Improving Building-Level Thermal Comfort and Indoor Air Quality in South Asia:

Energy-Efficient and Cost-Effective Interventions for a Changing Climate

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Cover and graphic design: Bradley Amburn

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Acknowledgements

This report is a collaborative effort between the World Bank and the Center for Advanced Research in Building Science and Energy (CARBSE) of CEPT University. The effort was led by Ella Kim with Sebastian Forsch at the World Bank and the report was prepared by the CARBSE team managed by Yashkumar Shukla with Rajan Rawal, Sammit Pancholi, Shivani Senthilkumar, Subham Das, and Vishnu Vardhan, with technical guidance from Leon Glicksman, Professor of Building Technology and Mechanical Engineering at the Massachusetts Institute of Technology (MIT).

Gratitude is owed to Ananda Swaroop for editing, Bradley Amburn for cover design and layout, and Rosemary Kyabukooli and Marie Elvie for administrative support. The team extends its appreciation to Abhas Jha for his guidance and support throughout the development of the report.

The team also expresses its deep gratitude for the financial support for this report from the Green Recovery Initiative of the Climate Support Facility (CSF). The CSF is a multi-donor trust fund administered by the World Bank. CSF's Green Recovery Initiative (GRI) assists developing countries in rebuilding better from the COVID-19 pandemic and achieving a green economic recovery.

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Acronyms and Abbreviations

µg	microgram
AAC	autoclaved aerated concrete
ACH	air change rate per hour
AHU	air handling unit
ASHRAE	American Society of Heating, Refrigerating, and Air-conditioning Engineers
BAU	business-as-usual
BMS	building management system
CADR	clean air delivery rate
CARBSE	Center for Advanced Research in Building Science and Energy
CAV	constant air volume
CFL	compact fluorescent lamp
CLC	cellular lightweight concrete
CSEB	compressed stabilized earth block
DCV	demand controlled ventilation
DGU	double glazed unit
ECBC	Energy Conservation Building Code
EPI	energy performance index
ERV	energy recovery ventilator
GDP	gross domestic product
HEPA	high-efficiency particulate air filter
HRV	heat recovery ventilator
HI	heat index
HVAC	heating ventilation and air conditioning
IAQ	indoor air quality
IMAC	India Model for Adaptive Comfort
IPCC	Intergovernmental Panel on Climate Change
IT	information technology
kVA	kilovolt-amperes
kW	kilowatt
kWh	kilowatt hour
m^2	square meter
m^3	cubic meter
m/s	meter/second
MERV	minimum efficiency reporting value
NZEB	net zero energy building
PM	particulate matter
PUF	polyurethane foam
RCC	reinforced cement concrete
REHVA	Representatives of European Heating and Ventilation Associations
RETV	residential envelope transmittance value
SHGC	solar heat gain coefficient
SPV	solar photovoltaic
SRI	solar reflectance index

UHI	urban heat island
uPVC	unplasticized polyvinyl chloride
UTCI	universal thermal climate index
VAV	variable air volume
VLT	visual light transmittance
VRF	variable refrigerant flow
W/m^2K	watt per square meter and Kelvin
WBGT	wet bulb globe temperature
WHO	World Health Organization
WWR	window-to-wall ratio

Definitions

Air changes per hour (ACH): The number of times the total air volume in a space is completely removed and replaced in an hour. The volume of fresh air required for proper ventilation of a space is determined by the size and the use of the space, number of occupants, and pollution from indoor processes and ambient conditions.

Solar Heat Gain Coefficient (SHGC): The fraction of solar radiation admitted through glass, and subsequently released as heat in space. The lower the SHGC, the less solar heat it transmits and the greater its shading ability.

U-Value (or U-factor): A measure of the rate of heat loss or gain through a construction of materials. The lower the U-factor, the greater the material's resistance to heat flow and the better the insulating value.

Visual light transmission (VLT): The percentage of visible light that is visible through a tinted glass is used to calculate visible light transmission. The darker the tint, the greater the amount of light that will be blocked and the lower the VLT. For example, a window which has a VLT tint of 5 percent only allows for 5 percent of visible light to pass through. If a window has a VLT of 50 percent, it lets in 50 percent of the visible light.

Window-to-wall ratio (WWR): The ratio of total window area to the total wall area. A greater WWR indicates more window area, which can lead to more natural light, outside vistas, and ventilation. However, depending on the positioning and shading of the windows, it may also result in an increase in heat intake or loss. Striking a balance between daylighting, energy economy, and visual comfort is therefore essential.

Executive Summary

Buildings are a critical part of adapting to and mitigating climate change as they not only moderate heat and other climate-related risks but are also major contributors to greenhouse gas emissions. In South Asia, where one in five people are estimated to be at high risk due to a lack of access to cooling[1], safe indoor temperatures are not a luxury but a development imperative. In addition, the COVID-19 pandemic has highlighted the need for better ventilation to reduce the risk of infectious diseases and cool indoor spaces, especially in densely populated areas.

As temperatures rise because of climate change, demand for cooling and ventilation is expected to skyrocket, with large energy and climate implications. In India, for instance, the number of air conditioners is projected to increase more than sixteen-fold in the next few decades, from 67 million units in 2022 to more than 1.1 billion units by mid-century. As a result, India's share of air conditioning in peak electricity load could reach 45 percent in 2050[2].

A building acts as a heat multiplier or heat diminisher, with indoor air temperatures ranging widely depending on its design and materials. Therefore, a building that is better able to withstand heat and ensure thermal comfort for the people inside can fundamentally reduce overall cooling needs and associated energy costs, power outages, and the use of climate-warming refrigerants.

This report provides evidence-based guidance on cost-effective and energy-efficient cooling and ventilation interventions to improve building-level thermal comfort and indoor air quality for a changing climate in South Asia. It focuses on Bangladesh, India, and Pakistan but also covers all the countries in the region, including Afghanistan, Bhutan, Maldives, Nepal, and Sri Lanka. After an introduction (Chapter 1), the report analyzes local climates and air quality issues, building types, and occupant behavior (Chapter 2), as well as available passive and active interventions and their relevance in the region (Chapter 3), before concluding with a set of recommendations (Chapter 4). Box 1 provides an overview of the twelve key recommendations for all building types. The report also identifies additional recommendations specific to residential and commercial buildings, along with policy and country-specific recommendations.

Overall, the report highlights the potential of passive interventions at the early stages of the design process, such as improving building orientation and layout, for cost-effective, low-carbon cooling and ventilation throughout South Asia (Recommendations 1 and 2). For instance, based on a quick solar exposure analysis at minimal cost, a building orientation and layout that minimize solar exposure can reduce the energy needs of a building by 5-20 percent, depending on the building's location.[3] Similarly, climatic analyses of South Asian cities conducted for this report show high potential for utilizing natural ventilation as a design strategy (15-40 percent of the time, depending on the city), especially if the buildings are expected to operate during night hours (such as residential buildings).

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[1] Sustainable Energy for All (2022), Chilling Prospects 2022. https://www.seforall.org/chilling-prospects-2022/global-access-to-cooling-gaps

[2] IEA (2018), The Future of Cooling, IEA, Paris. https://www.iea.org/reports/the-future-of-cooling, License: CC BY 4.0.

[3] Energy estimates are based on simulations carried out in EnergyPlus for all South Asian cities discussed throughout the report using typical residential and commercial building designs. The estimates vary with building type, occupancy schedule and local climate. In addition, the energy savings presented for each intervention are calculated with all other building factors held constant in business-as-usual scenarios. Due to the interdependency of building factors, the cumulative savings of all measures may not be equal to the sum of savings from individual measures. The details of the simulations for this report are in Annex 7: Simulation Details.

Box 1: Key recommendations to improve thermal comfort and indoor air quality at the building-level in South Asia

✓ **1.** Design building orientation and layout to minimize solar exposure.

✓ **2.** Maximize a building's natural ventilation potential.

✓ **3.** Integrate external shading devices in building design.

✓ **4.** Minimize air leakage through building envelopes.

✓ **5.** Select high-performance materials for building envelopes.

✓ **6.** Use high thermal mass in buildings.

✓ **7.** Design and operate buildings as per adaptive thermal comfort models.

✓ **8.** Increase the use of air circulation devices.

✓ **9.** Use mechanical ventilation, especially during cooler night hours.

✓ **10.** Use low-energy cooling systems, along with the application of the adaptive comfort thermal model.

✓ **11.** Use simple information technology to enhance building operations.

✓ **12.** Educate occupants in proper day/night building operations to minimize thermal extremes.

The report also recommends that features of more traditional or vernacular buildings be revisited across the region as they often incorporate effective cooling and ventilation traits not reflected in modern designs, such as portable external shading devices (Recommendation 3) and a higher thermal mass (Recommendation 6). Well-designed shading devices can reduce the energy needs of a building by 5-6 percent, depending on the building's location and total area designed for fenestration. The cost of adding shading devices in the building at the design stage is marginal (<1 percent). A high thermal mass strategy, supplemented by nighttime ventilation, can suppress daytime temperature extremes and reduce the energy needs of a building by 5-10 percent in hot and dry climates at moderate incremental costs in the range of 3-5 percent.

A well-designed building envelope can minimize air leakage (Recommendation 4) and significantly reduce heat gains (Recommendation 5). A well-sealed building envelope can reduce the energy needs of a building in the region by 5-10 percent through minimized air leakage, but necessitates enhanced awareness, training, and quality assurance across the construction process to ensure proper sealing. In addition, efficient building envelopes require higher-performance materials which can lead to a moderate increase (1-5 percent) in building costs. For example, hollow brick walls add marginal resistance to heat transfer compared to traditional brick construction at minimal incremental costs, while insulation materials provide significant resistance to heat transfer at moderate incremental costs. Overall, the selection of suitable envelope materials and technologies can reduce the energy needs of a building by 10-30 percent, depending on the location of the building.

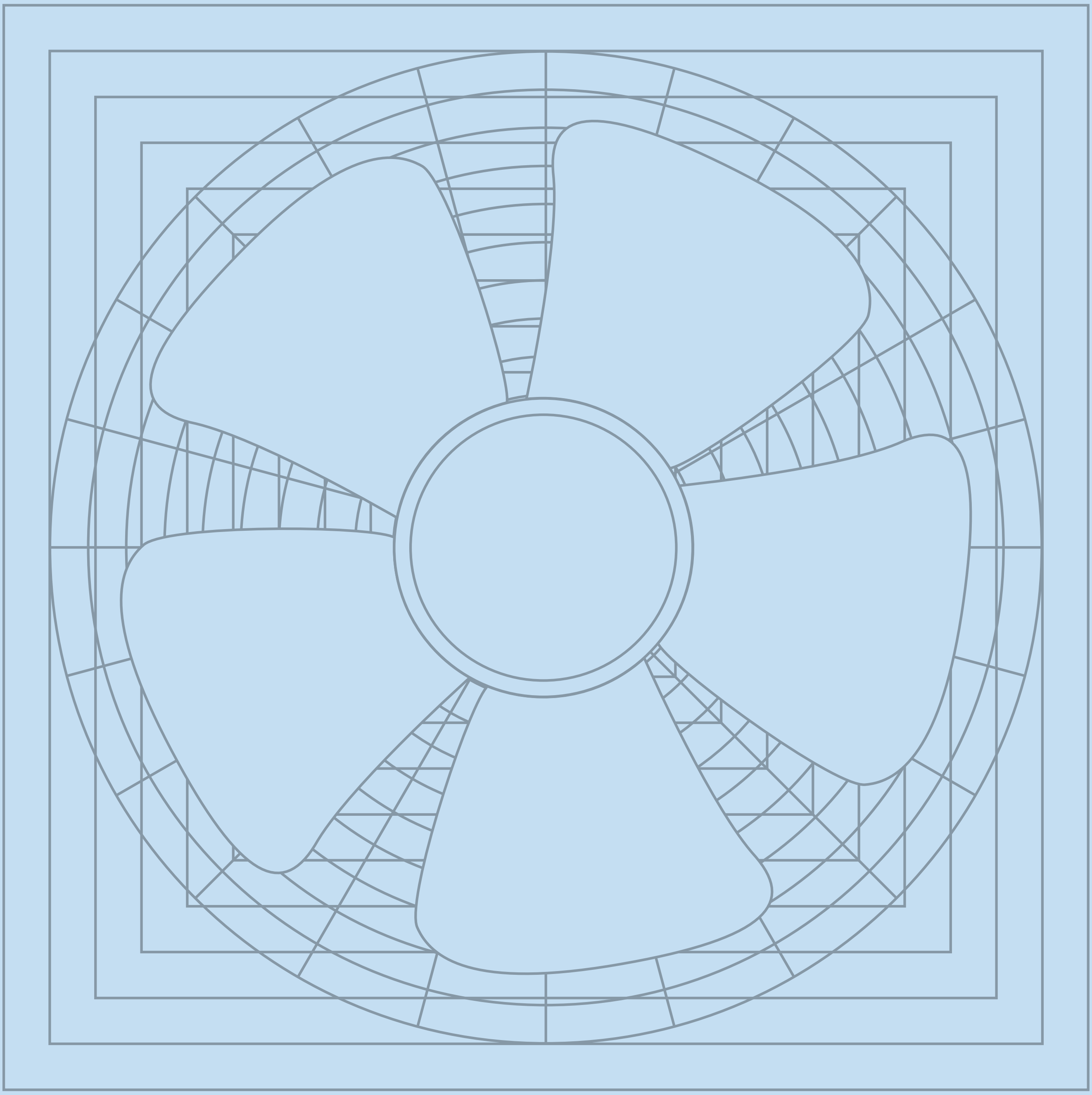
Designing and operating buildings per adaptive thermal comfort models is one of the most promising and effective measures for reducing energy use from cooling and ventilation (Recommendation 7), which can be complemented with other measures, including low-energy cooling systems where available (Recommendation 10). The adaptive thermal comfort model recognizes that the thermal comfort preferences of occupants vary based on contextual and historical factors and cooling options available to the occupants, such as the availability of operable windows or pedestal fans. Many modern buildings in South Asia are designed for and utilize mechanical cooling systems to achieve indoor temperatures of 24 degrees Celsius. However, adaptive thermal comfort studies show that occupants in South Asia are comfortable at higher temperatures (>27 degrees Celsius in the summer when outdoor temperatures are more than 35 degrees Celsius) than typically assumed by building designers. A one-degree Celsius increase in the cooling setpoint can reduce energy usage in buildings in a hot climate by 6-10 percent and may lead to even higher energy savings when combined with additional measures, such as the use of air circulation devices. Other measures can complement this approach to maintain indoor temperatures within safe and comfortable ranges. Where mechanical systems are required, low-energy cooling and ventilation solutions should be prioritized over traditional vapor compression systems that consume significant energy to deliver thermal comfort. The application of the adaptive thermal comfort model, along with hybrid cooling systems utilizing evaporative and vapor compression-based cooling, could lead to 20-25 percent energy savings in various cities of South Asia.

Conventional air circulation devices such as ceiling or pedestal fans and mechanical ventilation systems that circulate air between indoor and outdoor environments are cost-effective and widely available solutions to increasing thermal comfort (Recommendations 8 and 9). High air speeds increase operative temperature limits by 1.2–2.2 degrees Celsius when the average air speed in the space is 0.6-1.2 meter/second (m/s) inside occupant-controlled naturally ventilated spaces. Air circulation devices also improve air distribution within spaces, minimizing temperature gradients and increasing the consistency of temperatures throughout. As a result, they can reduce the energy needs of a building by 5-10 percent, with minimal costs due to the prevalence of affordable air circulation devices in the market. Mechanical ventilation can also be a cost-effective approach, even with the required operational energy, especially in buildings where ventilation requirements are more stringent or when building constraints, such as location or floor plan, inhibit sufficient air flow through natural ventilation.

The use of information technology can significantly enhance the operation of building-level cooling and ventilation systems (Recommendation 11). Simple information technology solutions such as carbon dioxide, temperature, and humidity sensors can help quickly modify ventilation and cooling processes according to real-time needs. The cost of incorporating information technology in buildings varies considerably based on the type of technology. For residences, simple automated systems may suffice. For commercial buildings, sophisticated integrated technologies, such as centralized systems with built-in algorithms based on specific building requirements, could lead to moderate capital cost (5-7 percent) increases while producing energy savings of 16-25 percent. With the increasing availability of low-cost sensors, the feasibility of integrating information technology in buildings will significantly increase over the coming years and become affordable for a larger share of the population.

Finally, occupants can be educated to optimize proper day/night building operations and minimize thermal extremes (Recommendation 12). Maximizing free natural cooling, either by window operation or mechanical systems, can result in significant energy savings and improved indoor air quality, as well as reduced peak temperatures for buildings without air conditioning. Depending on the location of the building, natural ventilation can be used for about 15-40 percent of the day. Cooling buildings using lower outdoor temperatures at night enhances occupant thermal comfort through higher radiant and convective heat exchange with cool surfaces. Efficient night cooling requires access to the thermal mass of the building structure. Window or attic fans can enhance air exchange in open-plan buildings at low energy consumption rates.

Introduction

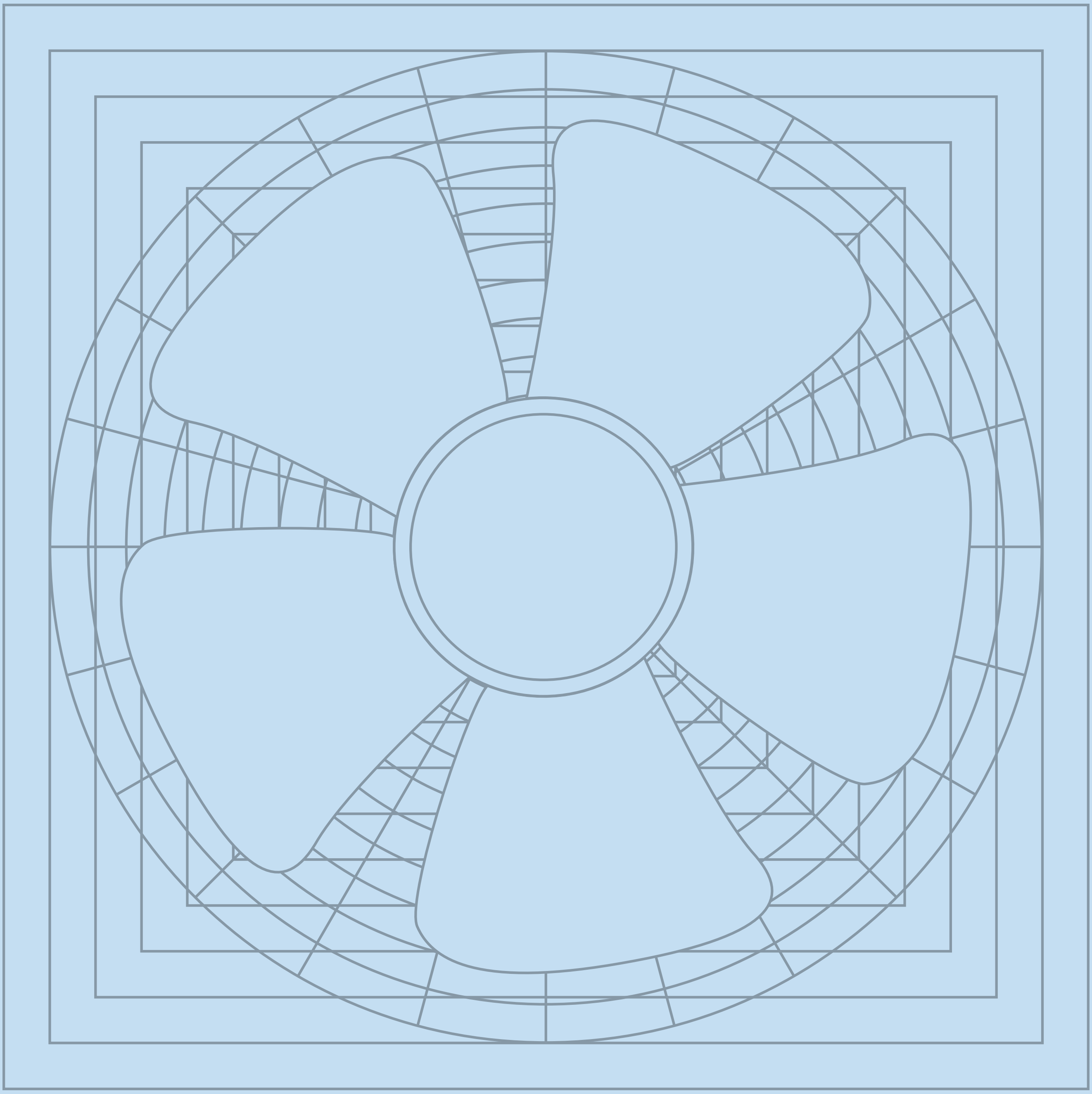


1 Introduction

This report provides evidence-based guidance on energy-efficient and cost-effective ventilation and cooling systems for practitioners to enhance air quality and thermal comfort inside buildings in South Asia. The report focuses on buildings in Bangladesh, India, and Pakistan, while covering South Asian countries, including Afghanistan, Bhutan, the Maldives, Nepal, and Sri Lanka. It summarizes recent research and policies, assesses the incremental costs of measures available today, and proposes pragmatic recommendations that can be implemented in buildings in South Asia.

