Envelope Performance Case & Intermediate Envelope Performance Case</td><td colspan="5">If the performance values for the baseline and intermediate envelope are selected, the estimated CEPI range exceed the CEPI range specified for the near-zero compliance scenario.</td><td rowspan="5">60-81</td></tr>
<tr><td rowspan="4">Best Envelope Performance Case</td><td>0.3</td><td>0,0.5m,1m</td><td>All orientations</td><td>0.3 to 0.45</td><td>0 & 1</td></tr>
<tr><td>0.4</td><td>0,0.5m,1m</td><td>All orientations</td><td>0.3</td><td>0 & 1</td></tr>
<tr><td>0.5</td><td>0,0.5m,1m</td><td>All orientations</td><td>0.3</td><td>0 & 1</td></tr>
<tr><td>0.6</td><td>0,0.5m,1m</td><td>All orientations</td><td>0.3</td><td>0 & 1</td></tr>
</table>

	0.7	0.5m,1m	All orientations	0.3 to 0.45	0 & 1	
	0.8	0.5m,1m	90,180	0.3 to 0.45	0 & 1	
	0.9	0.5m,1m	90,180	0.3 to 0.6	0 & 1	

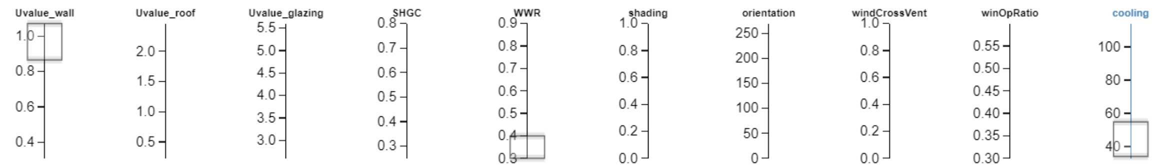


Figure 53 Results with Baseline Envelope Configuration to Achieve Near-Zero Scenario in the Office Building

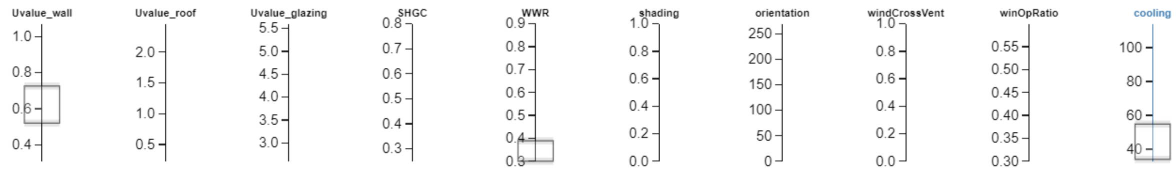


Figure 54 Results with Intermediate Envelope Configuration to Achieve Near-Zero Scenario in the Office Building

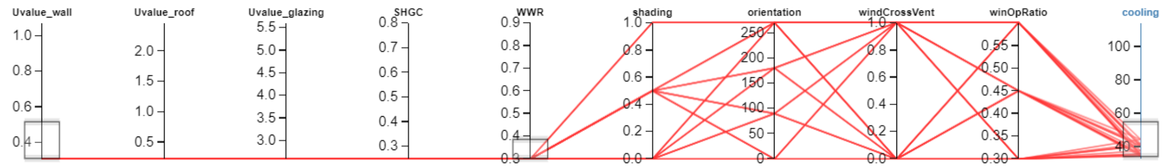


Figure 55 Results with Best-Performance Envelope Configuration to Achieve Near-Zero Scenario in the Office Building.

3.3.1.2.2 PCS Selection Matrix to Achieve the High-Performance Scenario

The CEPI range for the high-performance scenario falls between 60 and 81 kWh/m^2.year. The table below showcases the PCS selection matrix for achieving the high-performance scenario in high-rise office building types.

Table 29 PCS Selection Matrix to Achieve High-Performance Scenario in High-Rise Office Building Type

Building Envelope Configuration	**WWR**	**Shading Depth**	**Orientation**	**Window Opening Ratio**	**Window Cross Ventilation**	**CEPI Range (kWh/m^2.year)**
Baseline Envelope Performance Case	0.3	0.5 m, 1 m	All orientations	0.3 to 0.6	0 & 1	60-81
	0.4	0.5 m, 1 m	All orientations	0.3 to 0.6	0 & 1	
Intermediate Envelope Performance Case	0.3	0.5 m, 1 m	All orientations	0.3 to 0.6	0 & 1	
	0.4	0.5 m, 1 m	All orientations	0.3 to 0.6	0 & 1	
Best Envelope Performance Case	0.4	0.5 m, 1 m	0	0.3 to 0.6	0 & 1	
	0.5	No Shading	270	0.3 to 0.6	0 & 1	
	0.6	No Shading	180, 270	0.3 to 0.6	0 & 1	

	0.7	No Shading, 0.5 m	All orientations	0.3 to 06	0 & 1	
	0.8	0, 0.5 m, 1 m	All orientations	0.3 to 0.6	0 & 1	
	0.9	0, 0.5 m, 1 m	All orientations	0.3 to 0.6	0 & 1	

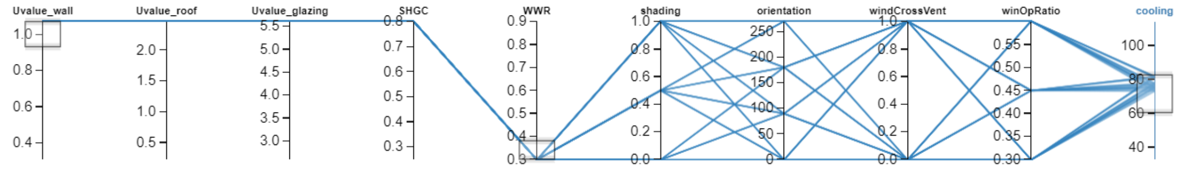


Figure 56 Results with Baseline Envelope Configuration to Achieve High-Performance Scenario in the Office Building

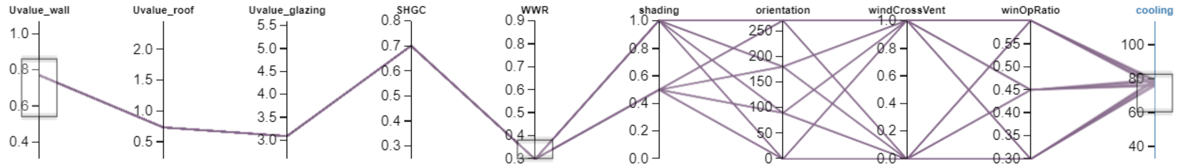


Figure 57 Results with Intermediate Envelope Configuration to Achieve High-Performance Scenario in the Office Building

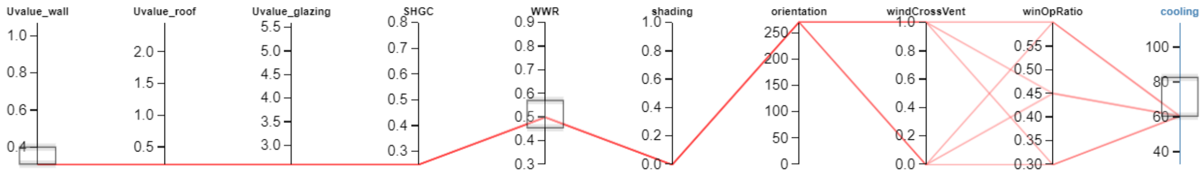


Figure 58 Results with Best-Performance Envelope Configuration to Achieve High-Performance Scenario in the Office Building

3.3.1.2.3 PCS Selection Matrix to Achieve Code Compliance Scenario

The CEPI range for the code compliance scenario falls between 82 and 89 kWh/m^2.year. The table below presents the PCS selection matrix for achieving the code compliance scenario in high-rise office building types.

Table 30 PCS Selection Matrix to Achieve Code Compliance Scenario in High-Rise Office Building Type

Building Envelope Configuration	WWR	Shading Depth	Orientation	Window Opening Ratio	Window Cross Ventilation	CEPI Range (kWh/m^2.year)
Baseline Envelope Performance Case	0.3	0	All orientations	0.3 to 0.6	0 & 1	82-89
	0.4	0.5m	All orientations	0.3 to 0.6	0 & 1	
Intermediate Envelope Performance Case	0.3	0.5m	All orientations	0.3 to 0.6	0 & 1	
	0.4	0.5m	All orientations	0.3 to 0.6	0 & 1	
	0.5	0	270	0.3 to 0.6	0 & 1	
	0.6	0	180,270	0.3 to 0.6	0 & 1	
	0.7	0	270	0.3 to 0.6	0 & 1	

	0.8	0	180,270	0.3 to 0.6	0 & 1	
	0.9	0	180	0.3 to 0.6	0 & 1	
Best Envelope Performance Case	If the best envelope performance values are selected, the estimated CEPI range surpasses the CEPI range specified for the code compliance scenario.					

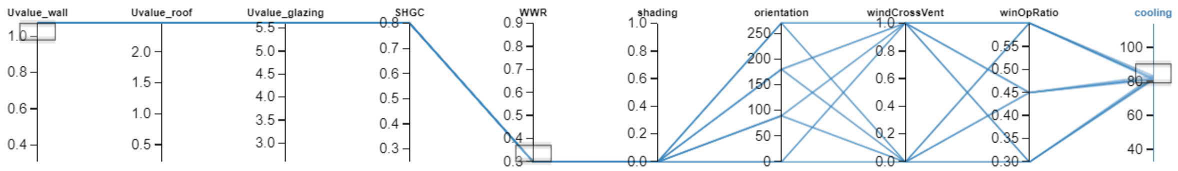


Figure 59 Results with Baseline Envelope Configuration to Achieve Code Compliance Scenario in the Office Building

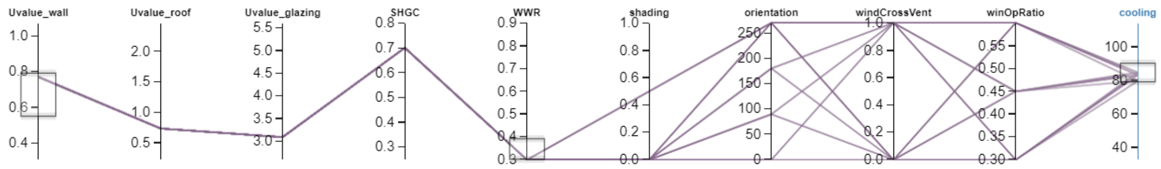


Figure 60 Results with Intermediate Envelope Configuration to Achieve Code Compliance Scenario in the Office Building

3.3.1.3 Summary of The Results of MHIH Condominium Type

To achieve the optimal CEPI targets for high-rise office buildings, prioritizes the construction of the building envelope, followed by design parameters such as WWR and shading, and the orientation of the building at the site. Building insulation significantly contributes to higher energy savings (9 to 27%), followed by shading (4 to 15%).

3.4 Hotel Buildings

3.4.1 Building 1 – High-Rise Hotel

3.4.1.1 Building Description

The parametric energy simulation focuses on a representative high-rise hotel unit in Phnom Penh, comprising nineteen floors (Ground +18) with a built-up area of 31,749 m^2. In this building, hotel rooms are air-conditioned, while spaces like toilets and corridors rely on natural ventilation based on outdoor conditions defined in the calculation inputs for natural ventilation (Section 2.2.4). The simulation considers the Ground, 8th, and 19th floors, each with an area of 1,671 m^2. The energy model and floor plan snapshot of the building are depicted in the figure below.

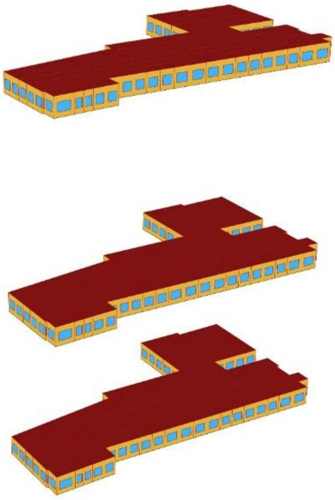


Figure 61 Building Energy Model: High-Rise Hotel

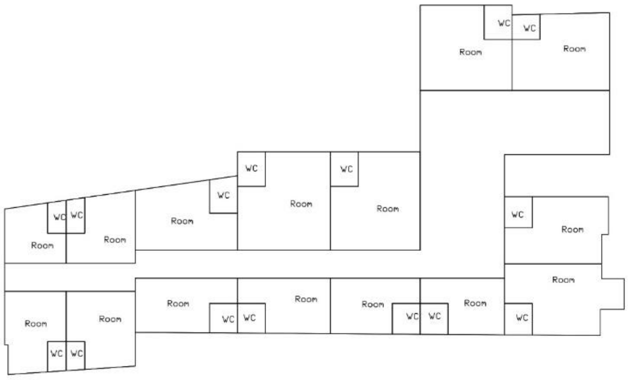


Figure 62 Floor Plan: High-Rise Hotel

The parametric energy simulation for this building typology incorporates various passive design strategies, including orientation with respect to True North, Window-to-Wall Ratio (WWR), shading (box type), Window Opening Ratio (WoR), and Window Cross Ventilation.

3.4.1.2 Results of the High-Rise Hotel Building

The comprehensive parametric analysis, encompassing all envelope construction and passive cooling strategies, revealed that the Cooling Energy Performance Index (CEPI) for the high-rise hotel building falls within the range of 51 to 112 kWh/m^2.year.

The comparison of the results for the four performance scenarios is presented in the table below:

Table 31 Energy Savings Potential Results for High-Rise Hotel Building

Indicator	Near-Zero Scenario	High-Performance Scenario	Code Compliance Scenario	BAU Scenario	Unit
Annual Cooling Demand	154-208	209-254	255-289	290-336	kWh$_{thermal}$/m^2.year
Annual Baseline Cooling Energy Performance Index	51-69	70-85	86-96	97-112	kWh/m^2.year
Annual Cooling Energy Savings	18-53	14-34	11-19	7	kWh/m^2.year
% Cooling Energy Savings Compared With Baseline	33-51%	19-34%	7-18%	0-6%	

3.4.1.2.1 PCS Selection Matrix to Achieve the Near-Zero Scenario

The CEPI range for the net-zero scenario falls between 51 and 69 kWh/m^2.year. The PCS selection matrix for achieving the near-zero scenario for high-rise hotel building types is presented in the table below.

Table 32 PCS Selection Matrix to Achieve Near-Zero Scenario in High-Rise Hotel Building Type

Building Envelope Configuration	WWR	Shading Depth	Orientation	Window Opening Ratio	Window Cross Ventilation	CEPI Range (kWh/m^2.year)
Baseline Envelope Performance Case &	If the performance values for the baseline and intermediate envelope are selected, the estimated CEPI range exceeds the CEPI range specified for the near-zero compliance scenario.					51-69

Intermediate Envelope Performance Case						
Best Envelope Performance Case	0.3	0, 0.5m,1m	All orientations	0.3 to 0.45	0 & 1	
	0.4	0.5m, 1m	All orientations	0.3 to 0.45	0 & 1	
	0.5	1m	All orientations	0.3 to 0.45	0 & 1	
	0.6	1m	0	0.3 to 0.6	0 & 1	

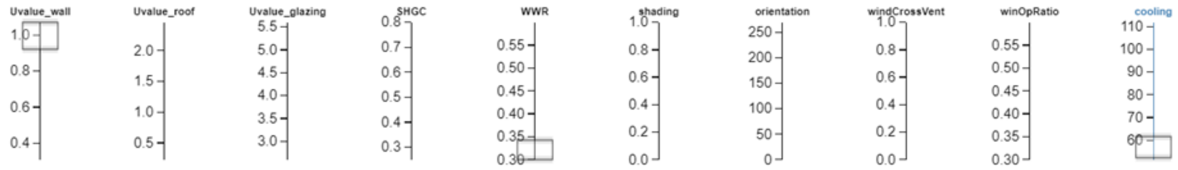


Figure 63 Results with Baseline Envelope Configuration to Achieve Near-Zero Scenario in High-Rise Hotel Building Type

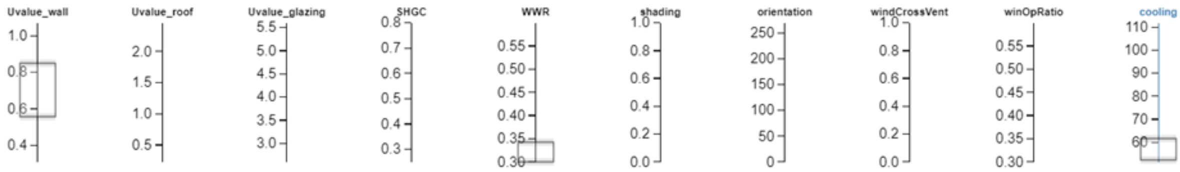


Figure 64 Results with Intermediate Envelope Configuration to Achieve Near-Zero Scenario in High-Rise Hotel Building Type

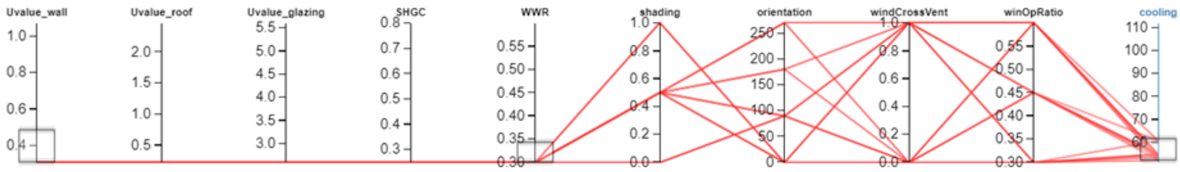


Figure 65 Results with Best-Performance Envelope Configuration to Achieve Near-Zero Scenario in High-Rise Hotel Building Type

3.4.1.2.2 PCS Selection Matrix to Achieve the High-Performance Scenario

The CEPI range for the high-performance scenario falls between 70 and 85 kWh/m^2.year. The table below presents the PCS selection matrix aimed at achieving the high-performance scenario for high-rise hotel building types.

Table 33 PCS Selection Matrix to Achieve High-Performance Scenario in High-Rise Hotel Building Type

Building Envelope Configuration	WWR	Shading Depth	Orientation	Window Opening Ratio	Window Cross Ventilation	CEPI Range (kWh/m^2.year)
Baseline Envelope Performance Case	If the baseline and intermediate envelope performance values are selected, the estimated CEPI range is higher than the near-zero compliance scenario CEPI range.					70-85

Intermediate Envelope Performance Case	0.3	0.5m ,1m	All orientations	0.3 to 0.45	0 & 1	
	0.4	0.5m, 1m	All orientations	0.3 to 0.45	0 & 1	
	0.5	0.5m,1m	All orientations	0.3 to 0.45	0 & 1	
Best Envelope Performance Case	0.4	0	180	0.3 to 0.6	0 & 1	
	0.5	0	All orientations	0.3 to 0.6	0 & 1	
	0.6	0, 0.5m	All orientations	0.3 to 0.45	0 & 1	

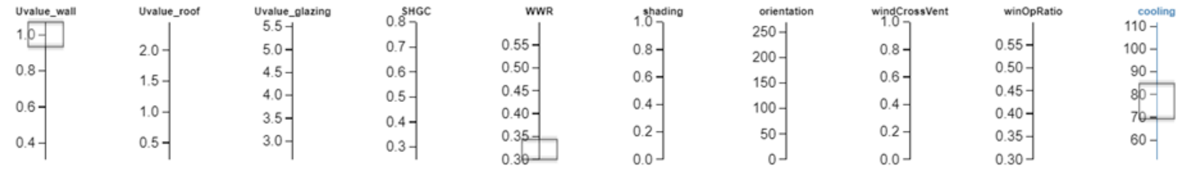


Figure 66 Results with Baseline Envelope Configuration to Achieve High-Performance Scenario in High-Rise Hotel Building Type

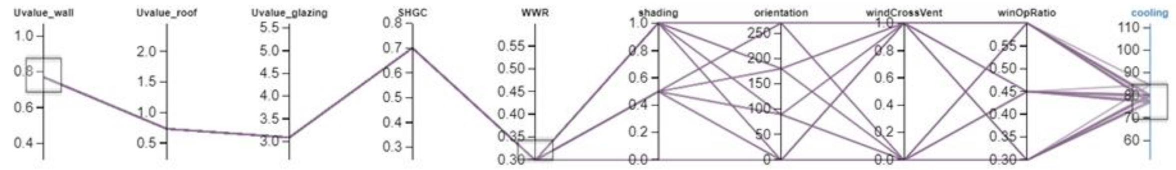


Figure 67 Results with Intermediate Envelope Configuration to Achieve High-Performance Scenario in High-Rise Hotel Building Type

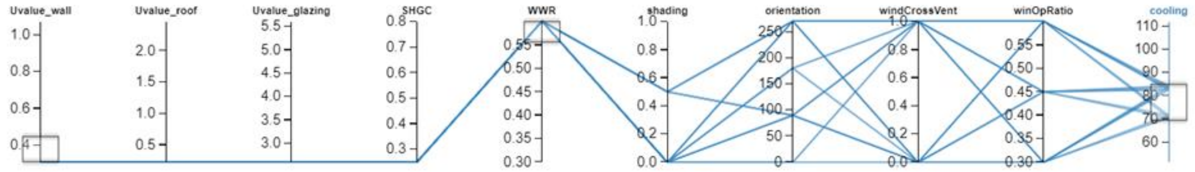


Figure 68 Results with Best-Performance Envelope Configuration to Achieve High-Performance Scenario in High-Rise Hotel Building Type

3.4.1.2.3 PCS Selection Matrix to Achieve Code Compliance Scenario

The CEPI range for the code compliance scenario falls between 86 and 96 kWh/m^2.year. The table below illustrates the PCS selection matrix targeting the achievement of the code compliance scenario for high-rise hotel building types.