The second section presents a high-level climatic analysis of selected cities in South Asia, as well as an overview of the region's prevalent building archetypes and typologies. The third section provides information on passive measures, active cooling technologies, air quality improvement strategies, and simple information technology (IT)-based interventions with a focus on energy efficiency and occupant comfort. The section ends with a review of the incremental costs of building-level cooling and ventilation measures in diverse regions of South Asia. The fourth section focuses on key recommendations for buildings in South Asia, along with recommendations specific to residential and commercial buildings. The annexes to the report provide case studies, policy and country-specific recommendations, and additional resources, such as software tools and guidelines to further explore selected topics. Lastly, there is more detailed information on the simulation models used to estimate energy and cost savings of different measures across South Asia.

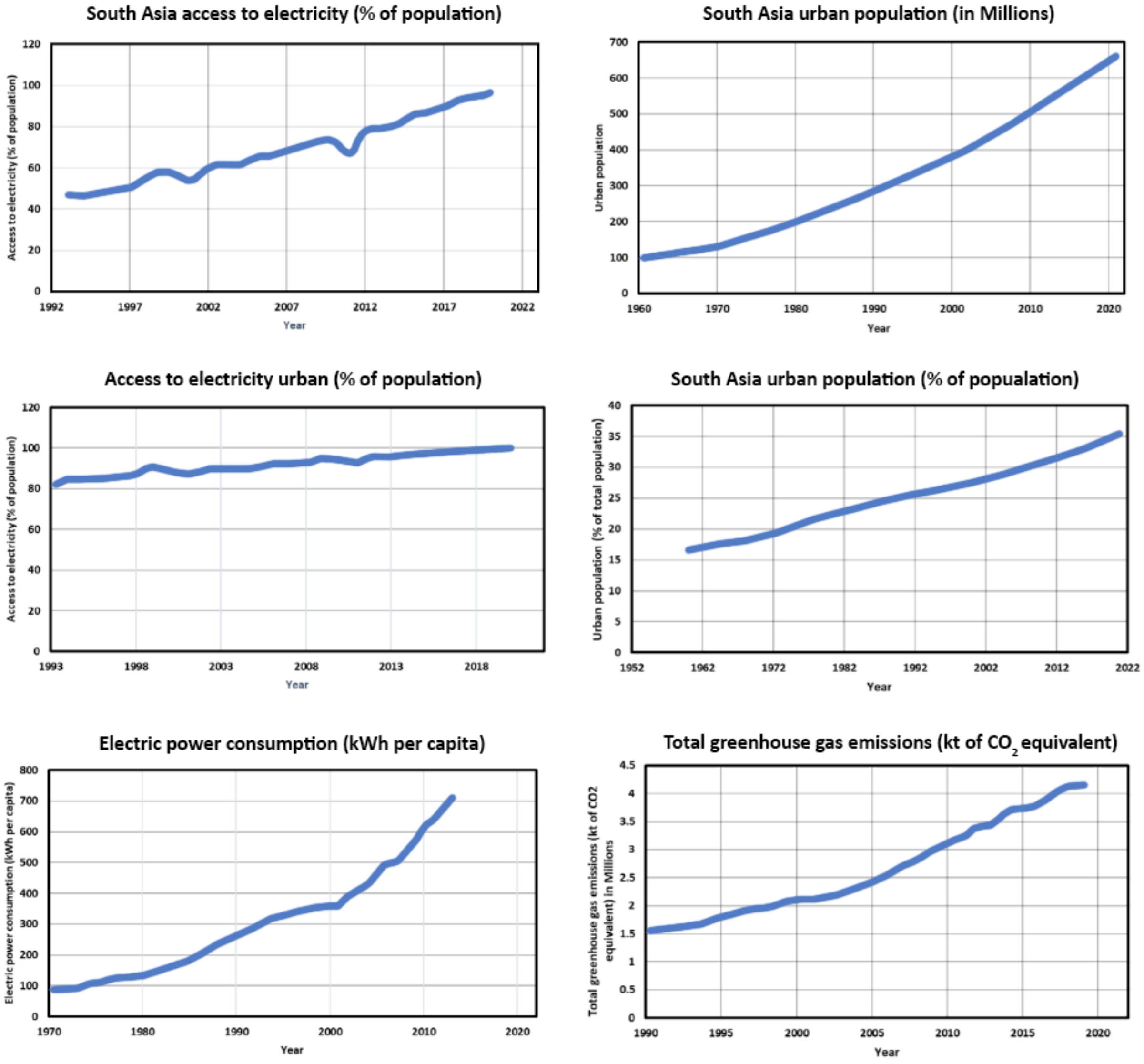
Understanding Cooling and Ventilation Needs in South Asia



2 Understanding Cooling and Ventilation Needs in South Asia

This chapter analyzes local climates, air quality issues, building types, and occupant behavior in South Asia, with the aim of better understanding cooling and ventilation needs in the region. Resources and climate analysis tools for further insights are provided in Annex 3: Additional Resources.

Figure 2.1. Historical trends of electricity use, population, and emissions in South Asia



South Asia access to electricity (% of population)

South Asia urban population (in Millions)

Access to electricity urban (% of population)

South Asia urban population (% of popualation)

Electric power consumption (kWh per capita)

Total greenhouse gas emissions (kt of CO_2 equivalent)

Source: The World Bank, 2022.
Note: kWh: kilowatt hour; kt: kiloton.

2.1 Relevance of Cooling and Ventilation in South Asia

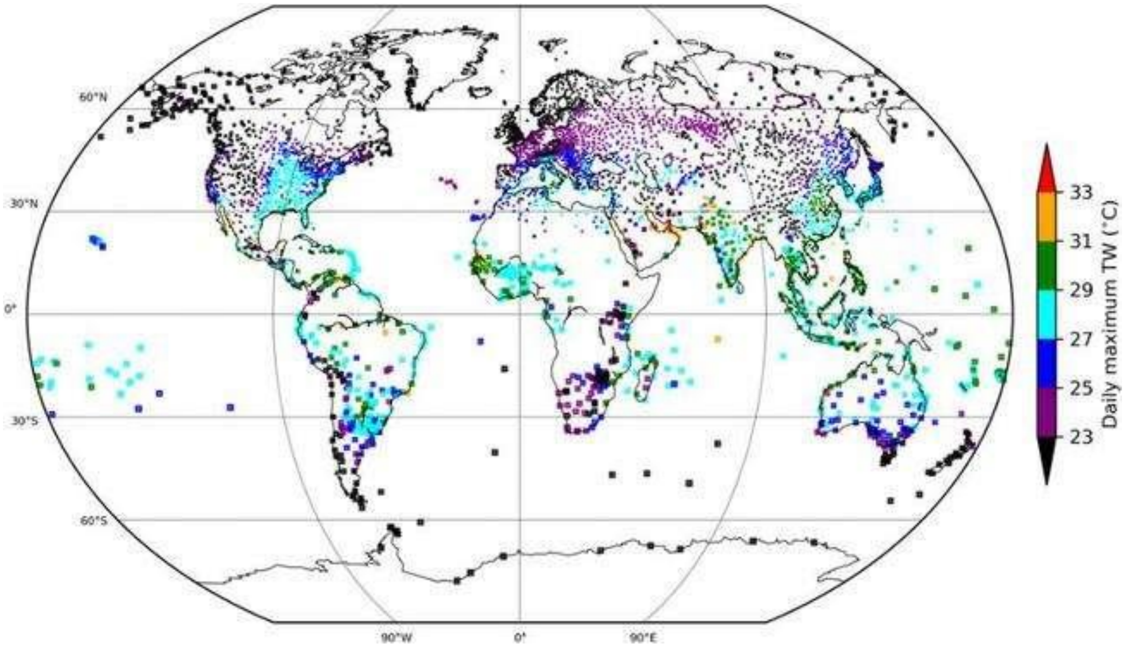
South Asia is home to 23 percent (1.9 billion[4]) of the world's population and faces significant risks due to climate change. These effects are expected to intensify with rising regional temperatures and magnitude of climate change.

Figure 2.1 shows trends in the South Asian region where the percentage of urban population with access to electricity has increased, and the per capita electric power consumption has grown exponentially.

Approximately 46 percent of the total population has access to electricity. This, coupled with the exponentially rising electricity consumption and emissions, suggests that buildings in the future will need to find ways to deliver cooling and ventilation without increasing the carbon footprint.

Climate data also show that several regions that exceed the recommended wet-bulb temperature values are concentrated in South Asia. The human body can lose heat up to a wet-bulb temperature of 35 degree centigrade (°C), by which time it would have already faced severe health and productivity impacts. Wet-bulb temperature is a strong indicator of heat stress – a high value indicates the human body's reduced ability to undergo thermoregulation through perspiration (Raymond et al., 2020).

Figure 2.2. Observed extreme humid heat throughout the globe



Source: Raymond et al., 2020.
Notes: Color symbols represent the 99.9th percentile of observed daily maximum TW (wet-bulb temperature) for 1979–2017 for HadISD stations with at least 50 percent data availability over this period. Marker size is inversely proportional to station density.

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[4] Data is sourced from United Nations Population Division, World Population Prospects: 2022 Revision.

South Asia comprises eight countries: Afghanistan, Pakistan, India, Nepal, Bhutan, Bangladesh, the Maldives, and Sri Lanka. Heat waves have become frequent, with 2018 being the sixth hottest year on record since 1880.

The identification of buildings as key contributors to global emissions is crucial. Buildings, directly and indirectly, can play a significant role in climate change mitigation and adaptation while addressing the growing regional population's needs for cooling and ventilation.

In India, Pakistan, and Bangladesh, the largest South Asian countries based on population, land area, and gross domestic product (GDP), the building sector has grown exponentially in response to their growing population. It is now a significant contributor to world energy demand. The building sector in these countries is the most significant contributor to energy usage (India: 47 percent; Pakistan: 55 percent; Bangladesh: 55 percent) (Salam et al., 2020).

As South Asia is one of the most vulnerable regions to climate change, urgent efforts are required to mitigate its contribution to global warming as well as to ensure that it adapts and prepares for more frequent extreme weather events. Geographical locations of the most extreme projected heat waves in the Indus and Ganges River valleys coincide with high population density and agricultural intensity. Approximately 75 percent of the population is expected to experience maximum wet-bulb temperatures exceeding 31°C by 2100 (Im et al., 2016), considered dangerous levels for most humans (Pal and Eltahir, 2016).

2.2 Localized Analysis of Outdoor Climate and Air Quality

Outdoor weather conditions primarily define the thermal environment within buildings. Prolonged periods of warm outdoor conditions are associated with increased cooling demand. Furthermore, the increasing frequency and intensity of weather extremes and the ongoing challenge of airborne COVID-19 pandemic have led us to establish the importance of climate-resilient and well-ventilated buildings. This necessitates a thorough understanding of local climatic variations and interdependencies. It is also crucial to understand the applicability of internationally established climate characterization methods and their relevance in the present climatic conditions. This section provides a climatic summary of cities in South Asia.

2.2.1 Outdoor Climate in South Asia

South Asia's unique geographical features limit the horizontal exchange of oceanic and continental air masses and distinctively alter the climate. There are lowland depressions as well as large mountains and upland systems. Several bays and gulfs enhance the impact of the ocean. A warm, westward-moving current affects the southeast coast of Sri Lanka throughout the winter when it reaches eastern Sri Lanka.

The southwest monsoon, which occurs from June to September and lasts for four months, is the most significant climatic element in the area. Precipitation during this period is significantly higher than it is throughout the rest of the year. The South Asian monsoon region experiences huge temperature drops in June and July because of the arrival of the monsoon, making March through May the hottest time of year (Xue and Yanai, 2005).

The sixth assessment report of the Intergovernmental Panel on Climate Change (IPCC) suggests that, as climate change continues to affect the region, heat waves and humid heat stress will be more intense and frequent during the 21st century. Both annual and summer monsoon precipitation will increase with enhanced inter-annual variability (medium confidence) (Asadnabizadeh, 2022).

Regional climates need to be demarcated into clear categories to compare the various cities in South Asia and propose suitable localized measures and interventions. The Köppen climate classification prescribes local climate categories within the context of global climate patterns (Chan and Chen, 2013). However, these categories may be perceived as nonintuitive terminologies for buildings in South Asia.

South Asia is a diverse region with distinct microclimates, urban heat island (UHI) effects that can significantly alter local climate conditions as well as cooling and ventilation requirements that are highly dependent on local climate conditions. A localized climate classification system can provide more detailed information on climate conditions, essential for building design and energy efficiency measures. Therefore, this report categorizes South Asian cities using the framework established by the Indian National Building Code, wherein five broad climate categories have been defined: hot-dry, warm-humid, temperate, cold, and composite.

To deal with the localized climate variations and interdependencies across the vast and diverse South Asia region, a sample of key South Asian cities was selected for analysis throughout the report. They are categorized into five climate types, using category-specific outdoor air temperature and relative humidity thresholds.

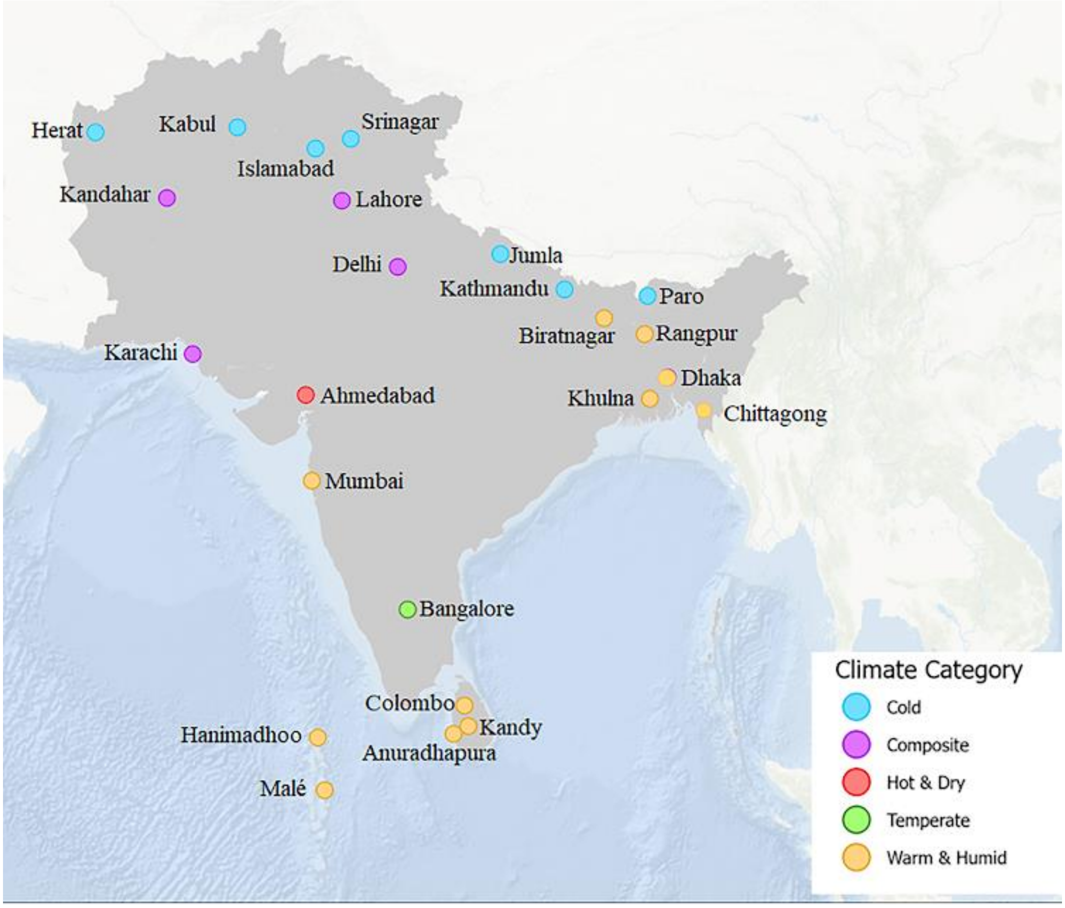
The choice of cities was based on factors of high population and level of urban development to cover all climate zones present within a given country (Table 2.1). The climate classification of the key South Asian cities shown in **Table 2.1** was derived from average monthly peak dry-bulb temperatures (ºC) and relative humidity (percent) for each city. These values were compared against climate classification limits specified by the Indian National Building Code of 2016, which attributes a specific region with a climate type based on whether a season exists for six months. Any climate zone not having a single season for more than six months may be attributed as a composite climate type (BIS, 2016).

Table 2.1. Climate categorization of South Asian cities

Country	City	Population	Climate Category
Afghanistan	Herat	2,187,169	Cold
	Kabul	4,601,789	Cold
	Kandahar	651,484	Composite
Bangladesh	Chittagong	2,581,643	Warm and humid
	Dhaka	7,000,940	Warm and humid
	Khulna	2,378,971	Warm and humid
	Rangpur	294,265	Warm and humid
Bhutan	Paro	11,448	Cold
India	Ahmedabad	5,570,585	Hot and dry
	Bangalore	8,425,970	Temperate
	Delhi	18,983,000	Composite
	Mumbai	18,414,288	Warm and humid
	Srinagar	1,180,570	Cold
Maldives	Hanimaadhoo	1,951	Warm and humid
	Malé	133,412	Warm and humid
Nepal	Biratnagar	244,750	Warm and humid
	Jumla	108,921	Cold
	Kathmandu	845,767	Cold
Pakistan	Islamabad	1,014,825	Cold
	Karachi	14,910,352	Composite
	Lahore	11,126,285	Composite
Sri Lanka	Anuradhapura	856,232	Warm and humid
	Colombo	752,993	Warm and humid
	Kandy	125,400	Warm and humid

Figure 2.3 shows the spatial distribution of cities selected for the report within South Asia, marked with different colors to highlight their climate types.

Figure 2.3. Climate types of all cities selected for study



Source: Author's analysis.

Table 2.2 summarizes the different building operation modes based on the India Model for Adaptive Comfort (IMAC) for residential buildings operating in naturally ventilated mode throughout the year. The classification of operational strategies is based on the boundary conditions under which hourly weather data fall. For example, if the hourly weather data lie between the temperature bands and between the comfortable relative humidity ranges of 30–70 percent (CARBSE, 2020), the comfort strategy is classified as "Natural Ventilation."

Adaptive thermal comfort models can significantly reduce energy use while maintaining occupants' comfort, productivity, and well-being. Traditional thermal comfort models target either completely air conditioned or naturally ventilated[5] spaces.