Table 34 PCS Selection Matrix to Achieve Code Compliance Scenario in High-Rise Hotel Building Type

Building Envelope Configuration	WWR	Shading Depth	Orientation	Window Opening Ratio	Window Cross Ventilation	CEPI Range (kWh/m^2.year)
Baseline Envelope Performance Case	0.3	0.5 m, 1 m	All orientations	0.3 to 0.45	0 & 1	86-96
	0.4	0.5 m, 1 m	All orientations	0.3 to 0.45	0 & 1	
	0.5	1 m	180	0.3 to 0.6	0 & 1	

Intermediate Envelope Performance Case	0.3	0	All Orientations	0.3 to 0.6	0 & 1	
	0.4	0	All Orientations	0.3 to 0.6	0 & 1	
	0.5	0, 0.5 m	All Orientations	0.3 to 0.45	0 & 1	
Best Envelope Performance Case	If the best envelope performance values are selected, the estimated CEPI range surpasses the CEPI range specified for the code compliance scenario.					

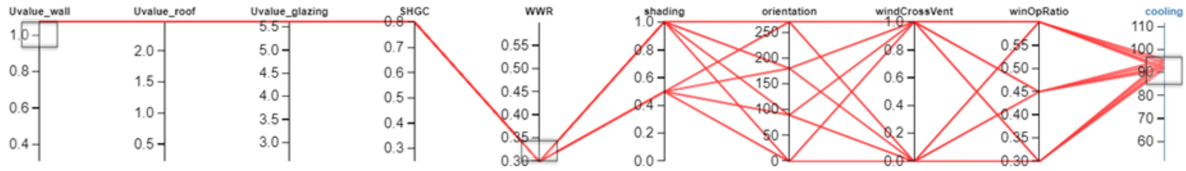


Figure 69 Results with Baseline Envelope Configuration to Achieve Code Compliance Scenario in High-Rise Hotel Building Type

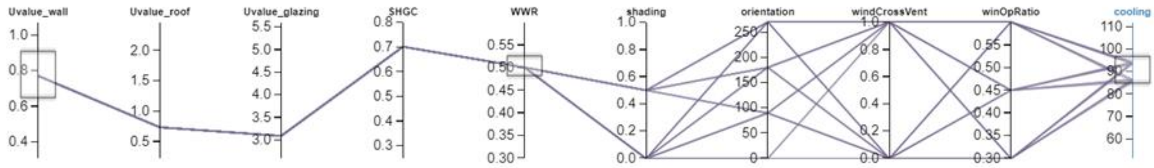


Figure 70 Results with Intermediate Envelope Configuration to Achieve Code Compliance Scenario in High-Rise Hotel Building Type

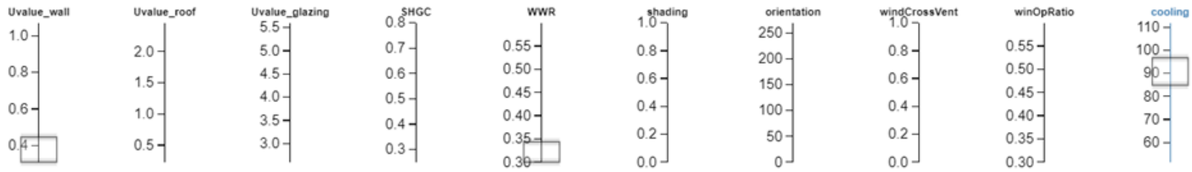


Figure 71 Results with Best-Performance Envelope Configuration to Achieve Code Compliance Scenario in High-Rise Hotel Building Type

3.4.1.3 Summary of the Results

To achieve the near-zero performance targets for high-rise hotel buildings, designers should prioritise building envelope construction, followed by design parameters such as WWR and shading, and finally, consider building orientation. Effective insulation contributes significantly to higher energy savings (9 to 15%), followed by shading (5 to 12%).

4 Self-Shading

Self-shading is a strategy wherein the building's own form and features are designed to mitigate solar heat gain and optimise natural light. This involves incorporating elements such as overhangs, fins, or external shading devices that block or diffuse direct sunlight. The objective is to diminish the building's reliance on artificial cooling systems by minimising heat gain during peak sunlight hours, while still facilitating maximum natural light.

4.1 Results from Self-Shading Analysis

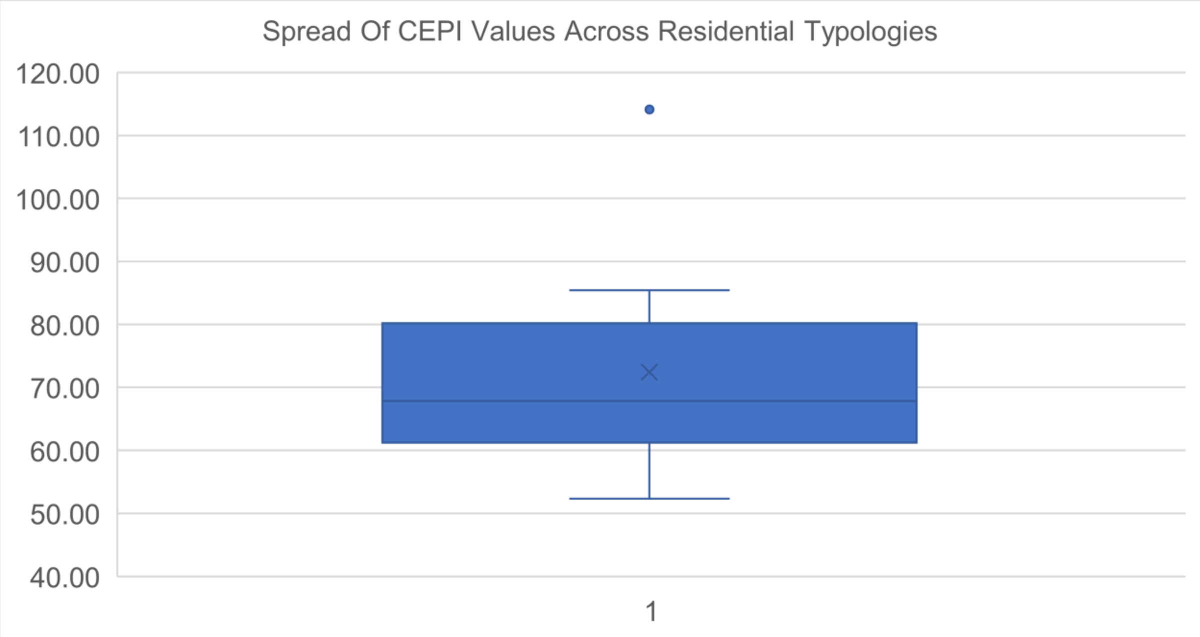


Figure 72 Spread of CEPI Values across Residential Typologies – Self-Shading

Table 35 Defining CEPI Range of Residential Typologies - Self-Shading

	Near-Zero Scenario	High Performance Scenario	Code Compliance Scenario	BAU Scenario
CEPI Range	60.03 - 49.33	70.47 -60.04	85.41 - 70.48	114.14 -85.42

Table 36 Percentage Difference from Base Case CEPI of Residential Typologies - Self-Shading

Building Typology	Case	CEPI (kWh/m^2.year)	% Difference From Base Case CEPI	Scenario
MHIH_RB	0	81.38	0%	BAU
	50	62.38	23%	High performance
	80	60.03	26%	Near zero
MHIH_RC	0	58.76	0%	Compliance
	50	49.99	15%	High performance
	80	49.33	16%	High performance
MHIH_AB	0	85.41	0%	BAU
	50	60.87	29%	Near zero

Building Typology	Case	CEPI (kWh/m^2.year)	% Difference From Base Case CEPI	Scenario
	80	52.33	39%	Near zero
MHIH_AC	0	114.14	0%	BAU
	50	75.88	34%	Compliance
	80	70.47	38%	Compliance

In all instances of self-shading across various typologies, the reduction in CEPI from the CEPI of the case with zero shading falls within the range of 15% to 38%. The percentage decrease appears to be higher in the affordable borey and affordable condominium typologies, while the residential condominium typology exhibits the lowest decrease in CEPI from the zero-shading case. Across all typologies, the classification of scenarios improves from the zero-shading case when there is 50% and 80% shading.

5 Mutual Shading

Mutual shading refers to the interaction where structures and vegetation cast shadows on each other, impacting the distribution of sunlight in the surrounding environment. This interaction is significant in urban and landscape design, affecting energy efficiency, microclimates, and overall comfort. Mutual shading between buildings can result in variations in solar exposure, thereby influencing heating and cooling demands.

5.1 Results from Mutual Shading Analysis

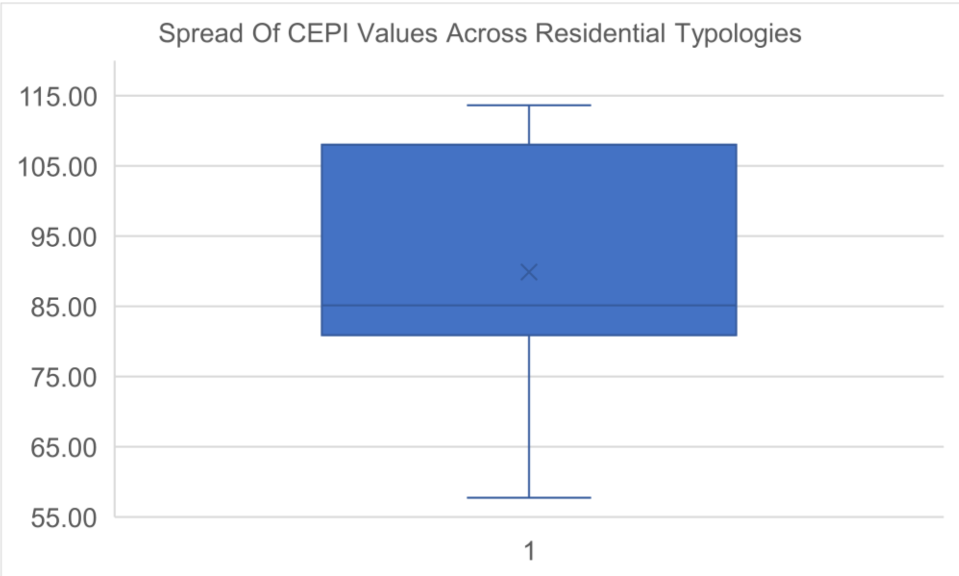


Figure 73 Spread of CEPI Values across Residential Typologies - Mutual Shading

The CEPI ranges for the four scenarios are delineated based on the quadrants in the box plot above.

Table 37 Defining CEPI Range of Residential Typologies - Mutual Shading

	Near-Zero Scenario	High Performance Scenario	Code Compliance Scenario	BAU Scenario
CEPI Range	80.78 - 57.72	83.13 - 80.79	103.98 - 83.14	113.63 -103.99

Under the mutual shading analysis for MHIH_RB, when the adjacent building is placed 5 metres away from the native building, the CEPI values appear to decrease from the CEPI of the base case by 0.96% to 0.1%. The percentage of decrease is marginally higher when the adjacent building is placed in the east and west, and very minimal when the adjacent building is placed in the north and south directions. For the same building, when the adjacent building for shading is placed 10 metres away, the percentage of decrease is around 0.66 to 0.11 %. The placement of adjacent building for mutual shading does not affect the CEPI in the north and south directions. However, the decrease in CEPI reaches as high as 0.96 % from the baseline CEPI on the east and west. The CEPI values mostly fall under the high-performance scenario for all cases and in the near-zero scenario when the building for mutual shading is placed at 5 metres on the east and west.

Table 38 Percentage Difference from Base Case CEPI of Residential Typologies - Mutual Shading

Orientation of Adjacent Building	CEPI (kWh/m^2.year)	% Difference from Base Case CEPI	Scenario
East	80.60	0.96%	Near zero
West	80.76	0.76%	Near zero
North	81.30	0.10%	High performance
South	81.17	0.26%	High performance
East_10 m	80.84	0.66%	High performance
West_10m	80.98	0.49%	High performance
North_10m	81.29	0.11%	High performance
South_10m	81.17	0.26%	High performance

MHIH_RC, for the case of mutual shading shows a steady decrease between 1.0 % to 2.0 % from the baseline CEPI and all the CEPI values for all four orientations of mutual shading fall under the near zero scenario. It's notable that the decrease in CEPI is comparatively lesser in the west.

Table 39 Percentage Difference from Base Case CEPI of MHIH_RC - Mutual Shading

Orientation of Adjacent Building	CEPI (kWh/m2.year)	% Difference from Base Case CEPI	Scenario
East	57.85	1.56%	Near zero
West	58.07	1.18%	Near zero

North	57.72	1.78%	Near zero
South	57.85	1.55%	Near zero

For MHIH_AB, in the case of mutual shading, there is a steady decrease ranging from 0.2 % to 0.55% compared to the baseline CEPI. Notably, the decrease in CEPI is more pronounced in the north and south orientations than in east and west. These findings can be attributed to the lower surface area of the building exposed to radiation on the east and west compared to the north and south. This clearly indicates that the building layout significantly impacts the CEPI. The CEPI values fall within the compliance scenario for all orientations of mutual shading.

Table 40 Percentage Difference from Base Case CEPI of MHIH_AB - Mutual Shading

Orientation of Adjacent Building	**CEPI (kWh/m2.year)**	**% Difference from Base Case CEPI**	**Scenario**
East	85.22	0.22%	Compliance
West	85.23	0.21%	Compliance
North	85.07	0.40%	Compliance
South	84.95	0.53%	Compliance

For MHIH_AC, in the case of mutual shading, there is a steady decrease in CEPI value ranging from 0.4 to 1.1 % compared to the baseline CEPI. All the CEPI values for the four orientations of mutual shading fall within the BAU scenario. The orientation of neighbouring building has a minimal effect on the native building. However, when the height of the neighbouring building, which shades the native building, is increased to 18.6 metres (around 6 floors), the CEPI values show a larger decrease of up to 14%. This indicates that the increase in shading of roof and the wall surfaces significantly reduces the CEPI values. The CEPI values predominantly fall under the BAU scenario for all orientations of mutual shading.

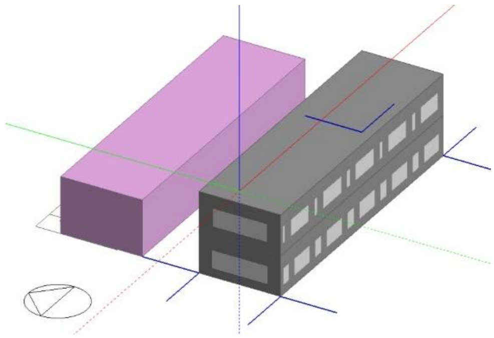


Figure 74 Mutual Shading with a Low-Rise Adjacent Building (1)

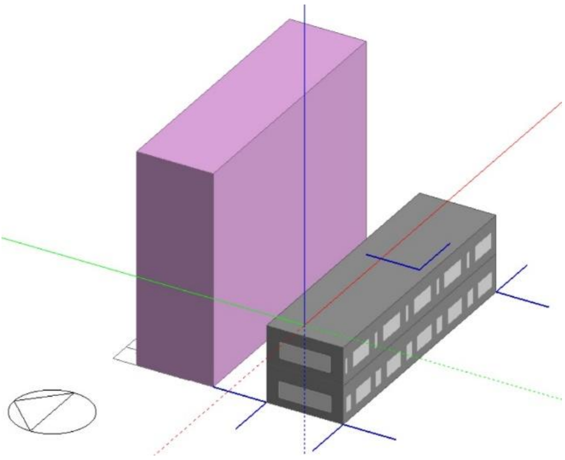


Figure 75 Mutual Shading with a High-Rise Adjacent Building (1)

Based on the simulation analysis for the MHIH, the variation in the CEPI with respect to placement of the adjacent blocks and their height is shown in table 43 below.

Table 41 CEPI Difference Based on the Height of the Adjacent Building – Mutual Shading

Orientation of Adjacent Building	CEPI (kWh/m^2.year)	% Difference from Base Case CEPI	Scenario
East	113.54	0.52%	BAU
West	113.63	0.45%	BAU
North	113.05	0.95%	BAU
South	112.92	1.07%	BAU
East_18.6m	109.33	4.21%	BAU
West_18.6m	110.76	2.96%	BAU
North_18.6m	111.16	2.61%	BAU
South_18.6m	97.28	14.77%	Compliance

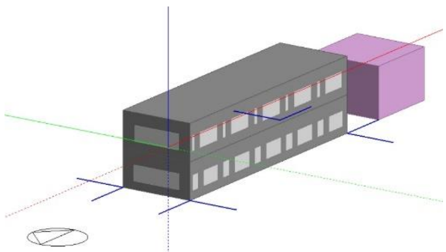


Figure 76 Mutual Shading with a Low-Rise Adjacent Building (2)

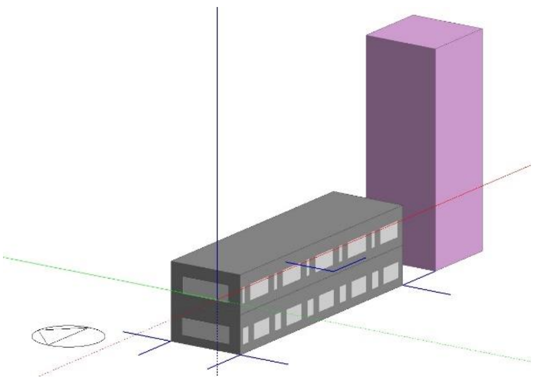


Figure 77 Mutual Shading with a High-Rise Adjacent Building (2)

6 Country-Level Assessment of the PCS Potential

Parametric energy simulation outputs for diverse building typologies are utilised to assess the energy savings potential at the national level by incorporating PCS across various energy performance levels. For the estimation of energy-saving potential, the floor area of new buildings[7] in Cambodia's three major provinces - Phnom Penh, Siem Reap, and Sihanouk - across various typologies was considered.

The findings of the LCRRB study conducted by UNDP and MLUMPC serve as the foundation for national-level projections in Cambodia. It indicates that the above-mentioned typologies will experience stronger growth. The country's buildings and construction sector face the dual challenge of being a global emissions contributor and highly susceptible to climate change impacts. The floor growth and energy demand growth data from the study are shown in the graphs below.

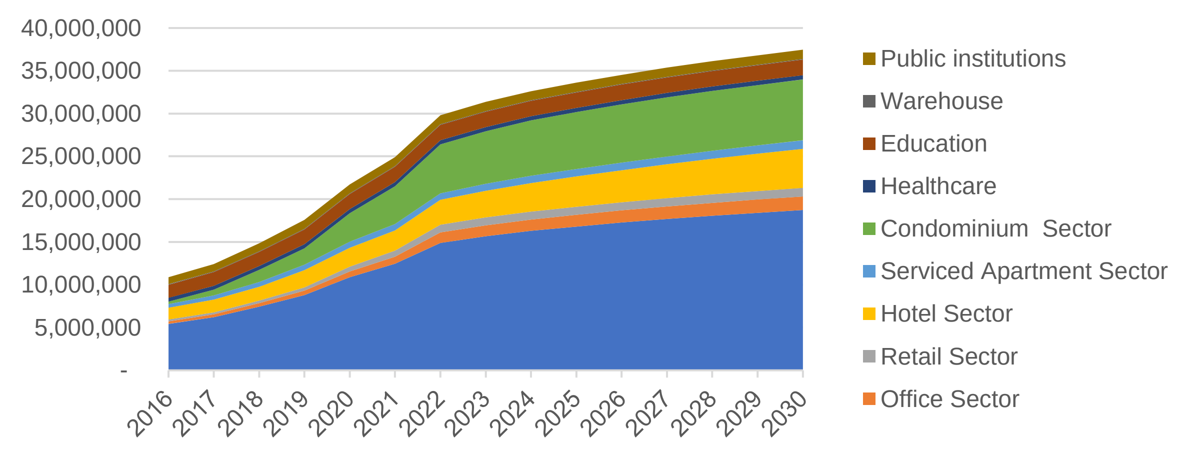


Figure 78 Floor Growth Rate of Cambodia from 2016 to 2030 in m²

[7] Projections on the floor area of the building typologies in the country is used from the UNDP Cambodia project on development of RLCCRB