Table 2.2. Classification of strategies for the India Model for Adaptive Comfort

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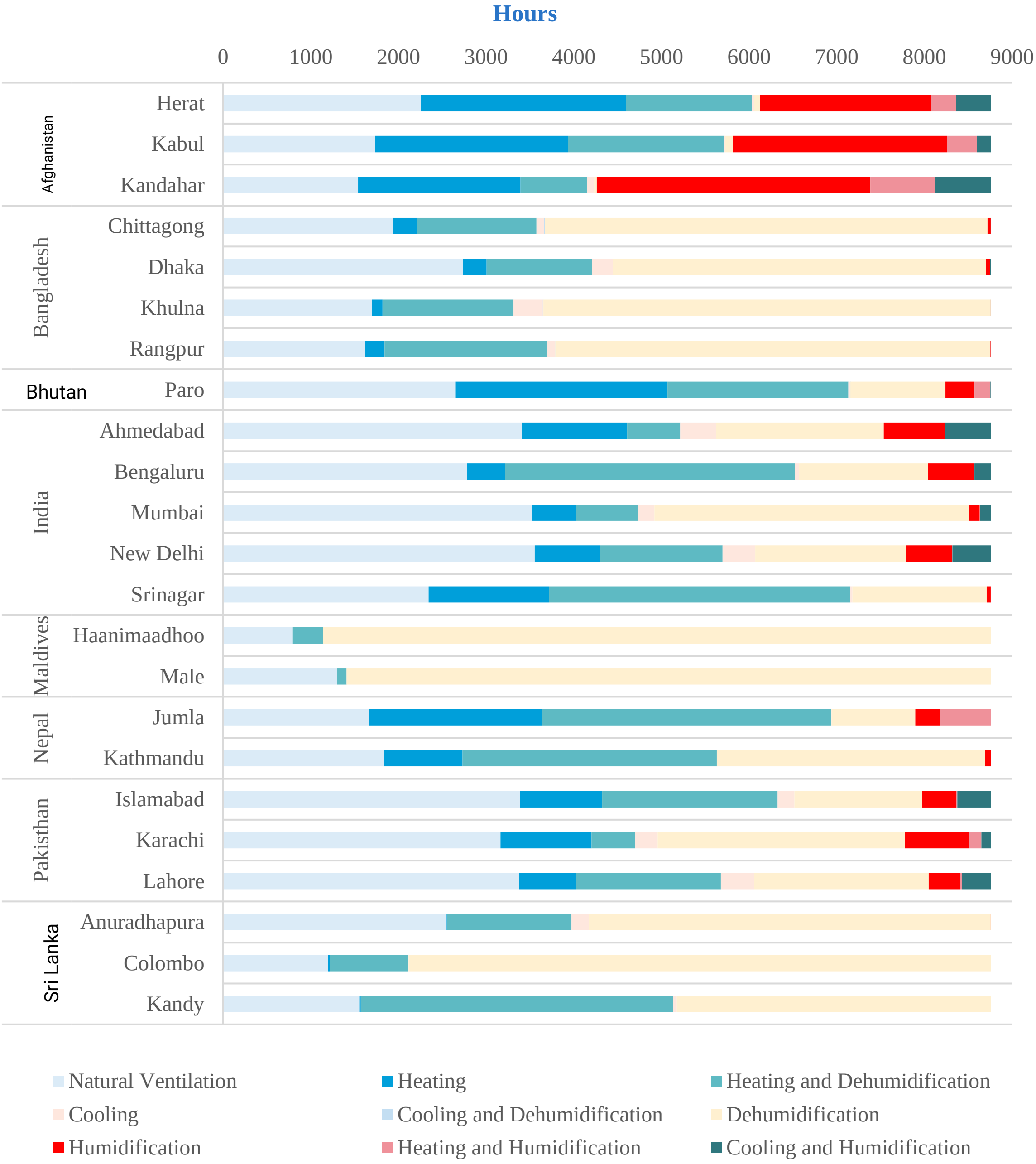
[5] Natural ventilation, unlike fan-forced ventilation, uses the natural forces of wind and buoyancy to deliver fresh air into buildings. Fresh air is required in buildings to alleviate odors, provide oxygen for respiration, and increase thermal comfort. However, unlike air conditioning, natural ventilation is ineffective in reducing the humidity of incoming air, limiting the application of natural ventilation in humid climates.

Number	Category	Description of the comfort strategy
1	Natural Ventilation	The comfort strategy is classified as natural ventilation if the hourly weather data are between the temperature bands and between comfortable relative humidity ranges of 30–70%
2	Heating	If the data point lies in the comfortable relative humidity band and below the lower limit of the comfortable temperature band, it is classified under the *heating* strategy
3	Cooling	If the data point lies in the comfortable relative humidity band but above the upper limit of the comfortable temperature band, it is classified under the *cooling* strategy
4	Dehumidification	If the data point lies in the neutral (comfortable) temperature band but above the comfortable relative humidity band (>70%), it is classified under *dehumidification*.
5	Humidification	If the data point lies in the neutral (comfortable) temperature band and below the comfortable relative humidity band (<30%), it is classified under *humidification*
6	Heating and Dehumidification	If a data point lies below the comfortable temperature band and above the comfortable relative humidity (>70%) band, the strategy to be adopted is *heating and dehumidification*
7	Heating and Humidification	If a data point lies below the comfortable temperature band and below the comfortable relative humidity (<30%) band, the strategy to be adopted is *heating and humidification*
8	Cooling and Dehumidification	If a data point lies above the comfortable temperature band and comfortable relative humidity (>70%) band, the strategy to be adopted is *cooling and dehumidification*
9	Cooling and Humidification	If a data point lies above the comfortable temperature band and below the comfortable relative humidity (<30%) band, the strategy to be adopted is cooling and humidification

Figure 2.4 depicts the operation strategies required in different cities after categorizing each hour in a year based on outdoor conditions into nine modes of operation and determining the most suitable operating mode shown in Table 2.2.

Figure 2.4. Strategy classification for residential buildings operating in naturally ventilated mode



Source: Author's analysis.

Rapid urbanization in South Asia has also increased the UHI effect. Understanding outdoor thermal conditions is highly relevant as they serve as the basis for all indoor thermal phenomena. The heat index (HI) assesses heat stress using ambient air temperature and relative humidity. Wet-bulb globe temperature (WBGT), another heat stress index, attempts to mimic human radiation exchange with the environment by accounting for naturally ventilated wet-bulb temperature, air temperature, and globe temperature. Furthermore, the universal thermal climate index (UTCI) is a comprehensive heat stress index based on human thermoregulation. It accounts for human metabolic activity, air temperature, relative humidity, and mean radiant temperature of the outdoor space.

Heat stress conditions were evaluated for all cities using the set of threshold values quoted in Blazejczyk et al. (2012) and the UTCI assessment.

Table 2.3 provides key insights[6] regarding heat stress in various South Asian cities. We can see that Ahmedabad (India), Karachi (Pakistan), and Khulna (Bangladesh) experience dangerously high WBGT and UTCI in combination with a significantly high population density (Macrotrends, 2022; Banglapedia, 2022; World Population Review, 2022).

Table 2.3. Heat stress classification in South Asian cities based on the number of days with daily maxima of key thermal indices[7]

Country	**City**	UTCI>46 Extreme heat stress	**UTCI between 38 and 46** Strong heat stress	**HI>54** Sweltering (extreme danger)	**HI between 41 and 54** Very hot (danger)	**WBGT>30** Sweltering (extreme danger)	**WBGT between 28 and 30** Very hot (danger)
Afghanistan	Herat	138	106	0	4	15	36
	Kabul	22	110	0	1	3	6
	Kandahar	124	120	0	33	51	35
Bangladesh	Chittagong	92	151	0	208	244	32
	Dhaka	130	109	0	195	240	29
	Khulna	204	100	1	221	256	19
	Rangpur	107	130	0	152	218	29
Bhutan	Paro	6	117	0	1	1	7
India	Ahmedabad	311	16	0	191	226	46
	Bengaluru	153	119	0	0	44	120
	Delhi	229	78	2	152	182	28
	Mumbai	242	36	0	220	276	58
	Srinagar	89	162	0	0	10	27
Maldives	Hanimaadhoo	183	102	0	308	365	0
	Malé	139	38	0	332	365	0
Nepal	Biratnagar	126	154	1	183	228	38
	Jumla	4	200	0	0	1	2
	Kathmandu	22	127	0	1	22	74
Pakistan	Islamabad	164	115	0	4	15	36
	Karachi	242	71	0	169	209	31
	Lahore	220	98	0	150	183	20
Sri Lanka	Anuradhapura	202	91	0	201	352	13
	Colombo	196	142	0	230	363	2

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[6] The colored boxes represent the maximum number of days in each thermal index for a country. For example, Biratnagar in Nepal has the maximum number of days in four of the six thermal indices in Table 2.3.

[7] The outdoor heat stress values are calculated using BioKlima, a tool for calculating bioclimatic and thermophysiological parameters. (Krzysztof Blazejczyk. BioKlima: Universal Tool for Bioclimatic and Thermophysiological Studies. Institute of Geography and Spatial Organization, Polish Academy of Sciences. 2017. Available from: https://www.igipz.pan.pl/bioklima-crd.html.). The figures in each cell represent number of days in a year.

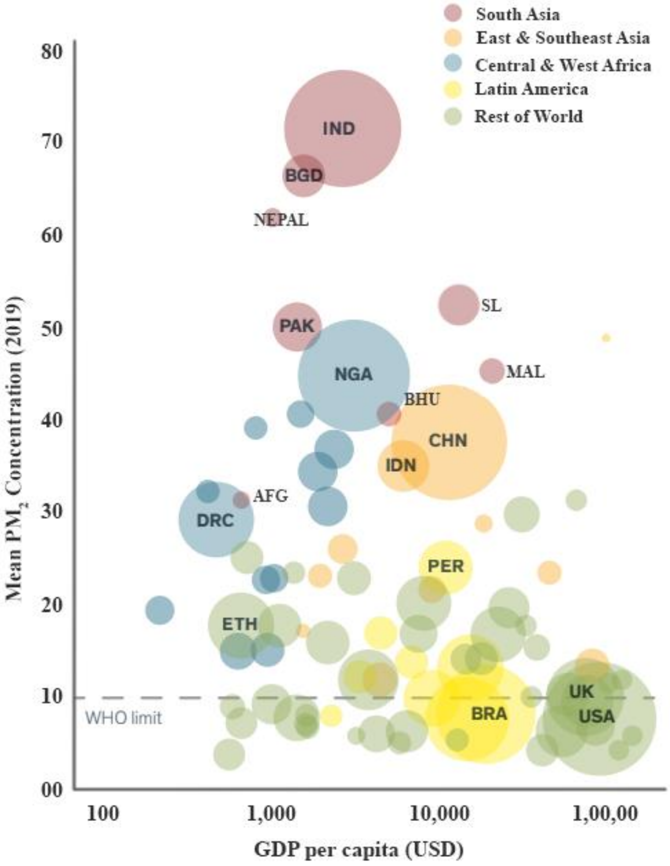
	Kandy	160	113	0	33	51	35

2.2.2 Outdoor Pollution in South Asia

Exposure to air pollution contributes to nearly 20 percent of all causes of death and exacerbates acute and chronic respiratory illnesses in millions in South Asia (Sharma et al., 2019). South Asia has one of the highest concentrations of black carbon emissions globally, emanating from vehicles, stoves, agricultural practices, and industries. Most air contaminants are often found at their highest levels in densely populated metropolitan regions and industrialized zones. Ozone and ammonia are the exceptions, which are frequently higher in rural locations.

Bangladesh, India, Nepal, and Pakistan consistently rank among the world's top four countries in terms of air pollution, while 42 out of the 50 cities with the poorest air quality are in South Asia (Figure 2.5).

Figure 2.5. Particulate matter concentration and GDP per capita in 2019



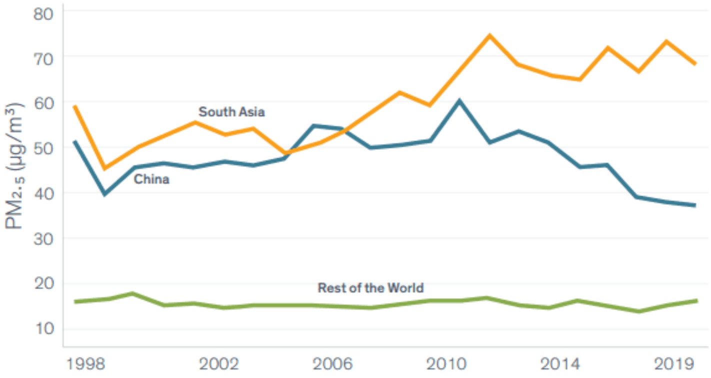
Source: Lee and Greenstone, 2021.
Note: AFG – Afghanistan, BGD – Bangladesh, BHU – Bhutan, IND – India, MAL – Maldives, PAK – Pakistan, SL – Sri Lanka. All countries referred to as South Asian for this report have been marked in red.

In residential areas, re-suspension of dust was responsible for up to half of fine particulate matter (PM 10) (Sharma et al., 2019). Populations in South Asia, except for the island nations of Sri Lanka and the Maldives, are among the most highly exposed to ultrafine particulate matter (PM 2.5) globally. Estimates from the Global Burden of Disease Study, 2015, indicate that the population-weighted mean ambient PM 2.5 concentration in South Asia was 73 microgram/cubic meter (µg/m^3), compared to the global average of 44 µg/m^3. Furthermore, ~99.9 percent of the South

Asian population lives in areas with poorer outdoor air quality than the World Health Organization (WHO)-recommended thresholds (Krishna, 2017).

Please refer to Annex 9: Air Quality in South Asian Countries to compare the annual mean concentration of PM 2.5 for each South Asian country with WHO standards. While there is improvement in air quality in certain regions, there has been deterioration in others, Figure 2.6 shows that air pollution remains a persistent problem, with South Asia witnessing unchanged or growing levels of air pollution from 1998-2019.

Figure 2.6. Global trends in particulate matter concentrations, 1998–2019



Source: Lee and Greenstone, 2021.

2.3 Localized Analysis of Building Types and Occupant Behaviors

Demand for comfort and ventilation significantly depends on the construction method, building material, building type, and occupant behavior. The building type— categorized by "type of building function" and "type of cooling and ventilation system"—largely influences the consequent indoor environment and resulting energy use.

Similarly, occupant behaviors such as window operation, plug load operation, lighting operation, and more, influence the indoor environment and energy use. Regional variations in climate and culture add more nuances to understanding the building–human interaction. The idea of humans (and not inherently buildings) as the primary consumers of energy and drivers of comfort calls for identification and categorization of building archetypes and occupant behavior within a regional context.

Table 2.4 lists existing cooling and ventilation measures typically adopted in cities in Bangladesh, India, and Pakistan. These broadly include air-circulation devices (such as ceiling, pedestal, and wall-mounted fans), thermal mass and walling technologies (such as thick walls made of mud or bricks and cavity walls), shading devices (such as external shading such as overhangs, including drapes or curtains), and specific design measures (such as orientation of the building and positioning of exterior openings).

These measures and other recommended passive and active measures are discussed in more detail in Section 3.1. The sources from which these measures are derived include a literature review of vernacular architecture and case studies.

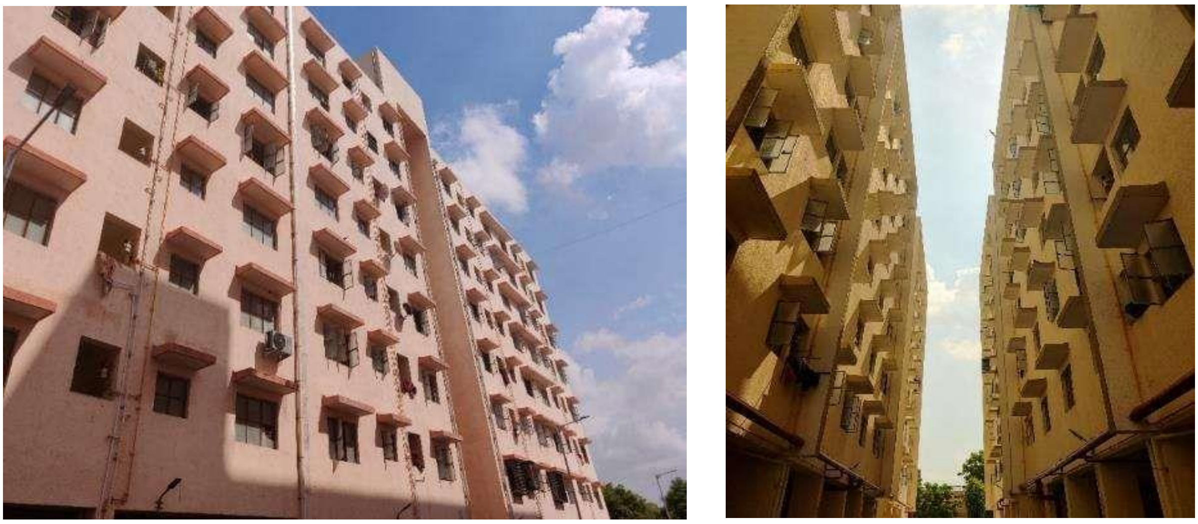
Table 2.4. Common measures observed for cooling/ ventilation in existing buildings in South Asia

Country	City	Climate	Measures
India	Ahmedabad	Hot-dry	Air-circulation devices, evaporative coolers, and split air conditioners (CARBSE, 2020)
	Bengaluru	Temperate	Natural ventilation, air-circulation devices (CARBSE, 2020)
	Delhi	Composite	Air-circulation devices (CARBSE, 2020)
Bangladesh	Dhaka	Composite	Natural ventilation, orientation, and air-circulation devices (WHO, 2005, 2006)
	Khulna	Warm and humid	Thermal mass, walling technologies (BEE, 2018)
	Rangpur	Warm and humid	Thermal mass (BEE, 2018)
Pakistan	Lahore	Composite	Orientation, thermal mass, split air conditioners (Shukla et al, 2015)
	Islamabad	Cold	Window shading, thermal mass (Amber et al., 2021)
	Karachi	Composite	Shading devices and fenestration systems (Amber et al., 2021)

2.3.1 Residential Buildings: Affordable Housing

The majority of affordable residential buildings are constructed with burnt red brick walls (CARBSE, 2020; Shukla et al., 2015; Amber et al., 2021), reinforced cement concrete (RCC) frame structures, and single pane glazing windows (as shown in the photograph). They also contain compact fluorescent lamps (BEE, 2018, Mahar et al., 2019) and ceiling or wall-mounted fans.

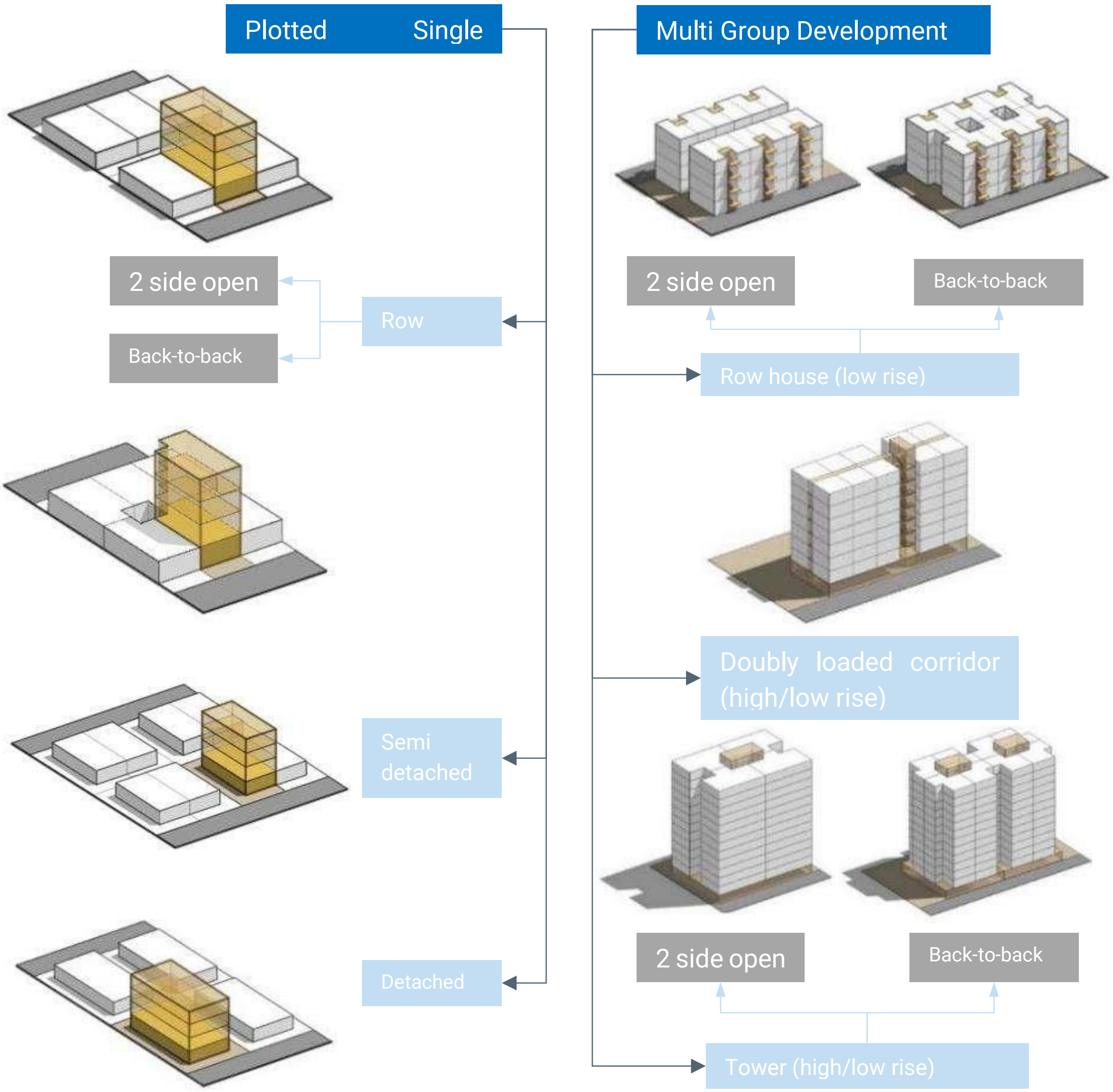
Affordable housing schemes in India often adopt measures to improve natural ventilation at the building level (BEEP, 2013), with appropriate window sizing and open floor plans to facilitate air circulation.