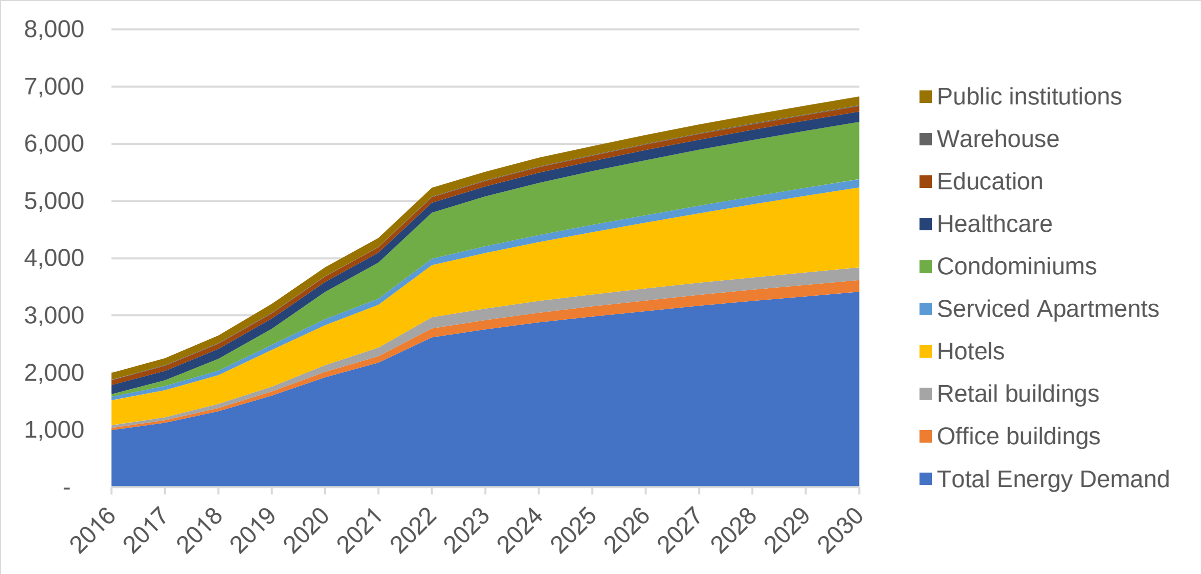


Figure 79 Energy Demand Growth Rate of Cambodia from 2016 to 2030 in GWh

The NDC Buildings and Construction Roadmap for 2020-2050, developed through multi-stakeholder collaboration, outlines key actions across eight activity areas to guide investments and advancements in this sector. The roadmap is designed to evolve over time, plating a crucial role in post-COVID-19 recovery by fostering climate resilience, sustainability, and economic growth. The methodology considers energy and emission savings, achievable through the use of PCS. It includes the process of establishing baseline energy demand scenarios at the national level, developing GHG emissions scenarios for residential and commercial sectors, identifying viable policy scenarios, conducting economic analyses, creating a Marginal Abatement Cost Curve, and prioritising energy efficiency measures through consultation based on evaluation criteria.

Table 42 Projections on Cooling Energy Savings in New Buildings with Near-Zero Scenario

Typology	2024	2025	2026	2027	2028	2029	2030
Residential: Borey	0.9	0.8	0.8	0.7	0.7	0.6	0.5
Residential: Condominium	14.4	8.5	7.0	5.5	4.0	2.5	2.5
Office	1.9	1.8	1.7	1.5	1.4	1.2	1.0
Hotel	11.8	11.8	11.8	11.8	11.8	11.8	11.8
Educational Institutional	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Total in GWh/year	**29**	**23**	**21**	**20**	**18**	**16**	**16**

The integration of PCS into new buildings can achieve a cumulative energy savings of 143 GWh/year in the country from 2024 to 2030, provided all new constructions attain the CEPI near-zero scenario. This initiative has the potential to mitigate approximately 99,000 tCO_2e of indirect GHG emissions over the span of seven years.

Table 43 Projections on Cooling Energy Savings in New Buildings with High-Performance Scenario

Typology	2024	2025	2026	2027	2028	2029	2030
Residential: Borey	0.5	0.5	0.4	0.4	0.4	0.3	0.3

Residential: Condominium	9.2	5.4	4.5	3.5	2.5	1.6	1.6
Office	0.9	0.8	0.8	0.7	0.7	0.6	0.5
Hotel	6.8	6.8	6.8	6.8	6.8	6.8	6.8
Educational Institutional	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Total In GWh/year	**17**	**14**	**13**	**11**	**10**	**9**	**9**

The incorporation of PCS into new buildings can result in a cumulative energy savings of 84 GWh/year in the country from 2024 to 2030. Achieving the CEPI high-performance scenario for all new constructions enables the mitigation of approximately 58,000 tCO_2e of indirect GHG emissions over the next seven years.

Table 44 Projections on Cooling Energy Savings in New Buildings with Code Compliance Scenario

Typology	2024	2025	2026	2027	2028	2029	2030
Residential - Borey	0.2	0.2	0.2	0.2	0.1	0.1	0.1
Residential - Condominium	3.4	2.0	1.6	1.3	0.9	0.6	0.6
Office	0.5	0.5	0.5	0.4	0.4	0.3	0.3
Hotel	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Educational Institutional	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total In GWh/year	**7**	**5**	**5**	**4**	**4**	**4**	**3**

Integrating PCS into new buildings can achieve a cumulative energy savings potential of 32 GWh/year in the country from 2024 to 2030. Adherence to the CEPI code compliance scenario for all new constructions has the capacity to mitigate approximately 22,000 tCO_2e of indirect GHG emissions over the next seven years.

7 Way Forward

7.1 Analysis of the Impacts of Other PCS Strategies

The following PCS strategies will undergo analysis to estimate cooling energy savings potential through energy simulations for the intermediate and best envelope performance cases, employing neighbourhood-level modelling. This analysis will be complemented by the UHIE impact assessment study, which will be conducted in the later stages of the project, connecting with the demonstration project and other related activities (For further details, please refer to: https://coolcoalition.org/pilot-projects/passive-cooling-in-cambodia/).

- Cool pavements
- Vegetation at the building site and neighbourhood levels
- Water bodies at the building site and neighbourhood levels
- Passive cooling through evapotranspiration component in green roofs and walls

7.2 Estimation of the Cooling Energy Savings Potential for the Other Cities with Climate Data

Utilising weather data for the other cities (Siem Reap and Sihanouk) (*\climatewebsite\WMO_Region_2_Asia\KHM_Cambodia*), the Cooling Degree Days for each city will be employed to estimate the CEPI for various typologies. The national-level energy savings calculations will be revised, considering floor area additions in individual cities, as estimated in the UNDP Cambodia project on RLCCRB (Roadmap for Low-Carbon Climate-Resilient in Cambodia).

7.3 Estimation of Performance under Future Weather Scenarios

The building performance, both with and without the inclusion of PCS, will undergo evaluation using future weather data generated in accordance with the Shared Socio-Economic Pathways (SSP) outlined by the International Institute of Applied Systems Analysis (IIASA) for climate modelling (Riahi et al. 2017). Indicators such as thermal comfort indices, cooling demand, energy consumption, and GHG emissions will be estimated for future weather scenarios in the years 2040, 2060, 2080 and 2100. This analysis will illustrate the impact of PCS on buildings.

8 Literature Review

8.1 Typologies of Buildings in Cambodia and Local Practices

Cambodia, once a French colony, achieved independence in the early 1950s. The post-independence era witnessed a convergence of Khmer culture and Western influences, giving rise to new forms of art, architecture and culture. The ‘New Khmer Architecture’ movement played a pivotal role in shaping the architectural developments during this period. Norodom Sihanouk, the first Prime Minister after independence, prioritised the economic and social advancement of Cambodia. With assistance from national and international experts, significant infrastructure development took place, encompassing urban planning, dikes, boulevards, monuments, airports, hospitals, universities, factories, sports complexes, and apartment buildings (*Roadmap for Low-Carbon Climate-Resilient in Cambodia*).

Cambodia’s tropical climate, characterised by temperatures ranging from 21°C to 35°C, influenced local architecture to address climatic challenges. The monsoon season, from May to October, brings high humidity (around 80 to 90%) and heavy rainfall, while the dry season spans November to April.

The New Khmer Architecture (1953-1970) embraced new construction materials, particularly reinforced concrete, while incorporating traditional Cambodian techniques such as raising buildings on stilts. Natural ventilation and shading were integral features designed to respond to the local tropical climate. Notable examples of this architectural style include the Olympic National Sports Complex, the Independence Monument, the White Building, and the Institute of Foreign Languages (*KHMER ARCHITECTURE PERIOD OF KHMER ARCHITECTURE PERIOD OF SANGKUM REASTR NIYUM (People’s Socialist Community)* 1955).

Vann Molyvann (1926-2017), the chief architect and urban planner, headed all teams responsible for development under the Cambodian government and played a key role in the expansion Phnom Penh. He observed a shift from nativity in current construction practices, influenced by Chinese and Korean styles. In contrast, earlier developments drew inspiration from colonial references, creating unique styles that resonated with the culture and people of Cambodia (*The Movement — The Vann Molyvann Project*).

8.2 Problem of Contemporary Architecture in Cambodia

The 2000s marked an economic boom in Cambodia, significantly impacting the construction sector. In Phnom Penh, however, there is a lack of laws dedicated to conserving buildings from older eras to preserve Cambodia's history and culture. The focus has shifted towards globalisation and the development of new structures to cater to the demands of a growing population, emphasising the need for increased infrastructure, both commercial and residential.

Unfortunately, the contemporary architectural landscape in Cambodia has faced criticism for its poor design, resulting in buildings that cannot withstand the local tropical climate. This has led to a reliance on air conditioning to maintain comfort. However, the sustainability of such construction practices, coupled with the high costs associated with air conditioning and the energy required to operate it, pose significant challenges. These challenges are further compounded by the country's low economic status (Ty 2017).

Examining the buildings designed by Vann Molyvann can serve as valuable case studies to understand how architectural strategies were employed to overcome the constraints posed by the local climate. These strategies encompassed ventilation, heat rejection, and the incorporation of natural lighting.

8.3 Tropical Strategies by Vann Molyvann

Public buildings designed by Vann Molyvann strategic elements to enhance cross ventilation and maintain a comfortable environment for occupants. These buildings were elevated above the ground, allowing for effective cross ventilation. Operable windows or perforated walls facilitated the flow of air through habitable spaces, contributing to user comfort. Additionally, these openings permitted the entry of diffuse solar radiation, minimising the impact of harsh direct light.

Water bodies were integral to the design, serving as a means of passive cooling. The roof surfaces were shielded or insulated from direct sunlight, often adopting a double roof design with a layer of air in between for insulation. Some buildings featured breathable skylights. Self-shading was another sustainable cooling strategy employed in these designs (Ty 2017).

The overall approach followed a Bioclimatic design, manipulating sunlight, water, and air to ensure optimal occupant comfort. Buildings from the New Khmer Architecture period offer valuable lessons on incorporating vernacular architecture concepts into modern architectural language. These structures effectively utilised simple techniques such as natural ventilation and avoiding direct sun, reducing reliance on air conditioning. Contemporary buildings can benefit from these case studies and strategies to promote sustainable construction and development .

Despite the efforts of organisations like Khmer Architecture Tours (KA-Tours) and the Vann Molyvann Project (*The Movement — The Vann Molyvann Project*), established in 2004 and

2009 respectively to preserve Cambodia's built heritage, their impact is constrained by limited support from the government.

8.4 Sustainability and Energy Efficiency

In Cambodia, a lack of awareness among stakeholders regarding energy efficiency has resulted in energy-intensive construction practises and new developments, including apartments, commercial buildings, and satellite towns. The prevailing ignorance about energy efficiency among end users has led to the failure of previous attempts to address this issue. The construction boom, primarily concentrated in the capital city of Phnom Penh, has occurred without the presence of a building energy code for both residential and commercial and high-rise development, encompassing new constructions and retrofit projects. This absence has contributed to the creation of unsustainable and energy-intensive buildings.