Affordable housing in Ahmedabad, India (Photos by Palak Patel).

Most residences have been observed to have three to seven occupants (Amber et al., 2021). The most common spaces are the bedroom, living space, and kitchen, with a total floor area between 30-80 square meter (m²) (Amber et al., 2021; Sarker et al., 2019). Figure 2.7 shows the affordable housing typologies that currently exist in the region.

Figure 2.7. Housing typology matrix



Source: BEE, 2018.

2.3.2 Occupant Behavior in Residential Buildings: Affordable Housing

Residential buildings remain the least occupied during working hours and the most occupied after work hours (Sharma et al., 2022; Lodi et al., 2013). In summer, these buildings often utilize evaporative coolers and ceiling fans (CARBSE, 2020). During extreme conditions or in modern houses, split air-conditioning systems are used to achieve comfortable conditions inside the bedrooms. Clothing plays a decisive role in comfort adaptation, and clothing insulation values (clo value) change based on the fabric and style of attire. Attire for women in this region has clo values in the range of 0.57 to 0.96 and for men from 0.61 to 0.99. During winter, sunlit spaces can provide warmth. Most buildings use LED-based (in modern houses) or incandescent fixtures, old refrigerators, televisions, and immersion rods for water heating. Occupants manually operate windows and curtains based on the required indoor conditions. Furthermore, occupants often sleep in outdoor thermal conditions such as balconies or terraces when outdoor conditions are favorable (Herlekar et al, 2021).

2.3.3 Commercial Buildings: Small and Medium Sized Office Spaces

Typical commercial buildings function with shops and restaurants on the lower floors and office spaces on the upper floors. However, for this report, the simulation and analysis focus on small and medium-sized office spaces. These buildings also have RCC-framed structures with single-pane glazing windows (see photograph). However, with development in materials and increased stakeholder awareness, contractors and developers have begun to replace conventional fired clay bricks with walling technologies such as fly ash and autoclaved aerated concrete (AAC) blocks for the non-load-bearing features (Sharma et al, 2022). Within these buildings, small retail spaces tend to have air-circulation devices and split air-conditioning units (Amber, 2021). Shops and small businesses at the ground or lower level have often moved away from natural ventilation as a passive measure to closed spaces with active cooling systems (such as split air conditioners) (Phadke et al., 2013).

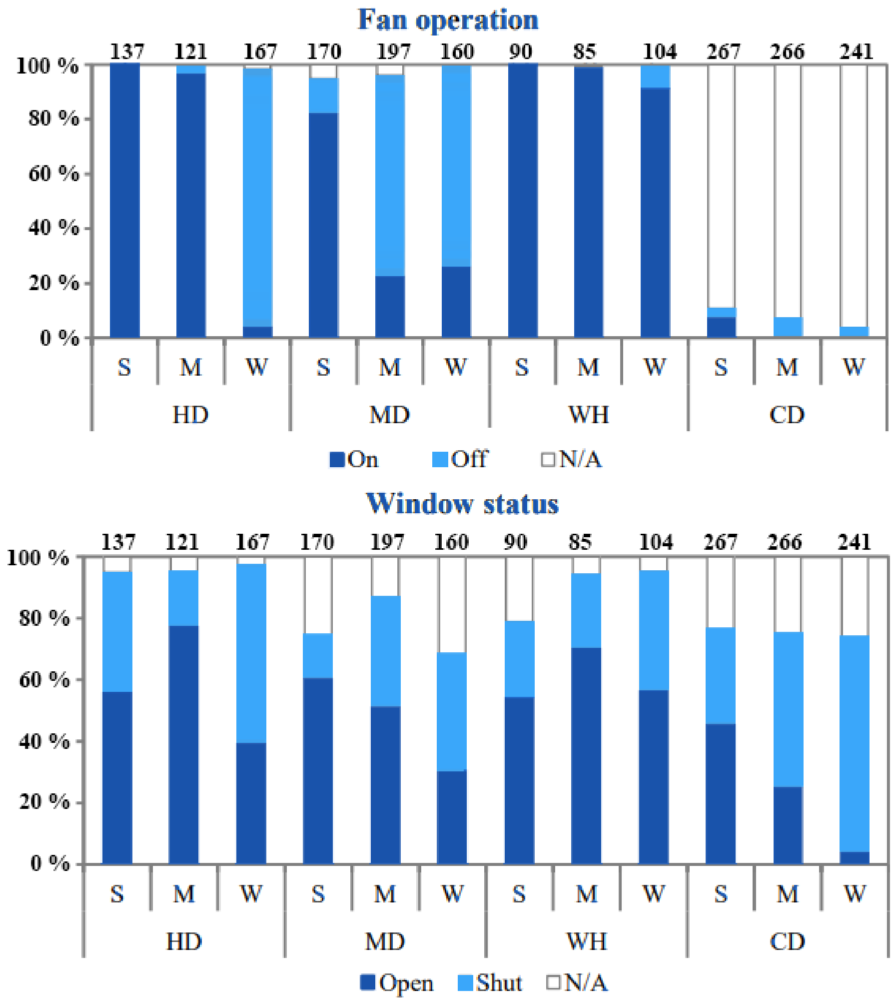
2.3.4 Occupant Behavior in Commercial Buildings

Apart from newly constructed commercial buildings, most existing buildings are low-rise structures constructed with bricks and mortar. New commercial buildings are often constructed with RCC framed structures with minimum or no daylight integration (Sharma et al, 2022). These buildings typically do not utilize natural ventilation in the design. They are equipped with ceiling or pedestal fans and are often retrofitted with an active cooling system (such as a split air-conditioning system) (Ambia et al., 2021). Although blinds are typically provided for office spaces, they remain closed throughout the day to limit thermal and visual discomfort (Lodi et al., 2013). The heating ventilation and air conditioning (HVAC) system and lighting controls are centralized and operate on a fixed operation schedule (Kumar et al., 2018).

Commercial buildings typically operate between 9 am and 7 pm. Figure 2.8 shows operation patterns of fans and windows in all three seasons based on field data collected for three seasons in four cities for each climate type in India. In the hot and dry zone, almost all fans were reported to be on in summer and monsoon, and almost all were off in winter (Manu et al, 2014).

Paharpur Business Centre, Delhi (Gulati, 2016).

Figure 2.8. Seasonal operation patterns of fans and windows in naturally ventilated buildings



Source: Manu, S. et al, 2014.
Notes: The three seasons are shown as S – summer, M – Monsoon, W – Winter. The climate types are shown as HD – Hot and Dry, MD – Moderate, WH – Warm and Humid, CD – Cold.

The cold climate zone had no fans available, except 4-10 percent of isolated cases of table/wall mounted fans. Window use was highest in hot and dry and warm and humid climate zones in monsoon, with 71-78 percent of responses indicating open windows (Figure 2.8). A large proportion, 45-60 percent, of responses reported open windows in summer across all climate zones.

With the higher availability of split air conditioners, their adoption rate in commercial buildings has significantly increased, leading to a reduction in the use of natural ventilation strategies in newer buildings (WHO, 2005,2006; Lodi et al, 2013).

Chapter 2 References

Amber, K.P., R. Ahmad, M. Farmanbar, M. A. Bashir, S. Mehmood, M. S. Khan and M. U. Saeed. 2021. Unlocking Household Electricity Consumption in Pakistan. Buildings, 11(11):566. DOI: 10.3390/buildings11110566

Ambia, A., MMR, P. Munzinger, C. Ghosh, A. Zwiener, Md. Z. R. Khan, F. Mamtaz, Md. A. Al Mamun, T. Rahman and D. Morgado. 2021. Asian Infrastructure Development Bank Energy Efficiency in Public Buildings in Bangladesh. Dhaka. https://reeep2.sreda.gov.bd/interventions/eepb.html.

Asadnabizadeh, M. 2022. Critical Findings of the Sixth Assessment Report (AR6) of Working Group I of the Intergovernmental Panel on Climate Change (IPCC) for Global Climate Change Policymaking a Summary for Policymakers (SPM) Analysis. International Journal of Climate Change Strategies and Management. Emerald. DOI: /10.1108/ijccsm-04-2022-0049.

Asian Disaster Reduction Centre. 2019. Information on Disaster Risk Reduction of the Member Countries. https://www.adrc.asia/disaster/.

Banglapedia. 2022. Khulna District. https://en.banglapedia.org/index.php/Khulna_District.

Bhargav, K. 2017. Tackling the health burden of air pollution in South Asia. British Medical Journal, 359. DOI: 10.1136/bmj. j5209.

Blazejczyk, K., Y. Epstein, G. Jendritzky, H. Staiger and B. Tinz. 2012. Comparison of UTCI to selected thermal indices. International Journal of Biometeorology, 56:515–35. DOI: 10.1007/s00484-011-0453-2.

Britannica. Housing of Pakistan. https://www.britannica.com/place/Pakistan/Housing.

Bureau of Energy Efficiency. 2018. Eco-Niwas Samhita 2018. New Delhi: Ministry of Power, Government of India. https://www.beeindia.gov.in/sites/default/files/ECBC_BOOK_Web.pdf.

Bureau of Indian Standards. 2016. National Building Code of India. New Delhi: Bureau of Indian Standards.

CARBSE. 2020. Low Energy Cooling And Ventilation For Indian Residences (LECaVIR) – (2017–2020). Available from: https://carbse.org/lecavir-3/.

CBS. 2017. Building Typology (as per CBS) 2017 [80]. http://hrrpnepal.org/maps/.

Chan, D. and H. W. Chen. 2013. Using the Koppen classification to quantify climate variation and change: An example for 1901–2010. Environmental Development. 6(1):69–79. DOI: 10.1016/j.envdev.2013.03.007.

Fruman, C. and J. Roome. Helping South Asia Navigate Shared Waters. World Bank Blogs. 2022. https://blogs.worldbank.org/endpovertyinsouthasia/helping-south-asia-navigate-shared-waters.

Gulati, K. 2016. LEED Dynamic Plaque Diaries: Paharpur Business Centre. U.S. Green Building Council. https://www.usgbc.org/articles/leed-dynamic-plaque-diaries-paharpur-business-centre .

Herlekar, V., T. Lashkari and A. Devanarayanan. 2021. Energy Efficiency: Brief 2. Promote Innovations to Improve Light, Ventilation, and Thermal Comfort. WIEGO/MHT. https://www.wiego.org/sites/default/files/publications/file/Energy_Efficiency_%28EE%29_Brief_2.pdf.

Im, E-S., J. S. Pal adE. A. B. Eltahir. Deadly heat waves projected in the densely populated agricultural regions of South Asia. 2017. Science Advances. 3(8): e160332. DOI: 10.1126/sciadv.1603322.

Indo-Swiss Building Energy Efficiency Project. Study C, Housing A, Iii SG. Ministry of Power, Government of India, and the Federal Department of Foreign Affairs (FDFA) of the Swiss Confederation. 2013. https://www.gkspl.in/project/indo-swiss-building-energy-efficiency-project-beep/.

Kumar, S., S. Sachar, T. Winter, S. Kachhawa, A. Goenka, S. Kasamsetty and G. George. 2018. Demand Analysis for Cooling by Sector in India in 2027. New Delhi: Alliance for an Energy Efficient Economy. https://aeee.in/wp-content/uploads/2020/09/2018-Demand-Analysis-for-Cooling-by-Sector-in-India-in-2027-v2.pdf.

Lee, K and M. Greenstone. 2021. Air Quality Life Index: Annual Update, September 2021. Chicago: Energy Policy Institute at the University of Chicago (EPIC). https://aqli.epic.uchicago.edu/wp-content/uploads/2021/08/AQLI_2021-Report.EnglishGlobal.pdf.

Lodi, S. H., A.J. Sangi and A. Abdullah. 2013. Reinforced Concrete Buildings with Masonry Infills, Pakistan. World Housing Encyclopedia. https://www.world-housing.net/masonry/report-167-reinforced-concrete-buildings-with-masonry-infills.

Macrotrends. 2022. Ahmadabad India Metro Area Population 1950–2022. https://www.macrotrends.net/cities/21152/ahmadabad/population#:$\sim$:text=The.

Mahar, W.A., N.U. R.Anwar and S. Attia. 2019. Building energy efficiency policies and practices in Pakistan: A literature review. AIP Conference Proceedings. 2119(1):020005. DOI: 10.1063/1.5115364.

Manu, S., Y. Shukla, R. Rawal, L. Thomas, R. de Dear, M. Dave and M. Vakharia. 2014. Assessment of Air Velocity Preferences and Satisfaction for Naturally Ventilated Office Buildings in India. Proceedings of the 30th International PLEA Conference Sustainable Habitat For Developing Societies Choosing The Way Forward, Volume 2. 411–418(8). http://hdl.handle.net/10453/35156.

Pal, J.S. and E. A. B. Eltahir. Future temperature in southwest Asia projected to exceed a threshold for human adaptability. 2016. Nature Climate Change, 6(2):197–200. DOI: 10.1038/nclimate2833.

Phadke, A., N. Abhyankar and N. Shah. 2013. Avoiding 100 new power plants by increasing efficiency of room air conditioners in India: Opportunities and challenges. 7th International Conference on Energy Efficiency in Domestic Appliances and Lighting (EEDAL'13), Coimbra (Portugal).

Raymond, C., T. Matthews and R. M. Horton. 2020, The emergence of heat and humidity too severe for human tolerance. Science Advances, 6(19): eaaw1838. DOI: 10.1126/sciadv.aaw183.

Salam,R.A., K.P. Amber, N.I. Ratyal, M. Alam, N. Akram, C. G. Muñoz, and F.P. G. Márquez. 2020. An overview on energy and development of energy integration in major South Asian countries: The building sector. Energies,13(21):5776. DOI: 10.3390/en13215776.

Sarker, M.A. H., R. Hafiza and H. Shahriyer. 2019. An Overview of Affordable Housing in Bangladesh. Civil and Environmental Research. 11(11):8–13. https://www.iiste.org/Journals/index.php/CER/article/viewFile/50601/52300

Sharma, M., Y. Singh and H. 2022. Burton. Reinforced Concrete Moment Frame Building with Infills and Slender Shear Wall Core, India. World Housing Encyclopedia. https://cerem.ufp.pt/reports:report_210.

Sharma, S., I. Khanna and P. Ghosh. 2019. Scoping Study for South Asia Air Pollution. New Delhi: The Energy and Resources Institute (TERI). https://www.gov.uk/research-for-development-outputs/scoping-study-for-south-asia-air-pollution.

Shukla, Y., R. Rawal and S Shnapp. 2015. Residential buildings in India: Energy use projections and savings potentials. ECEEE Summer Study Proceedings. https://www.eceee.org/library/conference_proceedings/eceee_Summer_Studies/2015/6-policies-and-programmes-towards-a-zero-energy-building-stock/residential-buildings-in-india-energy-use-projections-and-savings-potentials/.

Tiwari, K.R. 2016. Disaster management policies and practices in Nepal. In: Natural Disasters: Risk Assessment, Management Strategies and Challenges. ed. Deanna Romero, 31–46. New York: Nova.

UNEP. 2021. 5 Ways to Make Buildings Climate Change Resilient. https://www.unep.org/news-and-stories/story/5-ways-make-buildings-climate-change-resilient.

UTCI. UTCI Universal Thermal Climate Index. http://www.utci.org/

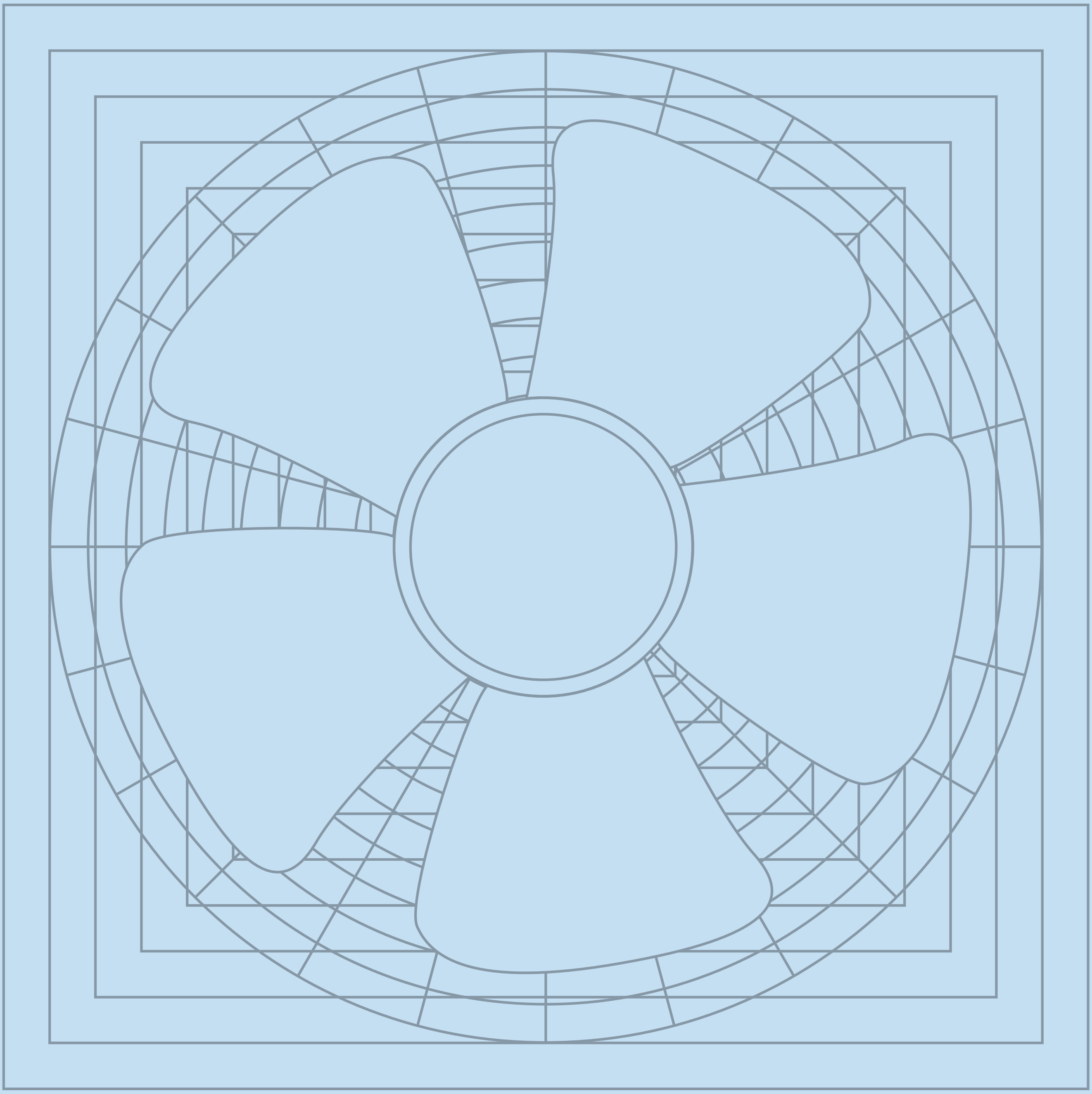
World Bank. Access to Electricity (% of Population) – South Asia. World Bank Global Electrification Database. 2022. https://data.worldbank.org/indicator/EG.ELC.ACCS.ZS?locations=8S.

World Health Organization. 2006. Occupational and Environmental Health Team. WHO Air Quality Guidelines for Particulate Matter, Ozone, Nitrogen Dioxide and Sulfur Dioxide: Global Update 2005: Summary of Risk Assessment. https://apps.who.int/iris/handle/10665/69477.

World Population Review. 2022. Karachi Population 2022. https://worldpopulationreview.com/world-cities/karachi-population.

Xue, Y. and M. Yanai.2005. Asia, Climate of South. In: Encyclopedia of World Climatology. Encyclopedia of Earth Sciences Series, ed. Oliver, J.E. Springer, Dordrecht. DOI:/10.1007/1-4020-3266-8_20

Evidence-based Improvements to Cooling and Ventilation in South Asia



3 Evidence-based Improvements to Cooling and Ventilation in South Asia

This chapter provides market-ready, practical, and cost-effective measures to improve South Asia's building-level cooling and ventilation systems. These building type-specific improvements are further explained with examples throughout the section. It also delves into market availability, incremental costs, and payback period for the measures discussed.

3.1 Building Envelope Optimization Strategies

This section assesses overarching approaches to optimizing the building envelope from the form, operation, and material perspective. All design measures contain a figure presenting the percentage savings from a business as usual (BAU) approach or base case through simulation. The simulation details of the base case are presented in Annex 7: Simulation Details.

3.1.1 Spatial and Passive Design Measures

This section analyses the design details and associated costs for passive measures in Bangladesh, India, and Pakistan, such as building orientation, shading, stack ventilation, and more. It includes information on implementation of passive design features by heat transfer modes and indoor ventilation types. Furthermore, guidance is provided on implementing each strategy, covering its initial cost, embodied carbon, operational energy savings, market availability, and climates in the most effective strategy. The section covers the following strategies: building orientation and thermal mass, external shading devices, facilitation of natural ventilation, and reduction of envelope leakage.

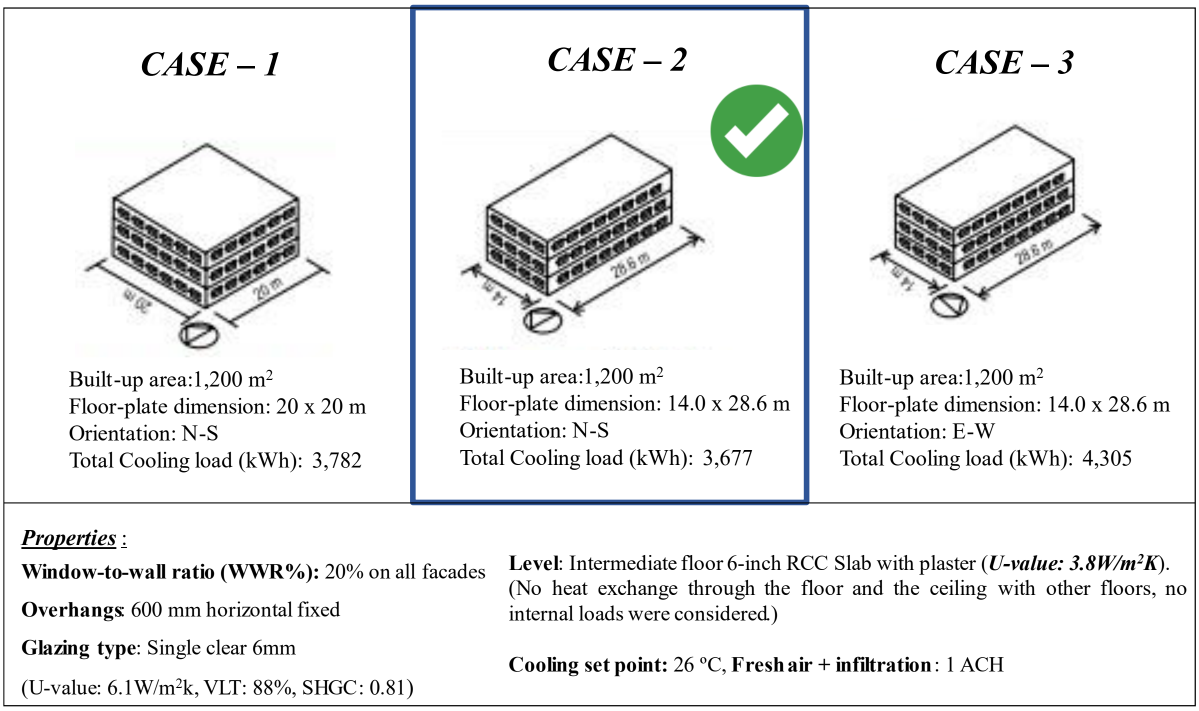
3.1.1.1 Building Orientation

The first and most cost-effective passive strategy that can be adopted at the design stage to reduce energy consumption is the orientation and layout of the building. Heat transfer is directly proportional to the surface area and, by making the building compact, the sun's heat in hot climates and heat loss in cold climates can be minimized.

Buildings must be responsive to site location and its elements, such as topography and vegetation, that affect wind flow and natural shading. Appropriate building orientation can result in a significant reduction of cooling/heating and electric lighting demand. The building design must also consider existing site elements, such as natural shading by vegetation. The orientation can also impact daylighting, which is essential to visual comfort, occupants' health, and productivity. Figure 3.1 shows the effect of orientation and building form on cooling loads for Belagavi, Karnataka, India (warm and humid climate type).

Figure 3.2 shows the percentage savings in the energy performance index (EPI). EPI is the annual energy consumption of a building divided by its total floor area. All strategies will have a similar figure, such as Figure 3.2, showing the resulting savings by applying active and passive strategies in a specific climate type, which is determined by the city in which the building is situated. These results were obtained from simulating a residential building in all the cities mentioned in Section 2.

Figure 3.1. Effect of orientation on cooling load



CASE – 1

Built-up area:1,200 m^2
Floor-plate dimension: 20 x 20 m
Orientation: N-S
Total Cooling load (kWh): 3,782

CASE – 2

Built-up area:1,200 m^2
Floor-plate dimension: 14.0 x 28.6 m
Orientation: N-S
Total Cooling load (kWh): 3,677

CASE – 3

Built-up area:1,200 m^2
Floor-plate dimension: 14.0 x 28.6 m
Orientation: E-W
Total Cooling load (kWh): 4,305

Properties :

Window-to-wall ratio (WWR%): 20% on all facades

Overhangs: 600 mm horizontal fixed

Glazing type: Single clear 6mm

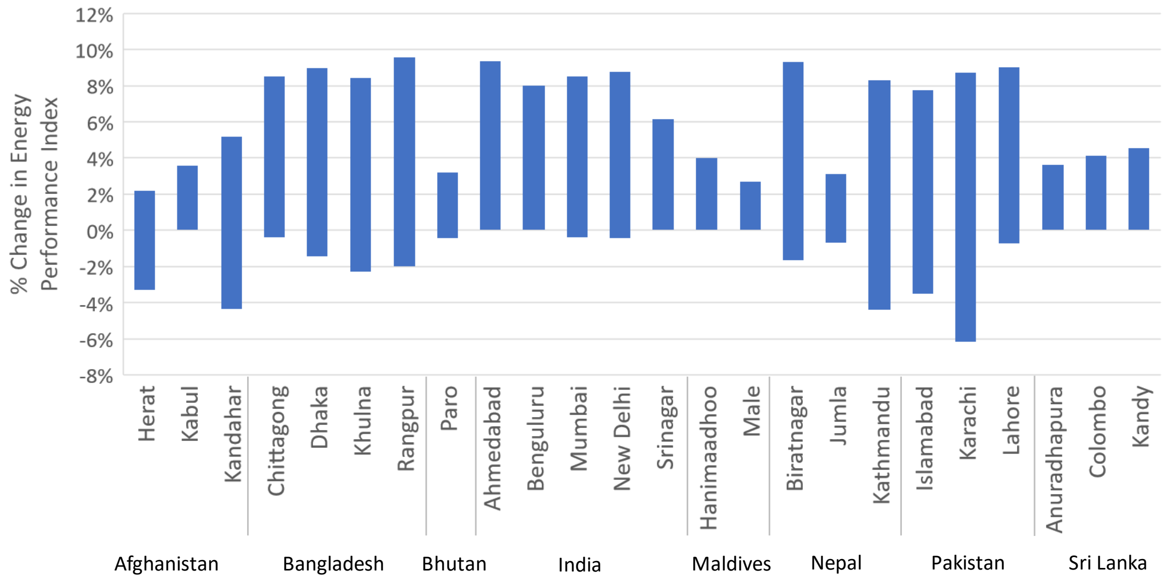
(U-value: 6.1W/m^{2}k, VLT: 88%, SHGC: 0.81)

Level: Intermediate floor 6-inch RCC Slab with plaster (***U-value: 3.8W/m²K***). (No heat exchange through the floor and the ceiling with other floors, no internal loads were considered.)

Cooling set point: 26 °C, **Fresh air + infiltration**: 1 ACH

Source: BEE, 2016.
Note: WWR - Window-to-wall ratio – Ratio of total window area to the total wall area.
SHGC – Solar Heat Gain Coefficient – Fraction of solar radiation admitted through glass, and subsequently released as heat in space.
VLT – Visual light transmission – The amount of visible light that passes through glass.
ACH – Air changes per hour – The number of times the total air volume in a space is completely removed and replaced in an hour.
U-Value – The rate of transfer of heat through matter.

Figure 3.2. Percentage savings in energy performance index through orientation

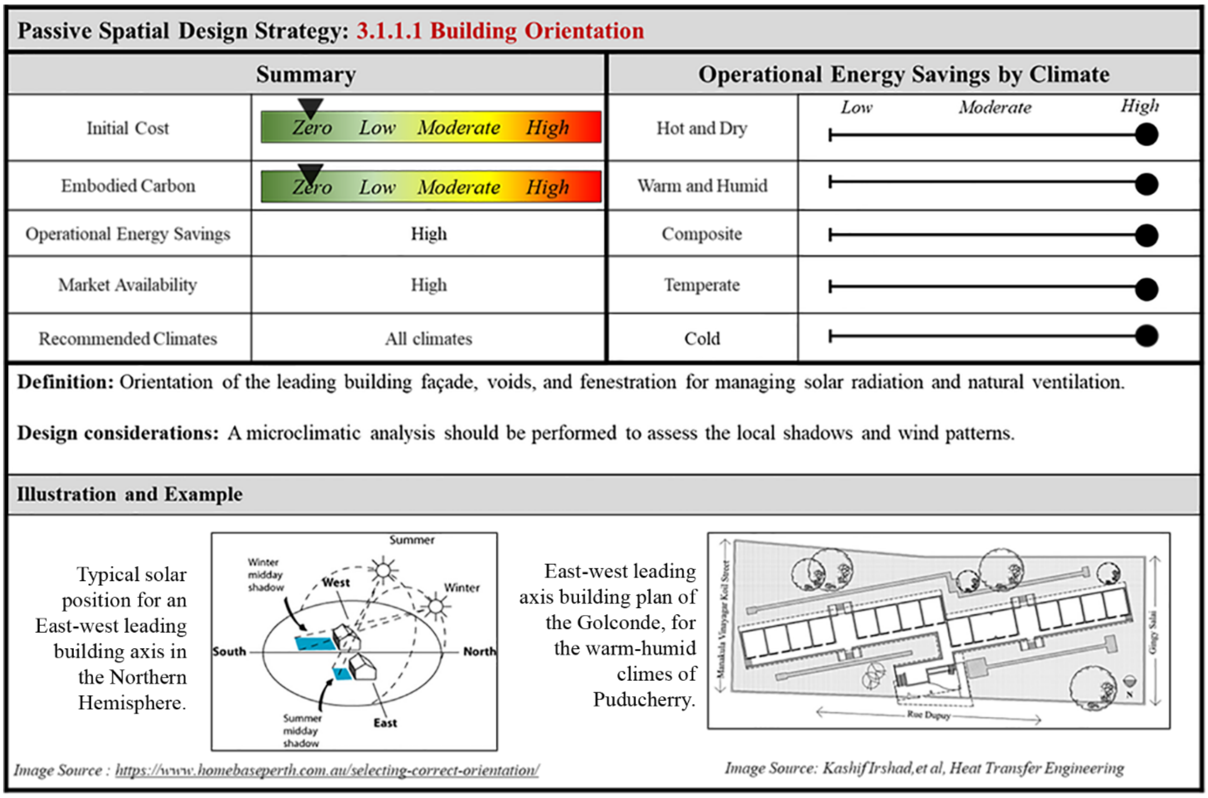


Source: Author's analysis.

As **Figure 3.2** shows, the percentage savings range from 2 to 10 percent in every city which demonstrates that, for no initial cost, the building has the potential to reduce its carbon footprint resulting in operational energy. The negative percentages, in this case, indicate that the various orientations simulated for the building may also include those that may not yield the optimum results or EPI savings and instead may increase EPI values. This also strengthens the case for selecting a suitable orientation.

Figure 3.3 summarizes the primary considerations for using building orientation as a passive spatial design strategy. It shows how the orientation needs to consider both the hemisphere and climate type that the building is located in to gain the best advantage from this strategy.

Figure 3.3. Passive spatial design strategy: building orientation



Passive Spatial Design Strategy: 3.1.1.1 Building Orientation

Summary		Operational Energy Savings by Climate	*Low* *Moderate* *High*
Initial Cost	▼*Zero* *Low* *Moderate* *High*	Hot and Dry	├──────────●
Embodied Carbon	▼*Zero* *Low* *Moderate* *High*	Warm and Humid	├──────────●
Operational Energy Savings	High	Composite	├──────────●
Market Availability	High	Temperate	├──────────●
Recommended Climates	All climates	Cold	├──────────●

Definition: Orientation of the leading building façade, voids, and fenestration for managing solar radiation and natural ventilation.

Design considerations: A microclimatic analysis should be performed to assess the local shadows and wind patterns.

Illustration and Example

Typical solar position for an East-west leading building axis in the Northern Hemisphere.

East-west leading axis building plan of the Golconde, for the warm-humid climes of Puducherry.

Image Source : https://www.homebaseperth.com.au/selecting-correct-orientation/

Image Source: Kashif Irshad, et al, Heat Transfer Engineering

Source: Author's analysis.
Notes: For additional information on climate analysis please refer to Annex 0 and 0.

3.1.1.2 Building Thermal Mass

The thermal mass of the building describes its ability to resist indoor temperature fluctuations compared to outdoor temperatures. For any material to be used successfully as thermal mass, it must have high specific heat capacity, high density, large volume, and moderate thermal conductivity. Figure 3.4 shows how the thermal mass of a building affects the time taken by heat to flow from outside to inside. For most common building materials, the higher the thermal mass, the longer the thermal lag.

Figure 3.4. Thermal lag due to thermal mass

Source: EULEB, 2006.

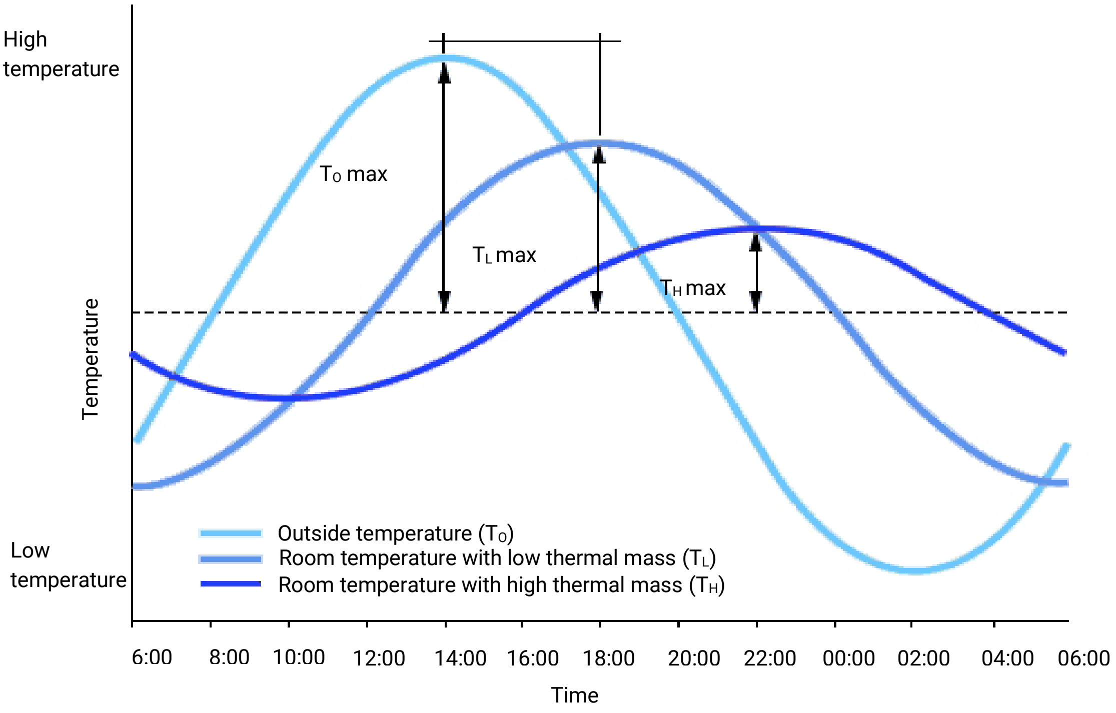


Figure 3.5. Passive spatial design strategy: building thermal mass

Passive Spatial Design Strategy: 3.1.1.2 Building Thermal Mass			
Summary		**Operational Energy Savings by Climate**	*Low* *Moderate* *High*
Initial Cost	*Zero Low Moderate* ▼ *High*	Hot and Dry	├──────────●
Embodied Carbon	*Zero Low Moderate* ▼*High*	Warm and Humid	├─────●─────┤
Operational Energy Savings	High	Composite	├──────────●
Market Availability	Moderate	Temperate	├─────●─────┤
Recommended Climates	Hot and dry, Composite, Cold	Cold	├──────────●

Definition: Thermal mass refers to the mass of a building envelope that helps maintain steady indoor air temperature even when outdoor temperatures fluctuate.

Design considerations: Materials must have high specific heat capacity, high density, and moderate thermal conductivity.

Complementary strategies: Night-time ventilation in climates having high diurnal temperature variation.

Illustration and Example

Thermal mass absorbs heat during the day, which night-time ventilation removes.

Source: Author's analysis.

Notes: For additional information on climate analysis please refer to Annex 0 and 0.

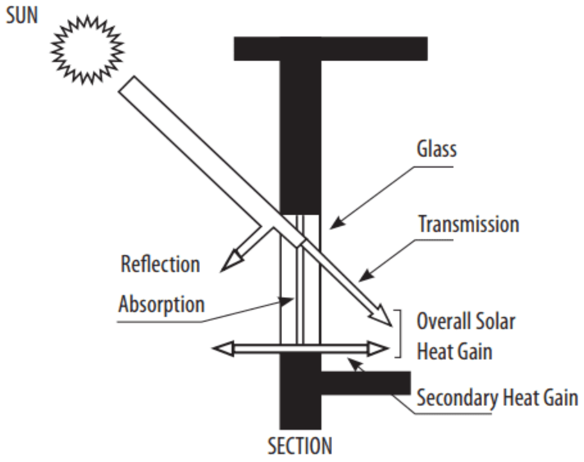
Thermal mass is beneficial if some means of cooling (for example, nighttime ventilation) can be used to remove the heat absorbed by the thermal mass during the daytime for hot climates, while cold climates would benefit from retaining the heat gained through the day. In warm and humid climates, high moisture content makes capture and release of heat significantly slower, making the indoor environment uncomfortable for occupants. **Figure 3.5 shows the essential points to consider when using thermal mass as a passive measure.**

3.1.1.3 External Shading Devices: Fixed and Moveable

Fixed and moveable building shading devices have great potential to reduce heat ingress through the windows by blocking direct solar gains with minimum energy consumption to improve thermal and visual comfort.

Various forms can be used depending on the window or glazing on which they will be mounted. These have low to moderate incremental costs and are efficient solutions that can be used along with other passive solutions. Some movable shading devices require motorization, which can increase the initial cost. However, the payback period is low considering the lower operational costs of HVAC systems (BEE, 2021). Figure 3.6 shows that solar heat gain takes place through non-opaque or glass components.