Current construction laws in practice primarily emphasise the quality of construction practises but do not incorporate considerations for energy efficiency or sustainable building practices. Consequently, these buildings are more vulnerable to the effects of climate change, including temperature increases and an increased frequency of floods. The escalating electricity consumption associated with these structures contributes to increased greenhouse gas emissions (*ENERGY EFFICIENCY IN BUILDINGS Accelerating Low-carbon Development in Cambodia Policy Brief & In-country Case Studies*).

8.5 Laws

8.5.1 Sub- Decree on Urbanisation of the Capital City, Towns and Urban Areas

The sub-decree was passed on 25 September 2008, with the aim of delineating the urbanisation of capital, cities, and provincial towns in the Kingdom of Cambodia.

This sub-decree is guided by the following key objectives:

- Ensure the effectiveness, sustainability, and equity of urbanisation.
- Contribute to the reduction of climate change.
- Ensure the protection of human rights and public and private interests to enhance the effectiveness of economic and social development, environmental protection, national security, food security, and conservation of cultural property.
- Ensure the quality of urbanisation to facilitate appropriate functioning for sheltering, employment, leisure, and traffic activities, including health, beauty, safety, public order, and a life of ease.
- Ensure the balance between development and conservation, as well as the relationship between urban and rural geographical factors, taking into account the unique features of each region.
- Define objectives and forecast the future development of urban development (*Sub Decree on Urbanisation of the Capital City Towns and Urban Areas*).

8.5.2 Law on Land Management, Urban Planning and Constructions

The Law on Land Management, Urban Planning, and Constructions, passed on May 24, 1994, has the overarching objective of fostering the organisation and enhancement of both urban and rural areas across the Kingdom of Cambodia. This is aimed at ensuring the country's development in alignment with the following principles:

- Respecting both common and individual interests, private rights, adhering to laws and regulations, and overseeing construction matters.
- Maintaining equilibrium between cities/towns and rural areas, considering their geographical conditions and special characteristics, throughout the development process.
- Safeguarding the value of natural and cultural wealth, ensuring the development of the economy and tourism sectors, and preserving the quality of the environment (*Law on Land Management, Urban Planning and Construction* 1994).

8.5.3 Law on Construction

The Law on Construction, passed on 02, November 2019, serves to establish principles, technical regulations, rules, and procedures for the management of construction sector in the Kingdom of Cambodia.

The key objectives of this law are to ensure:

- Construction quality, security, and safety, with a focus on protection of property and well-being of construction owners, users, and the public.
- Aesthetics and a conducive environment for sustainable living to enhance public well-being.
- Accountability and efficiency in working and practicing professions within the construction sector.
- Increased investor confidence in the construction sector and the promotion of an economically and socially efficient real estate market (*Kingdom of Cambodia Nation Religion King LAW ON CONSTRUCTION*).

8.6 Guidelines and Certification for Green Buildings in Cambodia Project

The Guidelines and Certification for Green Buildings in Cambodia Project, formulated in 2021 with support from the Mekong-RoK Cooperation Fund (MKCF), initiated a stocktaking report (*Stocktaking_and_Analytical_Options_for_Green_Building_in_Cambodia_2021_En*). The primary objectives of this report are to present the current state of construction and buildings in Cambodia, assess green perspectives, identify gaps in policy, legislation, strategies, and plans, and scrutinise actual practices in the country. Additionally, the report aims to outline the roles of ministries in the construction and building sector. Subsequently, the report will propose interventions for the development of green building guidelines and certification for green buildings in Cambodia, outlining a way forward for implementation.

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Annexure 1 – Climate Analysis of Phnom Penh

A 1.1 About Phnom Penh

Phnom Penh, the capital city of Cambodia, is located at latitude 13.41100°N and longitude 103.8130°E. Falling within the ASHRAE classification of an extremely hot and humid climate, it is strategically positioned at an elevation of 12.2 meters along the banks of the Tonle Sap and Mekong rivers, fostering its development and growth. The city's population has experienced steady growth, reaching approximately 2,211,000 residents in 2022, up from 2,129,371 in 2019. With a population density of around 3,136 individuals per square kilometre of city area, based on 2019 data, Phnom Penh presents a compact urban landscape characterised by concentrated economic activities.

Despite the effects of urbanisation, Phnom Penh retains a portion of its land for agricultural purposes. The city encompasses 34.6 square kilometres of agricultural land, supporting diverse farming practices and contributing to local food production. Furthermore, Phnom Penh values its natural environment, preserving approximately 30 square kilometres of forest cover within its limits.

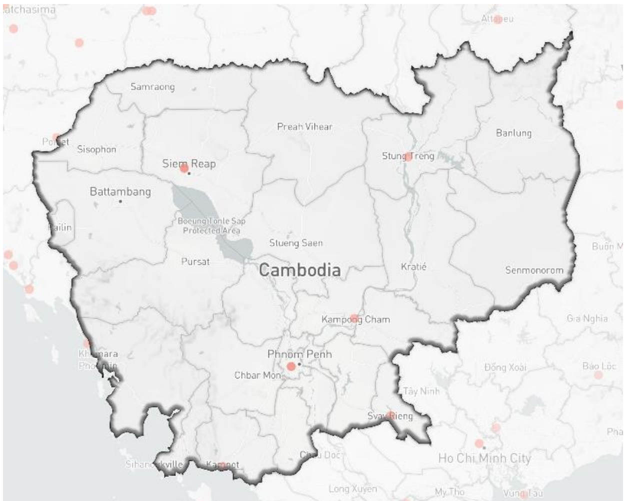

Figure 80 Phnom Penh - Capital City of Cambodia

A 1.2 Sun-Path

Phnom Penh, the capital city of Cambodia, exhibits distinct variations in the sun's path and solar intensity throughout the year. During the Summer Solstice in June, the sun rises from the northeast (NE) at 6:00 am, reaches its highest point at noon in the northern (N) direction, and sets in the northwest (NW) at 6:00 pm. Conversely, during the Winter Solstice in December, the sun rises from the southeast (SE) at 6:00 am, reaches its zenith at noon in the southern (S) direction, and sets in the southwest (SW) at 6:00 pm. Equinoxes occurring in March and September showcase a balance between these patterns.

Solar intensity is notably high 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 factors bear significance for urban planning, architectural considerations, and the effective utilisation of solar energy resources in Phnom Penh.

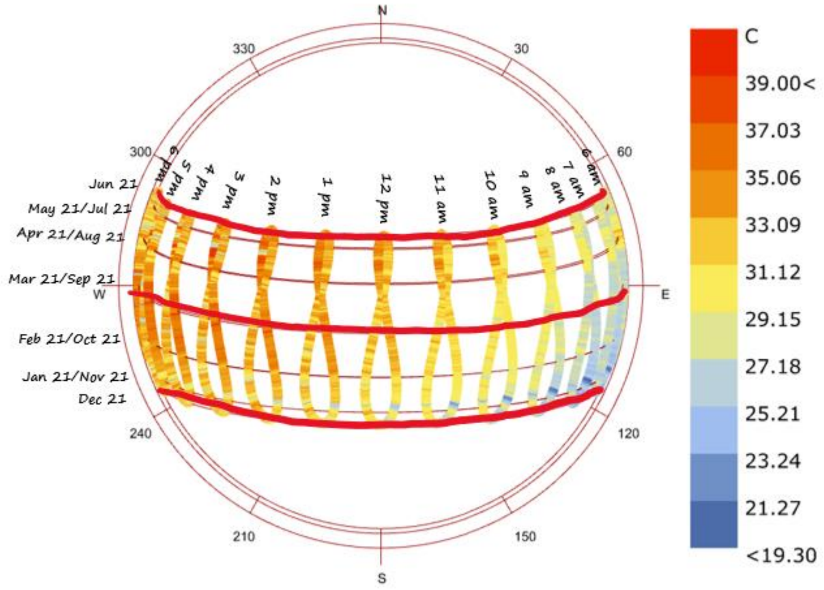

Figure 81 Sun Path Diagram - Phnom Penh

A 1.3 Radiation Analysis Heat Map

Phnom Penh, Cambodia, experiences a moderate level of solar intensity when compared to global standards. The direct radiation, representing unobstructed sunlight, reaches a maximum of 921 Wh/m² from 6:00 am to 6:00 pm. This measurement indicates the amount of solar energy received directly from the sun without interference from the atmosphere. However, in a global context, Phnom Penh's solar intensity is considered moderate.

In addition to direct radiation, the diffuse radiation in Phnom Penh reaches a maximum of 386 Wh/m² between 6:00 am and 6:00 pm. This component of solar radiation is influenced by factors such as cloud cover and humidity levels. It occurs when sunlight is scattered and diffused by atmospheric particles and molecules, resulting in a less intense form of solar energy reaching the Earth's surface. The diffuse radiation tends to be higher during the months of June to September, coinciding with a higher level of humidity and cloudiness.

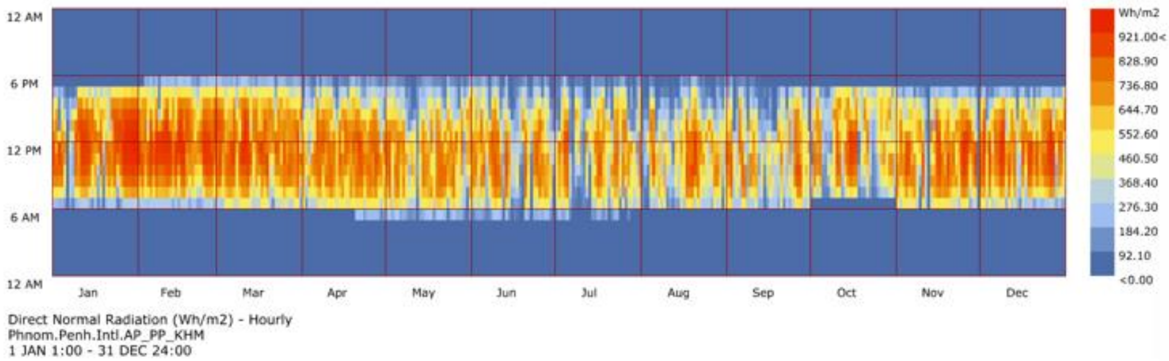

Figure 82 Heat Map of Direct Radiation - Phnom Penh

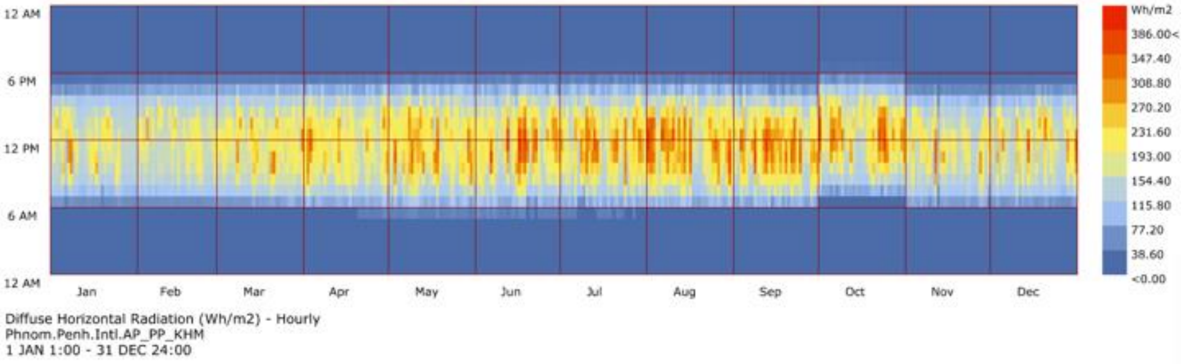

Figure 83 Heat Map of Diffuse Radiation - Phnom Penh

A 1.4 Rainfall

Phnom Penh receives an average annual precipitation of about 1432 mm (56.4 inches). Precipitation refers to the amount of rainfall or any form of moisture that falls from the atmosphere to the Earth's surface. The yearly precipitation level in Phnom Penh indicates the amount of water received through rainfall over the course of one year.

The monthly distribution of precipitation in Phnom Penh shows variations throughout the year. February is the driest month, with an average precipitation of 9 mm (0.4 inches) recorded over 1.87 days. Conversely, September experiences the highest amount of precipitation, with an average of 255 mm (10.0 inches) recorded over 26.07 days. This demonstrates a significant difference in precipitation between the driest and wettest months, amounting to 246 mm.

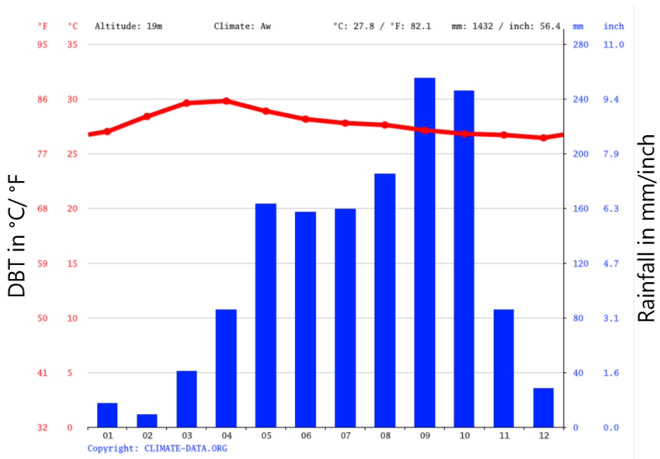

Figure 84 Rainfall Data Chart - Phnom Penh

	January	February	March	April	May	June	July	August	September	October	November	December
Precipitation / Rainfall mm (in)	17 (0)	9 (0)	41 (1)	86 (3)	163 (6)	157 (6)	159 (6)	185 (7)	255 (10)	246 (9)	86 (3)	28 (1)
Humidity(%)	60%	57%	60%	66%	75%	77%	77%	78%	82%	83%	76%	66%
Rainy days (d)	2	1	5	11	17	17	18	19	20	18	9	4

Figure 85 Rainfall Data - Phnom Penh

A 1.5 Dry Bulb Temperature and Universal Thermal Climate Index

Phnom Penh, Cambodia experiences high dry bulb temperatures exceeding 31°C from February to August between 12:00 pm and 6:00 pm. The dry bulb temperature represents the actual air temperature measured without accounting for humidity or other factors. However, when considering the Universal Thermal Climate Index (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). The UTCI provides a more comprehensive assessment of thermal comfort, considering the combined impact of temperature, humidity, wind speed, and radiation on the human body. Understanding these temperature trends and perceived feel temperatures is important for assessing thermal comfort and implementing measures to mitigate the effects of heat in Phnom Penh.

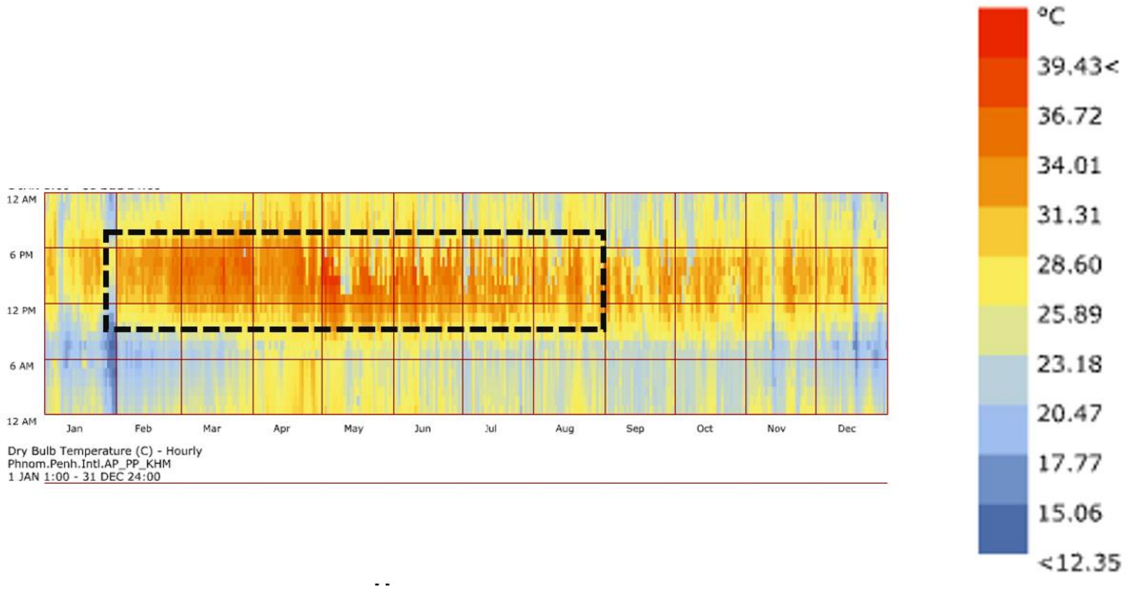

Figure 86 Heat Map of Dry Bulb Temperature (DBT) - Phnom Penh

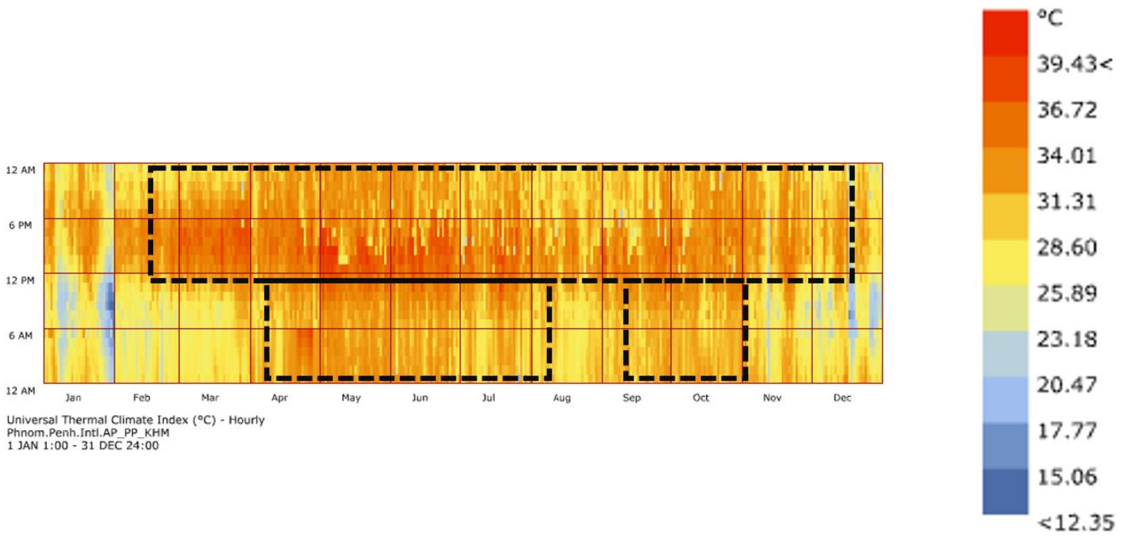

Figure 87 Heat Map of UTCI - Phnom Penh

A 1.6 Relative Humidity

Phnom Penh, Cambodia, consistently experiences high levels of relative humidity (RH) throughout the year. During the night time, the RH remains consistently above 70%. From 6:00 pm to 12:00 am, elevated RH levels persist between May and November. On average, humidity remains high from May to November. However, from November to April, the RH ranges between 40% and 70% during the day, providing a more comfortable environment. Understanding these variations in relative humidity is essential for assessing comfort levels and implementing appropriate measures in Phnom Penh.

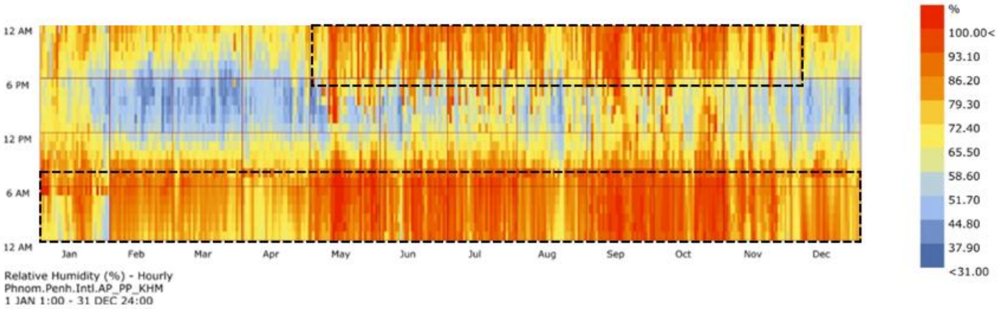

Figure 88 Heat Map of Relative Humidity - Phnom Penh

A 1.7 Wet Bulb Temperature

In Phnom Penh, it is crucial to monitor the Wet Bulb Temperature (WBT), as temperatures exceeding 35°C can be lethal, even for individuals in good physical condition. The WBT represents the lowest temperature that can be achieved through evaporative cooling, considering both temperature and humidity. The maximum WBT recorded in Phnom Penh is 30°C, indicating the highest temperature that can be achieved through evaporative cooling in the prevailing humidity levels.

It is notably high from April to October, implying a prolonged period of elevated heat and humidity. These months pose challenges in terms of thermal comfort and potential heat-related health risks. Conversely, from November to April, the WBT typically ranges between 22°C and 26°C, which is considered within the comfortable range. During this period, the temperature and humidity levels are more favourable, providing a more comfortable environment for individuals.

Monitoring the WBT is essential for understanding the heat stress levels and assessing the potential risks associated with prolonged exposure to high temperatures and humidity. It enables the implementation of appropriate passive measures and strategies.