Figure 3.6. Solar heat gain through glass

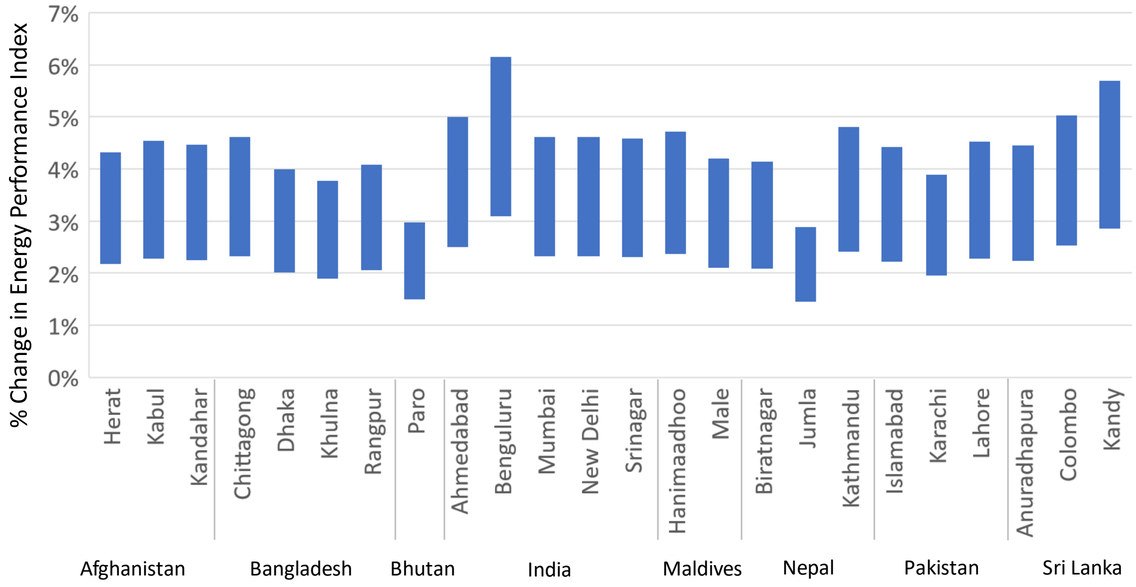


Source: BEE, 2018.

As shown in Figure 3.7, shading results in EPI savings of up to 6 percent. The results stem from a simulation comparing a building with no shading to one with fixed horizontal shading. Although vernacular architecture in South Asia had embraced shading as an essential and effective strategy, modern buildings often do not use shading devices opting instead for aesthetics such as glass facades.

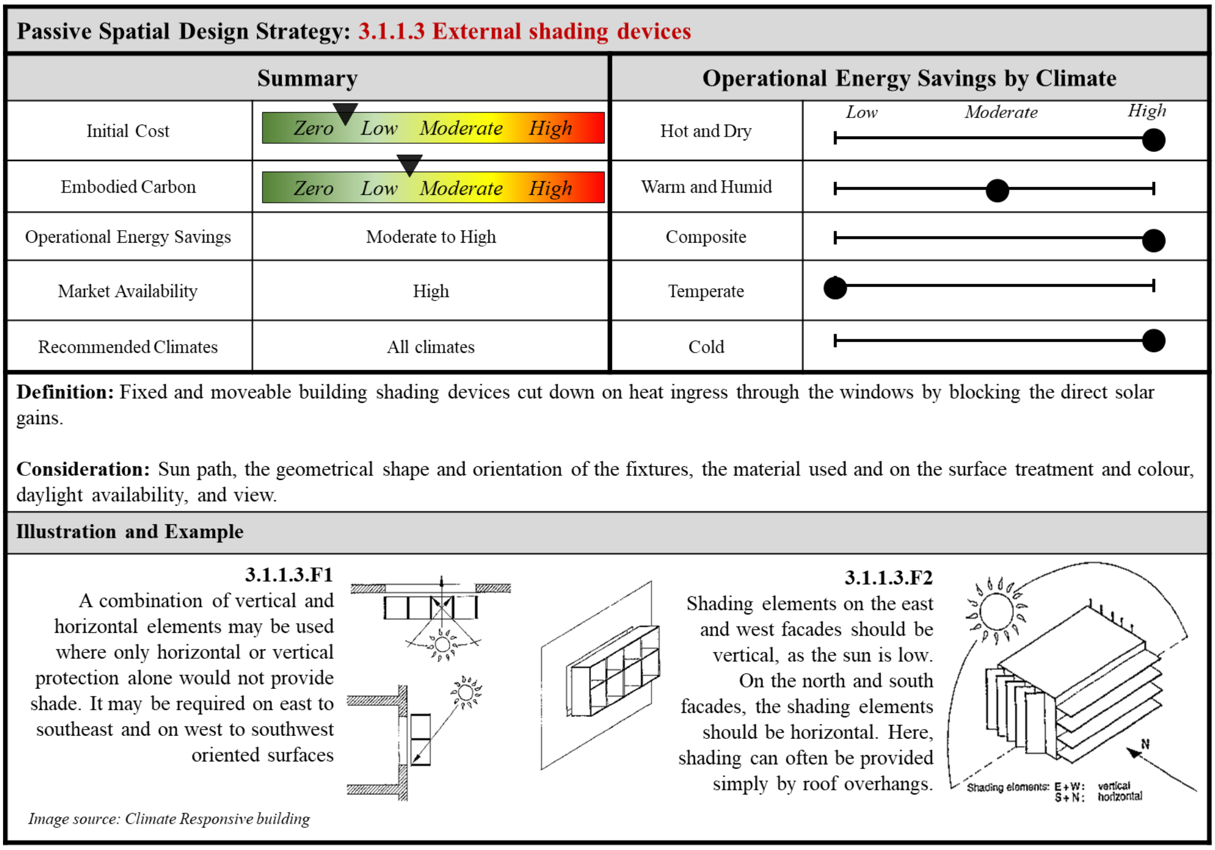
Figure 3.8 summarizes the primary considerations for using external shading devices as a passive spatial design strategy. The design of shading devices should take into account the orientation of surfaces, geometrical shape, and orientation of the shading device. Well-designed shading devices are low-cost interventions that can lower energy demand.

Figure 3.7. Percentage savings in energy performance index through shading



Source: Author's analysis.

Figure 3.8. Passive spatial design strategy: external shading devices



Passive Spatial Design Strategy: 3.1.1.3 External shading devices

Summary		Operational Energy Savings by Climate	
			Low *Moderate* *High*
Initial Cost	*Zero* ▼ *Low* *Moderate* *High*	Hot and Dry	├────────●
Embodied Carbon	*Zero* *Low* ▼ *Moderate* *High*	Warm and Humid	├────●────┤
Operational Energy Savings	Moderate to High	Composite	├────────●
Market Availability	High	Temperate	●────────┤
Recommended Climates	All climates	Cold	├────────●

Definition: Fixed and moveable building shading devices cut down on heat ingress through the windows by blocking the direct solar gains.

Consideration: Sun path, the geometrical shape and orientation of the fixtures, the material used and on the surface treatment and colour, daylight availability, and view.

Illustration and Example

3.1.1.3.F1
A combination of vertical and horizontal elements may be used where only horizontal or vertical protection alone would not provide shade. It may be required on east to southeast and on west to southwest oriented surfaces

3.1.1.3.F2
Shading elements on the east and west facades should be vertical, as the sun is low. On the north and south facades, the shading elements should be horizontal. Here, shading can often be provided simply by roof overhangs.

Image source: Climate Responsive building

Source: Author's analysis.
Notes: For additional information on climate analysis please refer to Annex 3.1 and 3.2

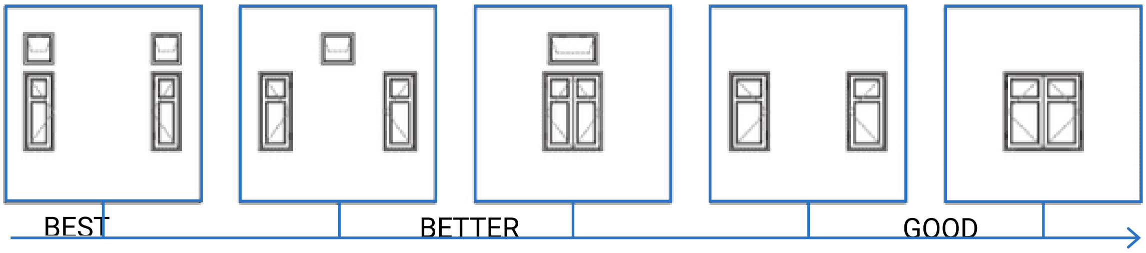
3.1.1.4 Natural Ventilation: Single-sided and Cross-ventilation

As a passive strategy, zero energy consumption, no maintenance, and no initial and running costs number among the benefits of natural ventilation. This ventilation strategy will depend on site location, building orientation, positioning of openings, and internal thermal loads, which must be assessed carefully. Buildings can take advantage of favorable outdoor temperatures to provide comfortable indoor temperatures and improved IAQ. Natural ventilation should be intentional and controlled though it is often seen as an unintentional and uncontrolled air movement, and is confused with infiltration (CARBSE, 2020).

Ventilation is divided into two categories at a space level: single-sided and cross-ventilation. Single-sided ventilation relies on airflow through openings on only one side of a closed space, where the air enters and exits through the same opening. Since the main driving force for natural ventilation, in this case, is wind turbulence, it has lower ventilation rates. This type of ventilation is not suitable for deep-plan spaces. In cross-ventilation, airflow depends on openings on the opposite sides of a space allowing air to move across the space. It is thus a better alternative than single-sided ventilation and is also suitable for floor plans with deep penetration.

Figure 3.9 shows that, for the same ratio of area of openings to the floor area of a room, thermal heat exchange increases as the number of openings on the wall increases. It is thus recommended that openable ventilators be used to aid better ventilation. It should be noted that some of the improvement in the ventilation rate is due to buoyancy-driven ventilation.

Figure 3.9. Effect of window positioning on ventilation

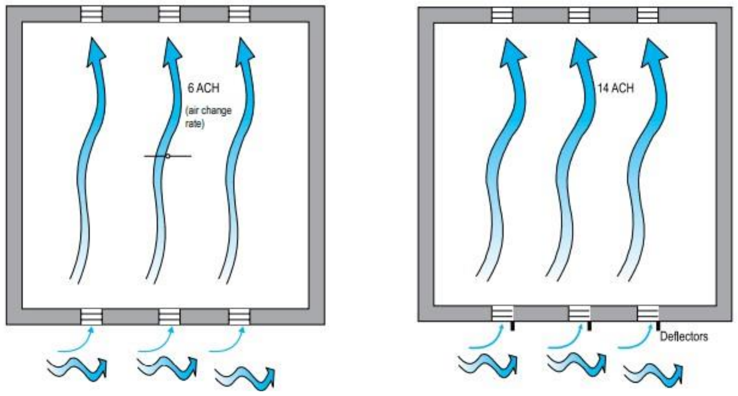


Source: BEE, 2018.

A parameter that measures the effectiveness of natural ventilation is the air change rate per hour (ACH), which quantifies how many times the air volume inside a room is replaced by fresh air in an hour. The greater the number, the better the cooling potential through natural ventilation. Usually, 5 to 20 ACH is considered good natural ventilation.

Other effective measures that can facilitate high ventilation rates are wing walls, louvers, window shutters, and strategically planted vegetation that can funnel air into a room. Wing walls are often advised if the predominant wind direction is at an angle greater than 60° to the surface normal of the window. The provision of vertical deflectors helps to improve cross-ventilation efficiency as they can increase the air change rates and thus improve cross-ventilation when the wind direction is perpendicular to the facades and their openings.

Figure 3.10. Deflectors facilitating natural ventilation



Without deflectors

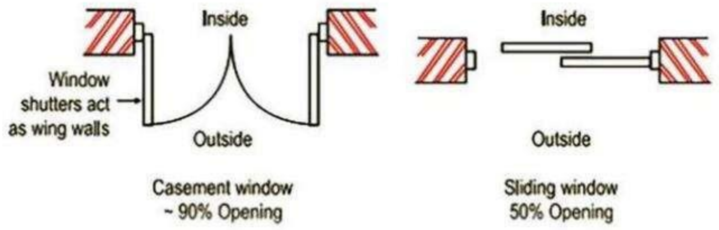
With deflectors

Source: BEE, 2016.

Natural ventilation is crucial for the warm-humid climate type, in general, as daytime temperatures range from 25°C to 35°C, the diurnal variation is less than 5°C–10°C, and humidity is high (> 50 percent). It is crucial to restrict solar heat gains into the building during the day, maintain good air ventilation to remove the heat generated by occupants, and conserve a thermally comfortable environment. Space cooling and fans account for a large share of electricity consumption in this climate type.

As shown in Figure 3.11, casement windows are recommended for all climate types, especially in warm-humid climates. They allow almost twice (90 percent) the openable area for natural ventilation compared to sliding windows (50 percent). The shutters of these windows can also act as wind steering features in different combinations.

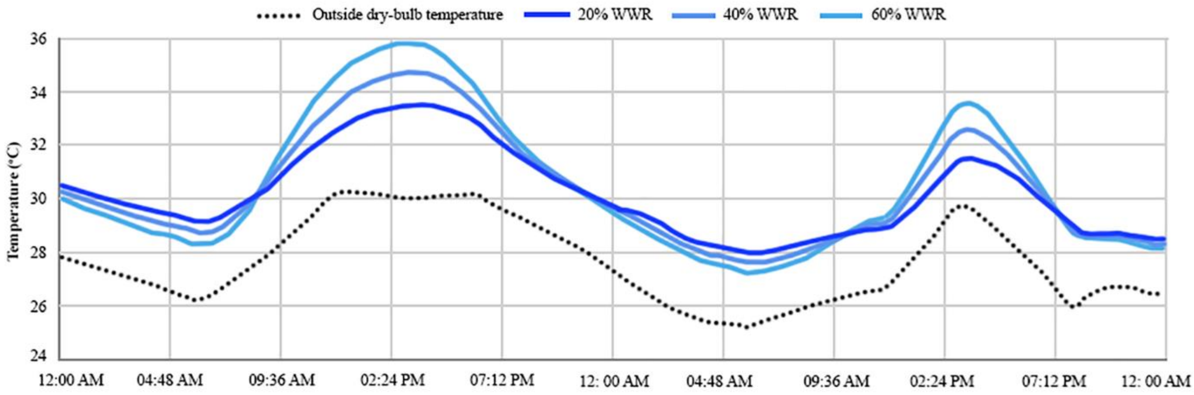
Figure 3.11. Comparison of natural ventilation potential of casement and sliding window



Source: BEE, 2016.

Figure 3.12 shows the effect of the window-to-wall ratio (WWR), calculated as the ratio of the wall fenestration area to the gross above grade wall area, on indoor operative temperatures in Ahmedabad using a simulation for a completely naturally ventilated single-story space. It implies that a lower WWR effectively reduces peak temperatures in a hot and dry climate type compared to a higher WWR.

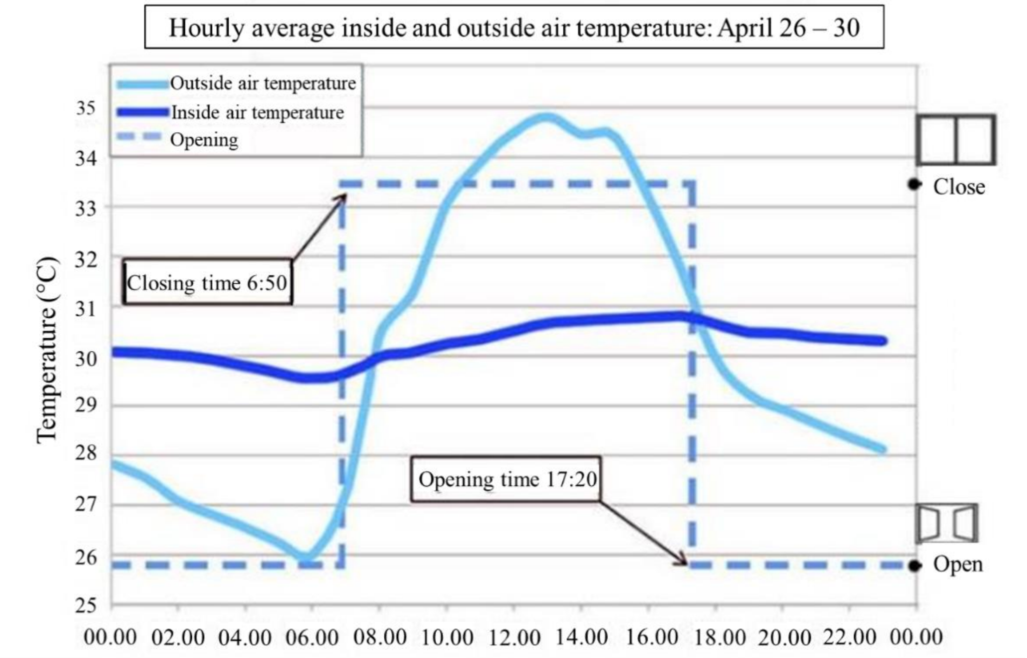
Figure 3.12. Effect of window-to-wall ratio on indoor operative temperature



Source: Author's analysis.

However, operating windows based on outdoor temperatures coupled with thermal mass in the building interior can help maintain stable indoor temperatures, as shown in Figure 3.13.

Figure 3.13. Indoor temperature control with window operations

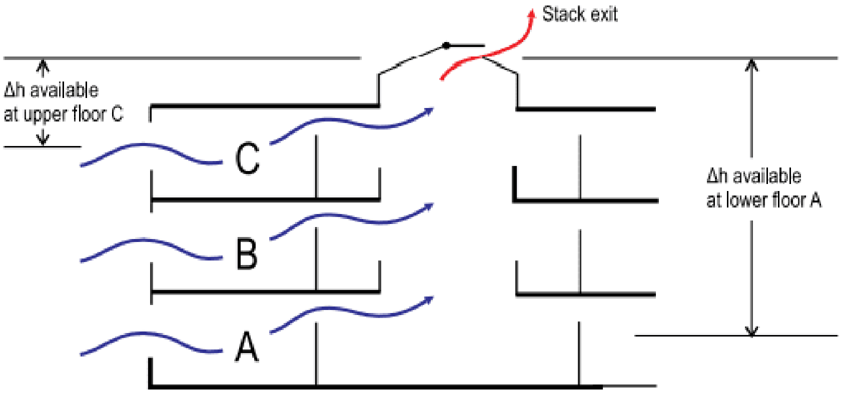


Source: Doctor-Pingel et al., 2019.

3.1.1.5 Natural Ventilation: Building Level

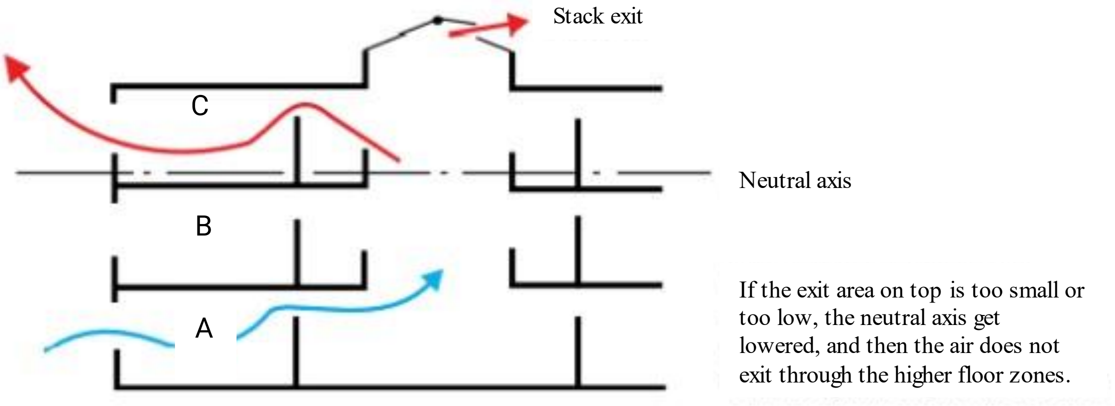
At a building level, thermal buoyancy causes airflow because of the difference between air density, which depends on humidity and temperature levels inside and outside the building. This phenomenon is known as the stack effect or buoyancy force. The airflow occurs mainly in the vertical direction through stairwells, elevators, atriums, and shafts. Narrow plans, two-sided facades, and high ceilings render natural ventilation a successful strategy. Figure 3.15 shows a sectional view of a building illustrating correctly and incorrectly designed stack ventilation.