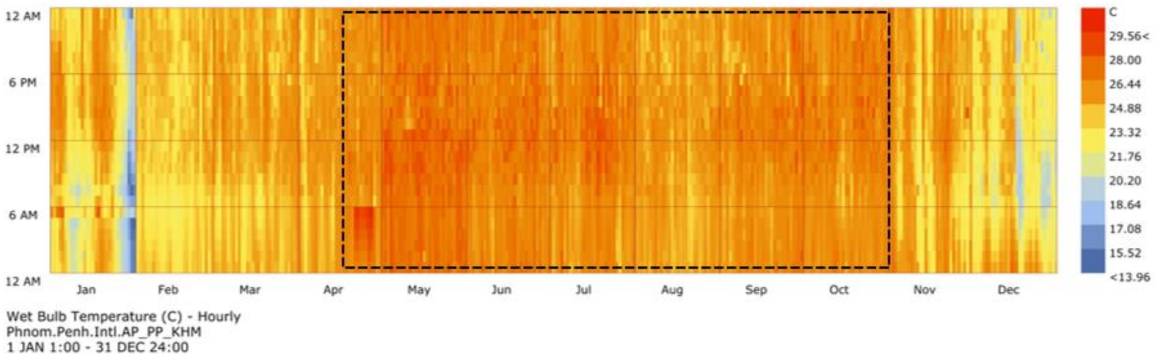

Figure 89 Heat Map of Wet Bulb Temperature - Phnom Penh

A 1.8 Wind Rose Diagram

The wind rose diagram is constructed based on 8760 hours of EPW weather data, with a focus on wind frequency, direction, and speed, along with its correlation with humidity levels and average temperature.

In Phnom Penh, the wind frequency and speed generally peak in the southwest, south, and southeast directions from February to September. During this period, the prevailing winds predominantly blow from these directions, indicating a consistent airflow pattern. In contrast, from October to January, the wind direction shifts towards the north and northeast. Winds originating from the south and southwest direction tend to carry higher levels of humidity, with relative humidity exceeding 70%. These winds contribute to the overall moisture content in the air, impacting comfort levels and potentially elevating the perceived temperature.

The average temperature of the wind throughout the year in Phnom Penh ranges from 24°C to 38°C. This variability in wind temperature characteristics influences the overall thermal perception in the region.

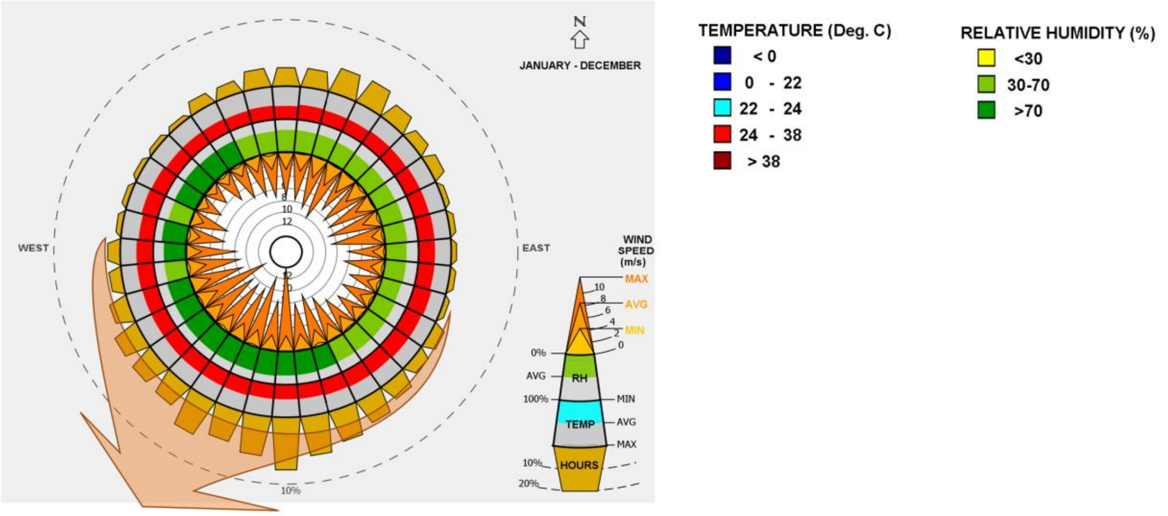

Figure 90 Wind Rose Diagram - Phnom Penh

10 Annexure 2 - Details of Representative Buildings

10.1 Residential – Condominium

10.1.1 Oxley World Bridge

Location	No 14 National Assembly Street
Type	1 BHK & 3 BHK
Source of data collection	Site and Website
Number of buildings	2
Number of floors	45
Site area	1 hectare
Residential units	734 units

Figure 91 Oxley world bridge

10.1.2 Booyoung Town

Location	Russian Blvd, Sangkat Teuk Tla, Khan Sensok
Type	1 BHK, 2 BHK (MIG)
Developer	Booyoung Khmer
Source of data collection	Online
Number of buildings	4
Number of floors	21
Year completed	2020
Residential units	13,800 units

Figure 92 Booyoung town

10.2 Borey (Landed Dwelling)

10.2.1 Borey Chankiri

Location	Thmey Village, Chroy Changvar
Type	1 BHK, 3 BHK
Developer	Urbanland
Source of data collection	Site Visit & Website
Beds in a unit	4
Number of units	37 units
Unit type	Villa
Site area	13 hectares
Floor areas	90 m^2 to 97 m^2

Figure 93 Borey chankiri

10.3 Residential – Affordable Housing

10.3.1 Borey Maha Boeng Trea

Location	Kandal Stueng
Type	1 BHK, 2 BHK
Developer	Creed from Japan
Source of data collection	Site Visit & Website
Number of units	1759 units
Unit type	Shop house, link house
Land size	59.4 sq.m to 72.9 sq.m
Built-in size	63 to 90.05 sq.m

Figure 94 Borey maha boeng trea

10.3.2 Bun Ches Flats

Location	Thmey Village, 12110, Chroy Changvar,
Type	1 BHK, 2 BHK (Affordable & MIG)
Source of data collection	Site Visit & Website
Number of units	600 units
Unit type	Retreat, unit
Built-in size	35.7 sq.m to 63 sq.m
Number of floors	2
Beds in a unit	2 to 4

Figure 95 Bun ches flats

10.4 Offices

10.4.1 Sathapana Bank Tower

Location	#63 Preah Norodom Blvd (41), Penh 12210
Type	High rise building
Architect	Aedes
Constructor	Lotte
Source of data collection	Site Visit & Website
Unit type	Large office, small office, sky restaurant or co-working
Floor plates size	933 m^2
Number of floors	19
Beds in a unit	2 to 4

Figure 96 Sathapana bank tower

10.4.2 Emerald Tower

Location	No, 64 Preah Norodom Blvd (41)
Type	High rise building
Developer	The Emerald
Source of data collection	Site Visit & Website
Floor to ceiling height	2.7m
Year established	2015
Floor plates size	480 m^2
Number of floors	12
Total units	20
Air-conditioning type	Ceiling/split

Figure 97 Emerald tower

10.5 Educational Institutional

10.5.1 Department Of Information Technology

Location	HW7G+WCV
Type	Low-rise building with a variety of PCS
Source of data collection	Site Visit & Website
Floor to ceiling height	4 m
Number of floors	19
Total area	20,415 m^2

Figure 98 Department of Information Technology

10.5.2 Institute Of Foreign Language

Location	Russian Federation Blvd (110)
Type	Low rise with a variety of PCS
Source of data collection	Site Visit & Website
Architect	Vann Molyvann
Number of floors	3
Project timeline	1970 to 1972

Figure 99 institute of Foreign Language

10.6 Hotels

10.6.1 Hotel Emion

Location	No.192 Preah Sisowath Quay	 Figure 100 Hotel Emion
Type	High rise building	
Source of data collection	Site Visit & Website	
Developer	Hunter Douglas Asia	
Number of floors	17	
Floor area	28,600 m^2	

10.6.2 Penh House

Location	JWX2+GX4	 Figure 101 Penh House
Type	Low rise	
Source of data collection	Website	
Number of floors	4	

10.7 Hospitals

10.7.1 National Pediatric Hospital

Location	HV9W+FX3, St 253	 Figure 102 National Pediatric Hospital
Type	Low rise	
Source of data collection	Website	
Speciality	Pediatric	
Established	1974	
Management	Ministry of health	
Number of floors	3	

10.8 Shopping Malls

10.8.1 Noro Mall

Location	#199 Preah Norodom Blvd (41)
Type	Low rise
Source of data collection	Site Visit & Website
Floor area	7,500 sq.m
Number of floors	6

Figure 103 Noro mall

10.8.2 Central Market

Location	Kamet St. (53)
Type	Low rise
Source of data collection	Site Visit & Website
Architect	Jean Desbois, Louis Chauchon
Established	1937
Number of floors	1

Figure 104 Central market

11 Annexure 3 – Simulation Details of All Typologies

11.1 Reference of Benchmarks

The below table shows the CEPI and EPI of all the typologies from different benchmarks.

Typologies	**LCCRB (EPI) (kWh/m^2)**	**Simulation CEPI (kWh/m^2)**	**ERIA (EPI)[8] (GWh)**
Office Buildings	92	268	3408
Hotels	699	336	3408
Serviced Apartments	103	131	3399
Condominiums	475	261	3399

8 https://www.eria.org/uploads/media/Research-Project-Report/RPR-2022-08/Cambodia-Energy-Statistics-2019-2020.pdf

11.2 Simulation Iterations and Run Time

The simulation runtime and the number of simulation iterations for each typology are listed in the table below:

Table 45 Simulation Iterations and Runtime

Typology	Option 1: Baseline Envelope Performance Case	Option 2: Intermediate Envelope Performance Case	Option 3: Best Envelope Performance Case	Total
Mid & High-Income Group Housing: Condominiums				
No. of simulation iterations	288	288	288	864
Elapsed simulation time of the parametric run	24 hours	26 hours	28 hours	78 hours
Mid & High-Income Group Housing: Landed Dwelling (Borey)				
No. of simulation iterations	288	288	288	864
Elapsed simulation time of the parametric run	8 hours	9 hours	11 hours	28 hours
Affordable Housing: Borey				
No. of simulation iterations	288	288	288	864
Elapsed simulation time of the parametric run	5 hours	5.3 hours	5.6 hours	16 hours
Affordable Housing: Condominiums				
No. of simulation iterations	288	288	288	864
Elapsed simulation time of the parametric run	4 hours 30 minutes	5 hours	5 hours 40 minutes	15 hours 10 minutes
Office				
No. of simulation iterations	504	504	504	1512
Elapsed simulation time of the parametric run	19 hours	21 hours	22 hours	62 hours
Hotel				
No. of simulation iterations	288	288	288	864
Elapsed simulation time of the parametric run	27 hours	29 hours	30 hours	86 hours
Institutional				
No. of simulation iterations	288	288	288	864
Elapsed simulation time of the parametric run	80 hours	84 hours	86 hours	250 hours