Figure 3.14. Airflow in a correctly designed stack ventilation system in a multi-story building



Source: BEE, 2016.

Figure 3.15. Airflow in an incorrectly designed stack ventilation system in a multi-story building



Source: BEE, 2016.

Night ventilation is another effective strategy that uses lower nighttime temperatures to flush heat out of the building and precool the building structure. Cooler inside surfaces of the buildings early in the day help reduce the inside air temperature and enhance the occupants' thermal comfort due to higher radiant heat exchange with these cool surfaces. However, for night cooling to be efficient, the thermal mass of the building structure needs to be accessed by the air flowing through the building. Thermally closed false ceilings must be avoided, and air circulation across the ceiling must be facilitated by opening at least 40 percent of its area (BEE, 2016). For open-plan buildings, window fans or attic fans can enhance the air change rates at very low energy consumption rates.

Table 3.1 shows the potential period when occupants and buildings can take advantage of free cooling, calculated using IMAC for residential and commercial buildings operating in mixed and naturally ventilated modes. **The analysis shows 15–40 percent potential time, depending on the city, for using natural ventilation as a design technique, particularly if the buildings are planned to run at night (such as residential buildings)**.

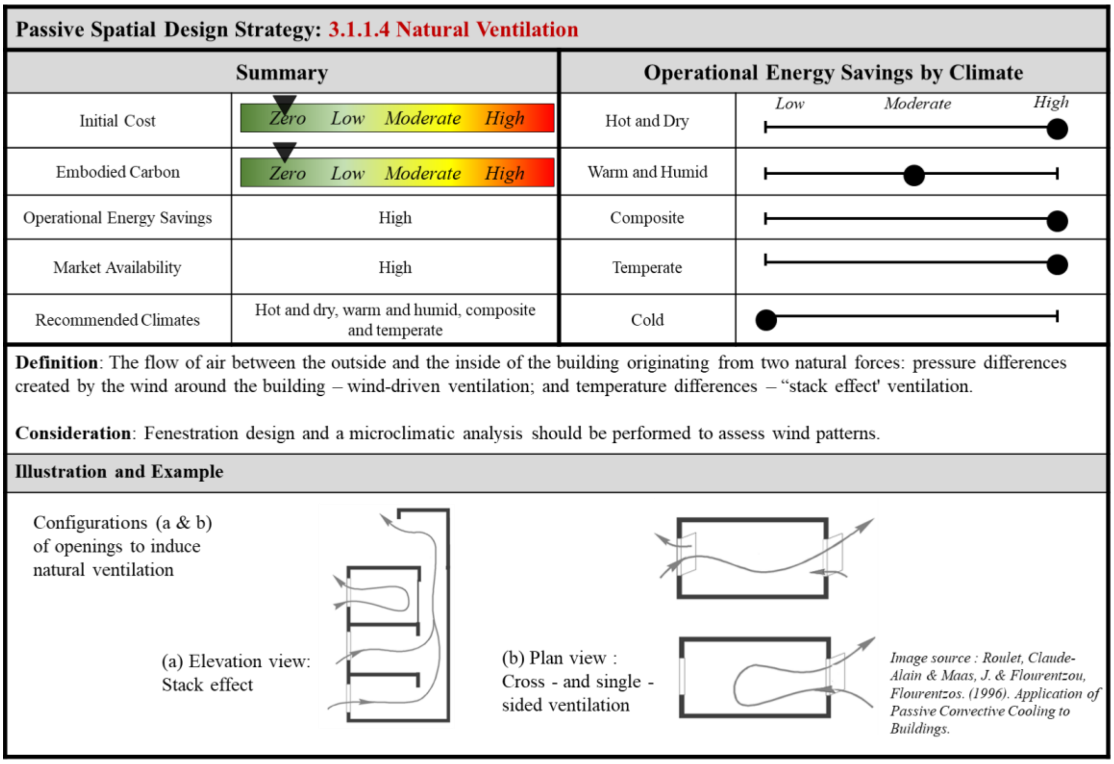
Table 3.1. Natural ventilation potential as a percentage time of the year using adaptive comfort models

Operation mode: Natural ventilation				
Country	**City**	**Residential**	**Naturally ventilated commercial**	**Mixed mode commercial**
Afghanistan	Herat	26%	35%	30%
	Kabul	20%	27%	22%
	Kandahar	18%	23%	20%
Bangladesh	Chittagong	22%	24%	23%
	Dhaka	31%	30%	31%
	Khulna	19%	20%	16%
	Rangpur	19%	20%	19%
Bhutan	Paro	30%	39%	34%
India	Ahmedabad	39%	45%	43%
	Bengaluru	32%	34%	35%
	Mumbai	40%	43%	41%
	New Delhi	41%	45%	41%
	Srinagar	27%	32%	29%
Maldives	Hanimaadhoo	9%	9%	8%
	Male	15%	15%	15%
Nepal	Biratnagar	17%	18%	17%
	Jumla	19%	28%	25%
	Kathmandu	21%	28%	27%
Pakistan	Islamabad	39%	43%	40%
	Karachi	36%	41%	37%
	Lahore	39%	42%	37%
Sri Lanka	Anuradhapura	29%	28%	25%
	Colombo	14%	14%	13%
	Kandy	18%	17%	17%

Source: Author's analysis.

Natural ventilation is effective in all climates; its effects can be enhanced with shading, positioning windows to facilitate cross-ventilation in large spaces, vegetation cover, and others. For hot and dry climates and cold climates, a heat recovery ventilator/energy recovery ventilator can be used in addition to the cooling/heating system to provide fresh air when outdoor temperatures are uncomfortable. **Figure 3.16 summarizes the key points when considering natural ventilation as a design strategy.**

Figure 3.16. Passive spatial design strategy: natural ventilation



Passive Spatial Design Strategy: 3.1.1.4 Natural Ventilation

Summary		Operational Energy Savings by Climate	
Initial Cost	▼ *Zero* *Low* *Moderate* *High*	Hot and Dry	*Low* *Moderate* *High* ├────────────●
Embodied Carbon	▼ *Zero* *Low* *Moderate* *High*	Warm and Humid	├──────●──────┤
Operational Energy Savings	High	Composite	├────────────●
Market Availability	High	Temperate	├────────────●
Recommended Climates	Hot and dry, warm and humid, composite and temperate	Cold	●────────────┤

Definition: The flow of air between the outside and the inside of the building originating from two natural forces: pressure differences created by the wind around the building – wind-driven ventilation; and temperature differences – "stack effect' ventilation.

Consideration: Fenestration design and a microclimatic analysis should be performed to assess wind patterns.

Illustration and Example

Configurations (a & b) of openings to induce natural ventilation

(a) Elevation view: Stack effect

(b) Plan view : Cross - and single - sided ventilation

Image source : Roulet, Claude-Alain & Maas, J. & Flourentzou, Flourentzos. (1996). Application of Passive Convective Cooling to Buildings.

Source: Author's analysis.
Notes: For additional information on climate analysis please refer to Annex 3.1 and 3.2

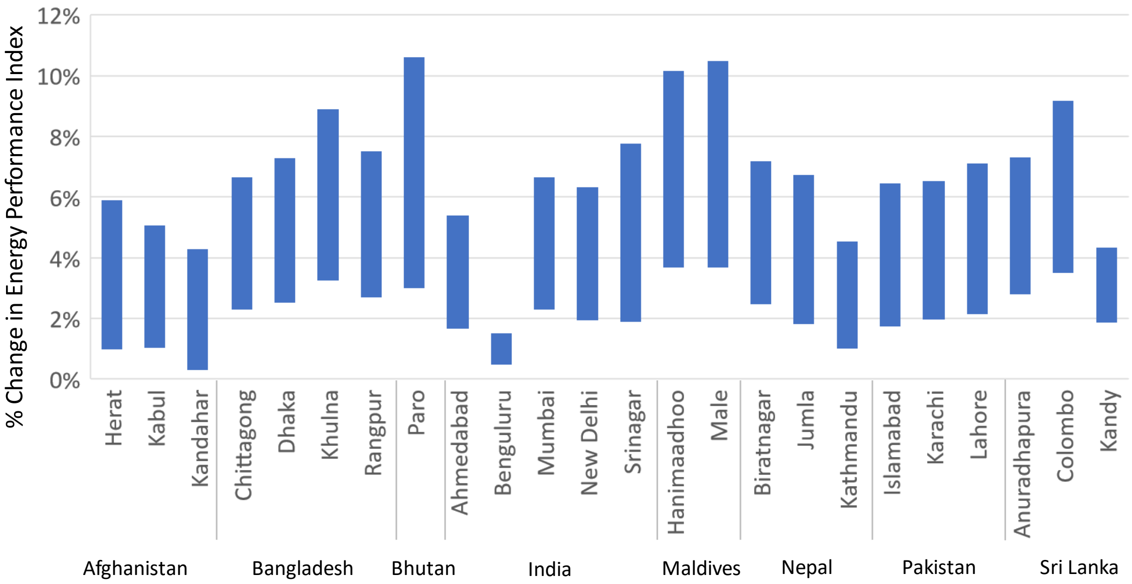
3.1.1.6 Envelope Leakage

Efficient envelope design facilitates the use of thermal mass and natural ventilation as passive measures. In weather conditions when natural ventilation is not useful, air leakage reduction, moisture diffusion into walls, air-transported moisture, and airtight window frames minimize conduction losses and moisture penetration, thereby improving the thermal performance of walls, roofs, and windows.

Infiltration losses can also be gauged using the ACH metric. These losses can be minimized by improving building airtightness. This is achieved by effectively sealing the joints in the building envelope using caulks, gaskets, and weather strips. A building with simple, effective sealing can achieve an ACH of 0.35. This can also be paired with thermal insulation for optimum thermal performance of the envelope.

Figure 3.17 shows that tighter building envelopes can result in savings ranging from 4 to 10 percent. As tighter envelopes reduce infiltration and moisture transfer, they decrease the load on cooling systems. However, tighter envelopes do not significantly impact EPI savings for the temperate climate type.

Figure 3.17. Percentage savings in energy performance index through a tighter building envelope

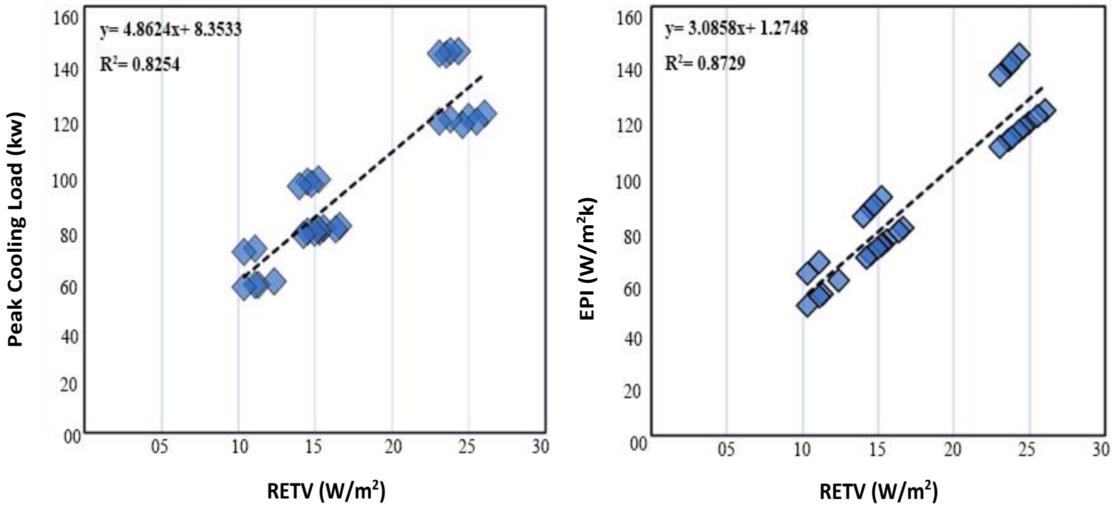


Source: Author's analysis.

India's Eco-Niwas Samhita sets minimum performance standards for building envelopes to limit heat gains, suggesting that the residential envelope heat transmittance (RETV) for the building envelope (except the roof) for four climate zones, namely, composite climate, hot-dry climate, warm-humid climate, and temperate climate, must be less than 15 watt/m². RETV is the net heat gain rate (over the cooling period) through the building envelope (excluding the roof) of the dwelling units divided by the area of the building envelope (excluding the roof) of the dwelling units. Figure 3.1This implies that buildings with lower RETV values or tighter building envelopes have lower peak cooling loads and EPI values.

Figure 3.18 shows the correlation between RETV values, peak cooling load, and EPI. This implies that buildings with lower RETV values or tighter building envelopes have lower peak cooling loads and EPI values.

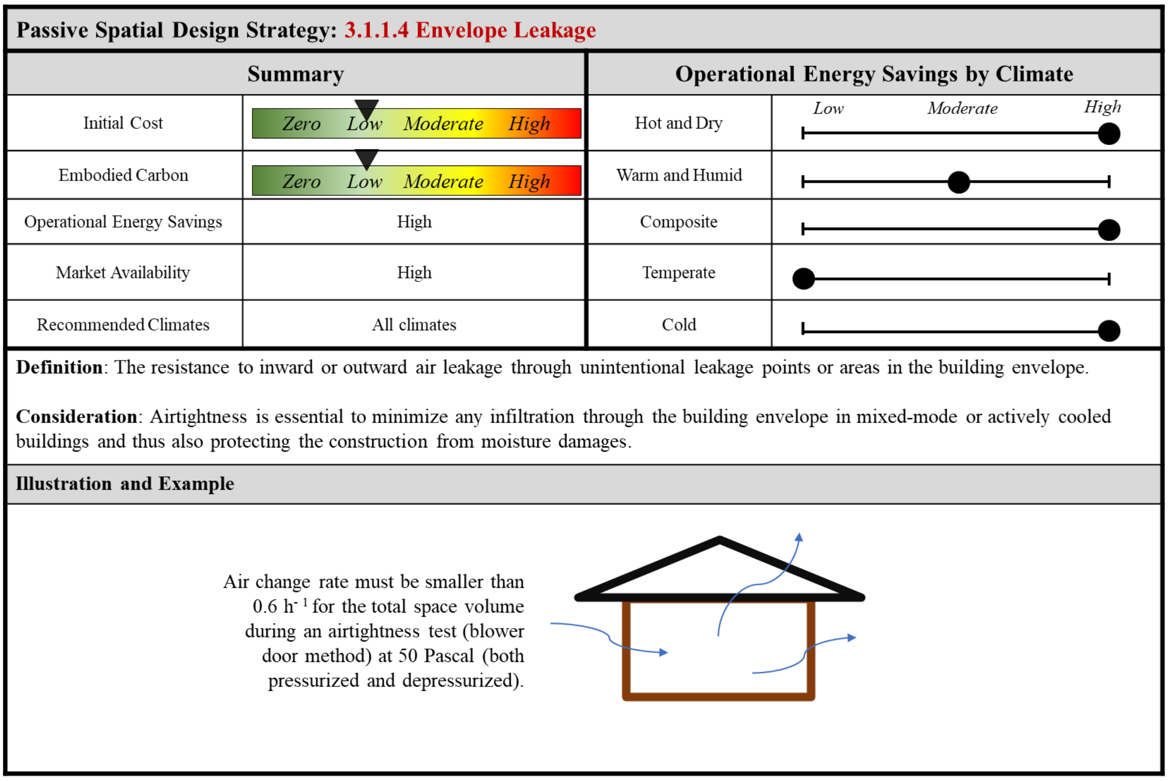
Figure 3.18. Correlation between peak cooling load and residential envelope heat transmittance values



Source: Roulet, 2015.

Figure 3.19 summarizes key points to be considered when tighter envelopes are incorporated as a passive design strategy.

Figure 3.19. Passive spatial design strategy: envelope leakage



Passive Spatial Design Strategy: 3.1.1.4 Envelope Leakage

Summary		**Operational Energy Savings by Climate**	*Low*	*Moderate*	*High*
Initial Cost	*Zero* ▼*Low* *Moderate* *High*	Hot and Dry			●
Embodied Carbon	*Zero* ▼*Low* *Moderate* *High*	Warm and Humid		●	
Operational Energy Savings	High	Composite			●
Market Availability	High	Temperate	●		
Recommended Climates	All climates	Cold			●

Definition: The resistance to inward or outward air leakage through unintentional leakage points or areas in the building envelope.

Consideration: Airtightness is essential to minimize any infiltration through the building envelope in mixed-mode or actively cooled buildings and thus also protecting the construction from moisture damages.

Illustration and Example

Air change rate must be smaller than 0.6 h^{-1} for the total space volume during an airtightness test (blower door method) at 50 Pascal (both pressurized and depressurized).

Source: Author's analysis.
Notes: For additional information on climate analysis please refer to Annex 3.1 and 3.3

3.1.2 Construction Materials and Technologies

This section discusses construction details and associated costs of energy-efficient building construction materials and technologies such as cavity walls, cool roofs, and high-reflectivity paints.

3.1.2.1 Walling Materials and Technologies

With rapid urbanization and an increase in high-rise buildings, concrete and steel have become common-used construction materials around the globe, including in South Asia. They also use considerable amounts of energy and emit ample carbon dioxide into the atmosphere during their manufacturing phase.

Properties of the walling material, such as thermal transmittance (BEE, 2016), can significantly impact the envelope transmittance values of the building, thus affecting the building's heat gain. This section qualitatively explores different walling technologies, evaluating their carbon footprint (embodied energy), cost, and availability. Table 3.2 describes current walling material and technology, their embodied carbon, incremental cost, and availability. The most important criteria are a low carbon footprint, low cost, high availability, and thermal performance indicated by the U-value (Figure 3.20). The U-value, or thermal transmittance, is the rate of transfer of heat through a single or composite material divided by the difference in temperature across the material. It is measured in watt per square meter and Kelvin (W/m^{2}K); lower the U-value, lower the rate of heat transfer through the material.

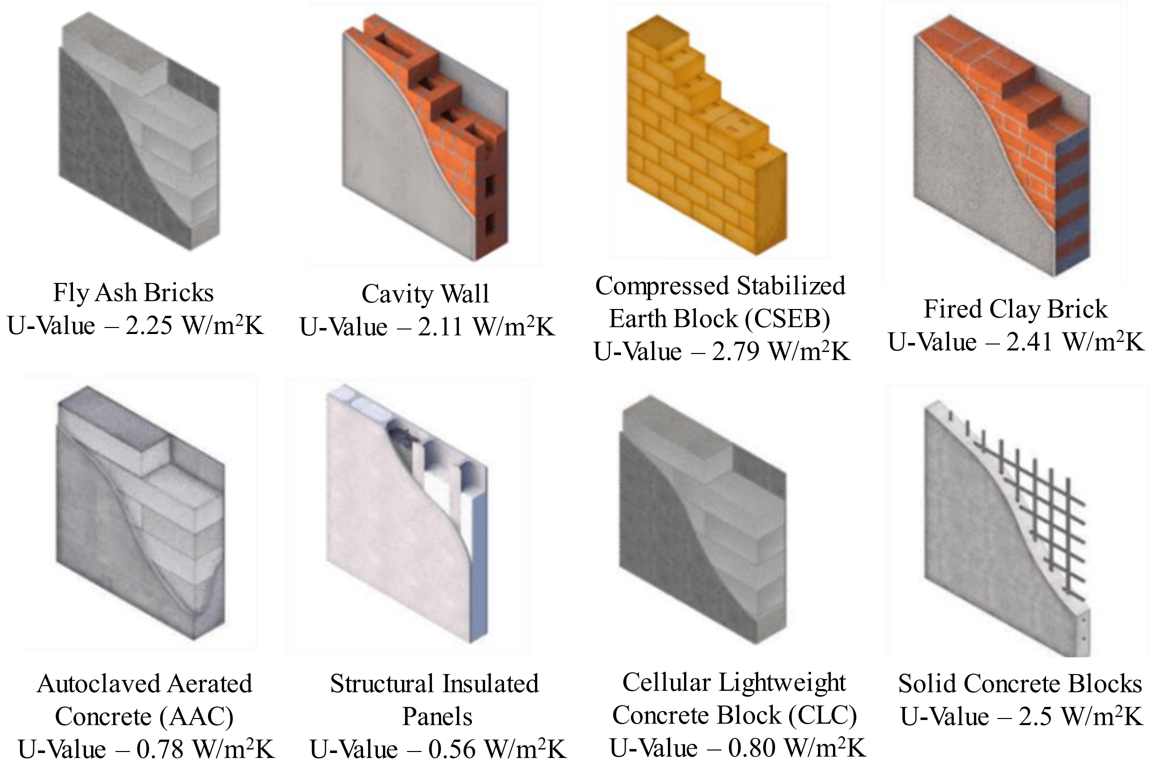
Table 3.2. Comparative assessment of walling materials and technologies

Walling material and technology	Description	Embodied carbon	Cost	Availability
Fly ash bricks	They are made from cement, slag, and fly ash. These are lighter in weight than conventional fired clay bricks and absorb less water. They have a higher compressive strength and are made from the waste generated by coal combustion in thermal power plants. They have a similar thermal performance as compared to fired clay bricks.	Low	Low	High
Cavity wall	A hollow space or cavity separates a cavity wall. These masonry walls can provide good insulation due to slow-moving air through the cavity and perform better than solid masonry, but they can be more efficient if used with low-density foam or fibrous insulation.	Moderate	Low	High
Compressed stabilized earth block (CSEB)	CSEB blocks are a low-cost and environmentally friendly material in developing countries with hot or tropical climates. They consist of basic components such as gravel, sand, silt, and clay. They have a high thermal transmittance value, moderate compressive strength, and a high-water absorption percentage.	Low	Low	Moderate
AAC block	Aerated concrete has entrained air voids, making it lightweight, load bearing, and having a high-water absorption percentage. AAC blocks have low U-values, making them excellent thermal insulators.	Moderate	Moderate	Moderate
Cellular lightweight concrete (CLC) block	CLC blocks use foam concrete, cement, fly ash, sand water, and a foaming agent. They entrain 30–35% of air by volume into the concrete, which is less dense and has the lowest compressive strength compared to the other walling materials.	Moderate	Moderate	Moderate
Fired clay brick	Fire bricks are made from refractory clay and can withstand high temperatures. They have high compressive strength, a low water absorption percentage, and moderate thermal transmittance.	High	Low	High
Structural insulated panel	A structural insulated panel is an insulating foam sandwiched between two structural faces. They have high airtightness, minimize thermal bridging, and also avoid condensation. These are typically used in residential and light commercial construction (glass fiber reinforced gypsum panels with RCC and nonstructural filling).	High	High	Low
Solid concrete block	Made using a mixture of cement, water, sand, and gravel, concrete blocks are the most common type of walling material used in construction. They have a high structural capacity and resistance to fire, and their	High	Moderate	High

Walling material and technology	Description	Embodied carbon	Cost	Availability
	properties can be altered to meet specific insulating requirements.			

Source: Rawal et al., 2020

Figure 3.20. Walling materials



Fly Ash Bricks
U-Value – 2.25 W/m^{2}K

Cavity Wall
U-Value – 2.11 W/m^{2}K

Compressed Stabilized Earth Block (CSEB)
U-Value – 2.79 W/m^{2}K

Fired Clay Brick
U-Value – 2.41 W/m^{2}K

Autoclaved Aerated Concrete (AAC)
U-Value – 0.78 W/m^{2}K

Structural Insulated Panels
U-Value – 0.56 W/m^{2}K

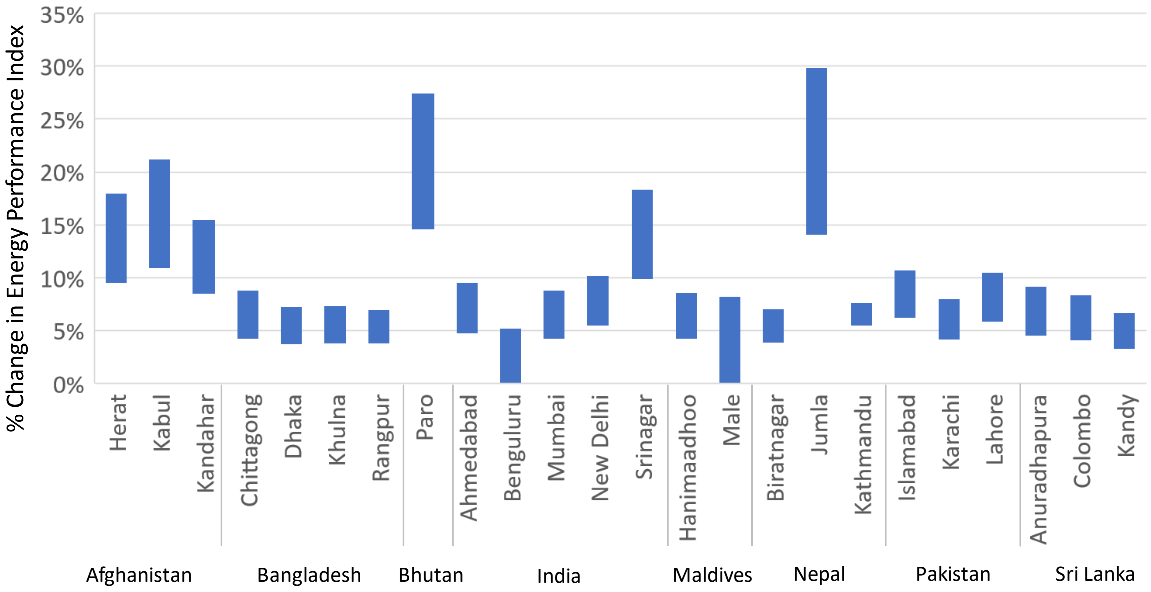
Cellular Lightweight Concrete Block (CLC)
U-Value – 0.80 W/m^{2}K

Solid Concrete Blocks
U-Value – 2.5 W/m^{2}K

Source: Rawal et al., 2020.

Figure 3.21 shows the percentage savings ranging from 5 to 30 percent, depending on climate type, by improving the thermal performance of the wall assembly.

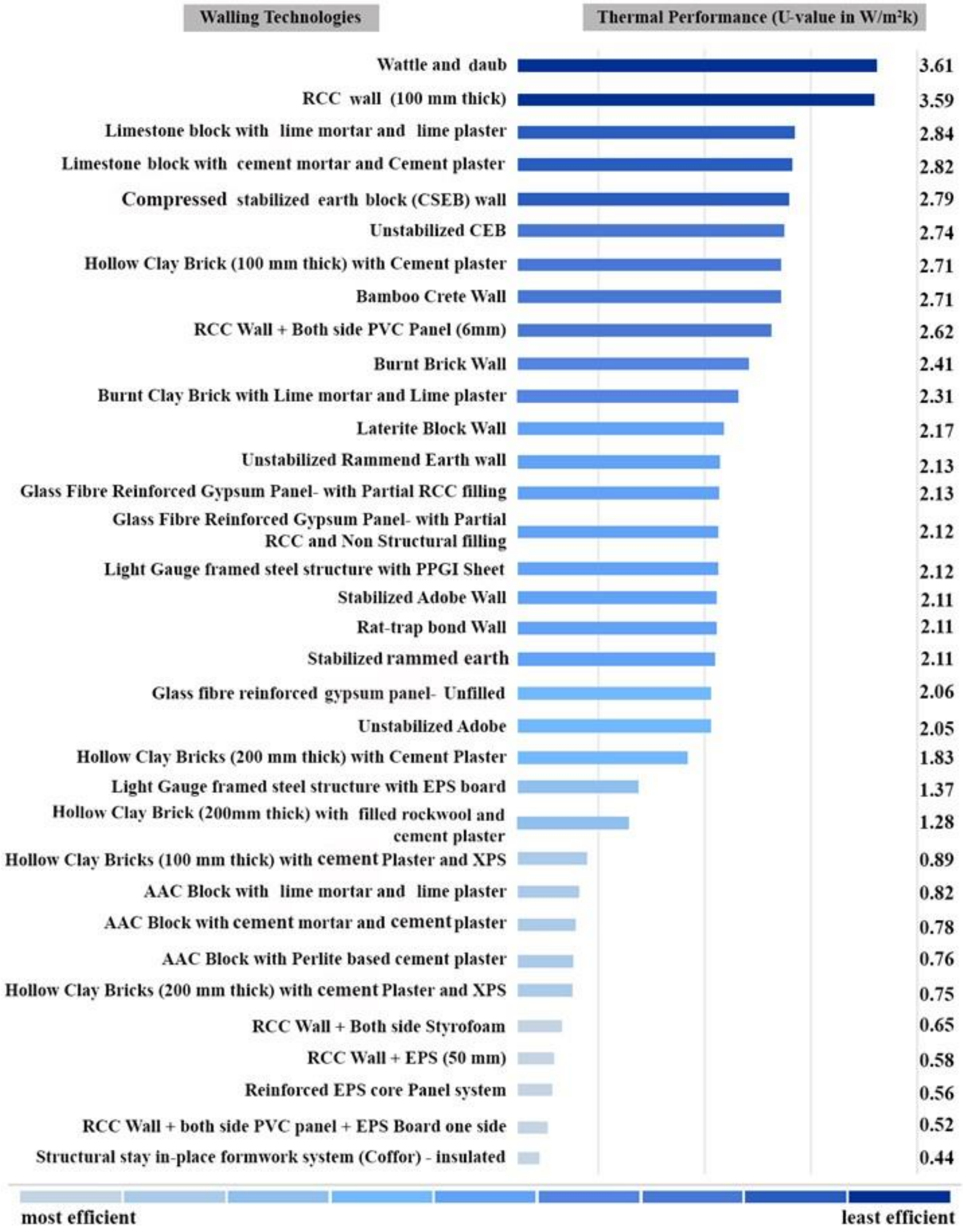
Figure 3.21. Percentage savings in energy performance index through walling materials and technology



Source: Author's analysis.

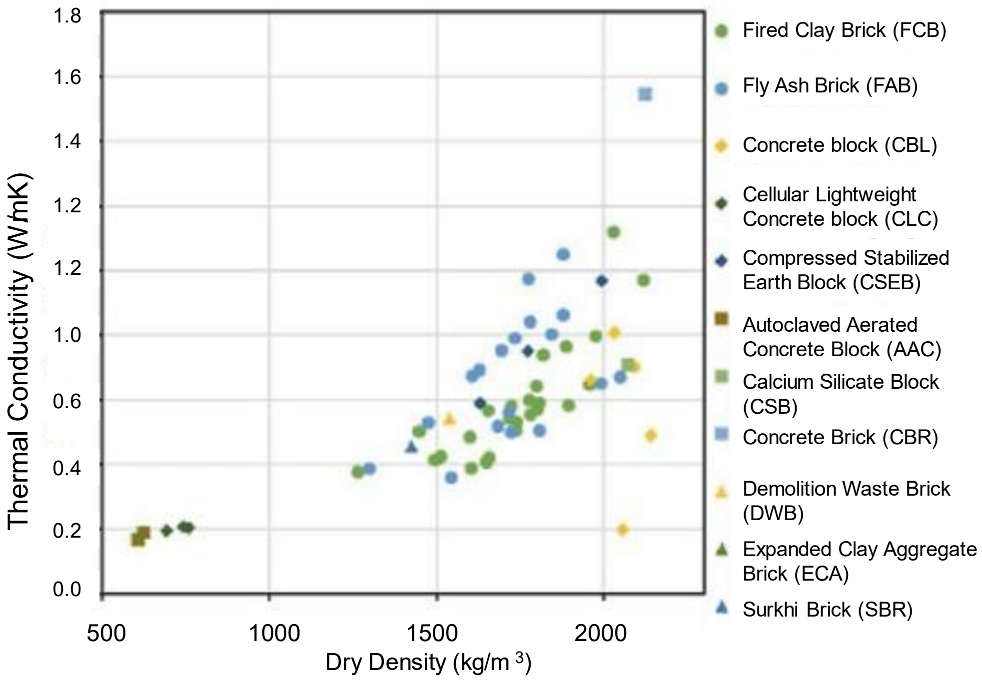
Figure 3.22 shows the thermal performance evaluation of different wall assemblies. The correlation between dry density, which is the density of the brick when it is completely dry, and thermal conductivity for each category was analyzed, as shown in Figure 3.23. The goodness-of-fit (R^2 = 0.70), helps understand how well a set of observations fit a statistical model and shows that dry density is a significant factor governing the thermal conductivity of solid-fired clay bricks. Similarly, for cured fly ash brick, the goodness-of-fit (R^2 = 0.3045) indicates a strong correlation between the two parameters.

Figure 3.22. Thermal performance evaluation of the selected wall assemblies



Source: Rawal et al., 2020.

Figure 3.23. Variation of thermal conductivity with dry density for other non-fired bricks

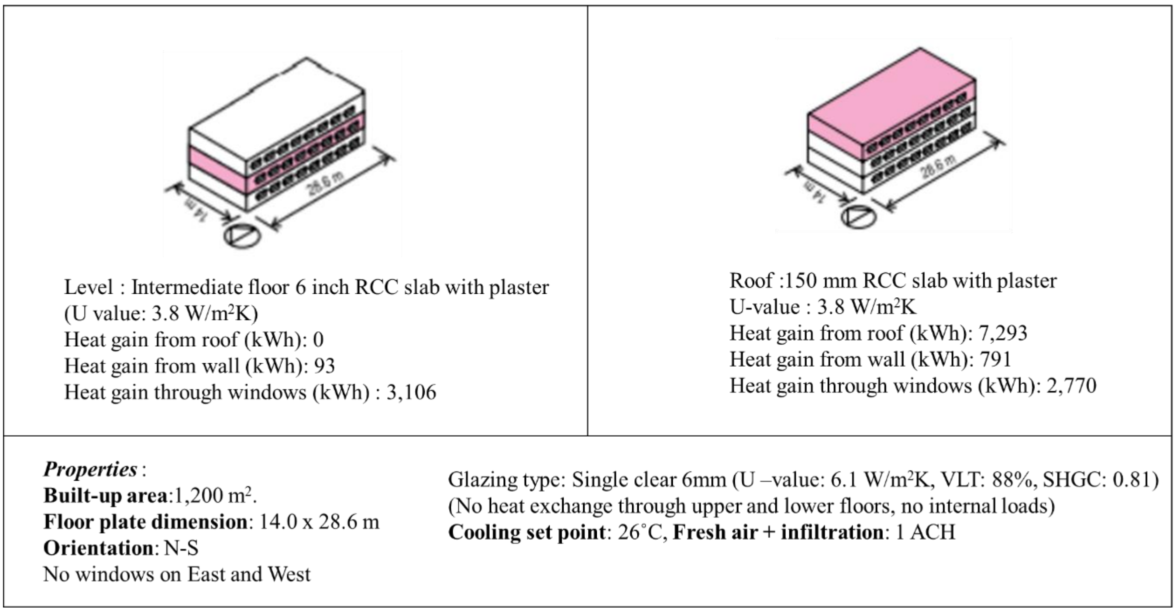


Source: Rawal et al., 2020.

3.1.2.2 Roofing Materials and Technologies

Construction of exposed roofs needs to curb excessive heat transmission through the roof. The overall thermal transmittance from the exposed roof should be maintained at as minimum a value as possible and, under normal conditions, the desirable value should not exceed 0.3 W/m²K (Material W, Assemblies W., 2020). Where required, the overall heat transfer coefficient (U) of the roof exposed to the sun shall be reduced effectively by using appropriate construction materials and the proper type of insulation material(s). Figure 3.24 compares heat gain for top and intermediate floors for Belagavi, Karnataka, India (warm and humid climate type).

Figure 3.24. Comparison of heat gain for the top floor and intermediate floor



Level : Intermediate floor 6 inch RCC slab with plaster (U value: 3.8 W/m^{2}K)
Heat gain from roof (kWh): 0
Heat gain from wall (kWh): 93
Heat gain through windows (kWh) : 3,106

Roof :150 mm RCC slab with plaster
U-value : 3.8 W/m^{2}K
Heat gain from roof (kWh): 7,293
Heat gain from wall (kWh): 791
Heat gain through windows (kWh): 2,770

Properties :
Built-up area:1,200 m^2.
Floor plate dimension: 14.0 x 28.6 m
Orientation: N-S
No windows on East and West

Glazing type: Single clear 6mm (U –value: 6.1 W/m^{2}K, VLT: 88%, SHGC: 0.81)
(No heat exchange through upper and lower floors, no internal loads)
Cooling set point: 26˚C, **Fresh air + infiltration**: 1 ACH

Source: BEE, 2016.
Note: WWR - Window-to-wall ratio – Ratio of total window area to the total wall area.
SHGC – Solar Heat Gain Coefficient – Fraction of solar radiation admitted through glass, and subsequently released as heat in space.
VLT – Visual light transmission – The amount of visible light that passes through glass.
ACH – Air changes per hour – The number of times the total air volume in a space is completely removed and replaced in an hour.
U-Value – The rate of transfer of heat through matter.

For the intermediate floor, the heat gained through windows is much higher than that gained through walls. For the top floor, heat gain from the roof is the highest, while heat gain from windows is also significant. The analysis suggests that reduction of heat gains from the roof and windows should be a priority.

A. Reinforced Cement Concrete

RCC is a popular building material due to its structural properties: high compressive strength, ease of use, adaptability in form, durability, and affordability. It is fire and weather-resistant and has very low maintenance costs. RCC roofs can be used along with other measures, such as cool and vegetated roofs. **Figure 3.25 highlights the points to ponder when considering an RCC roof**.

B. Ventilated Cavity Roof

Ventilated cavity roofs use thermal buoyancy in the air cavity of roofs as a driving force for cavity ventilation and thus perform well when it comes to heat and moisture removal from a building. **Figure 3.26 shows the operating principle of a ventilated cavity roof and the points that must be considered to implement the roofing technology.**

C. Green Roofs

Vegetated roofs, called green roofs, consist of a vegetative layer grown over a rooftop. They perform several functions simultaneously: providing shade, heat removal by transpiration, and reducing roof surface temperatures. The complexity of green roof layers can vary depending on the roof type and must also consider the structural load capacity. They can also incorporate water recycling and rainwater harvesting while helping improve air quality. **Vegetated/green roofs, as shown in Figure 3.27, are an important strategy for mitigating UHI effects**.

Figure 3.25. Passive spatial design strategy: RCC roof

Construction Materials and Technologies : 3.1.2.2.A Reinforced Concrete Roof

Summary		Operational Energy Savings by Climate			
			Low	Moderate	High
Initial Cost	Zero Low Moderate ▼ High	Hot and Dry			●
Embodied Carbon	Zero Low Moderate ▼High	Warm and Humid		●	
Operational Energy Savings	High	Composite			●
Market Availability	High	Temperate		●	
Recommended Climates	All climates	Cold			●

Definition: A composite material made up of cement, coarse aggregates (such as gravel or crushed stone), fine aggregates (such as sand), water, and steel reinforcement bars. They are relatively easy to construct and maintain and are durable structures.

Consideration: Structural load analysis must be performed.

Complementary strategies: Several strategies can be adopted along with a concrete roof, such as cool roofs, vegetated roofs, and insulation.

Illustration and Example

Reinforced concrete roofs are long-lasting, and have high impact resistance, fire resistance, and low maintenance.

Source: Author's analysis.

Figure 3.26. Construction materials and technologies: ventilated cavity roof

Construction Materials and Technologies : 3.1.2.2.B Ventilated Cavity Roof

Summary		Operational Energy Savings by Climate			
			Low	Moderate	High
Initial Cost	Zero Low ▼Moderate High	Hot and Dry			●
Embodied Carbon	Zero Low ▼Moderate High	Warm and Humid	●		
Operational Energy Savings	High	Composite			●
Market Availability	High	Temperate		●	
Recommended Climates	Hot and dry, composite	Cold	●		

Definition: An air cavity between the inner and outer layers of the roof, reducing heat flow via the roof by allowing airflow through the cavity.

Consideration: The design should consider cavity width, the height of the ridge vent and moisture condensation in the vent.

Illustration and Example

A ventilated cavity significantly reduces heat influxes. A cavity represents a resistance, which is not proportional to its thickness. For a thickness greater than 20mm, the resistance to heat flow remains nearly constant. Its effect may be enhanced by adding an insulating layer on the roof.

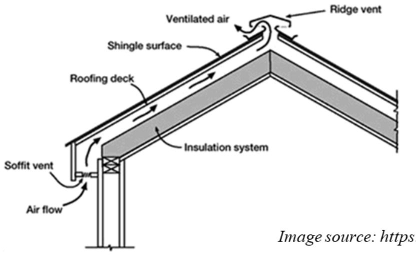
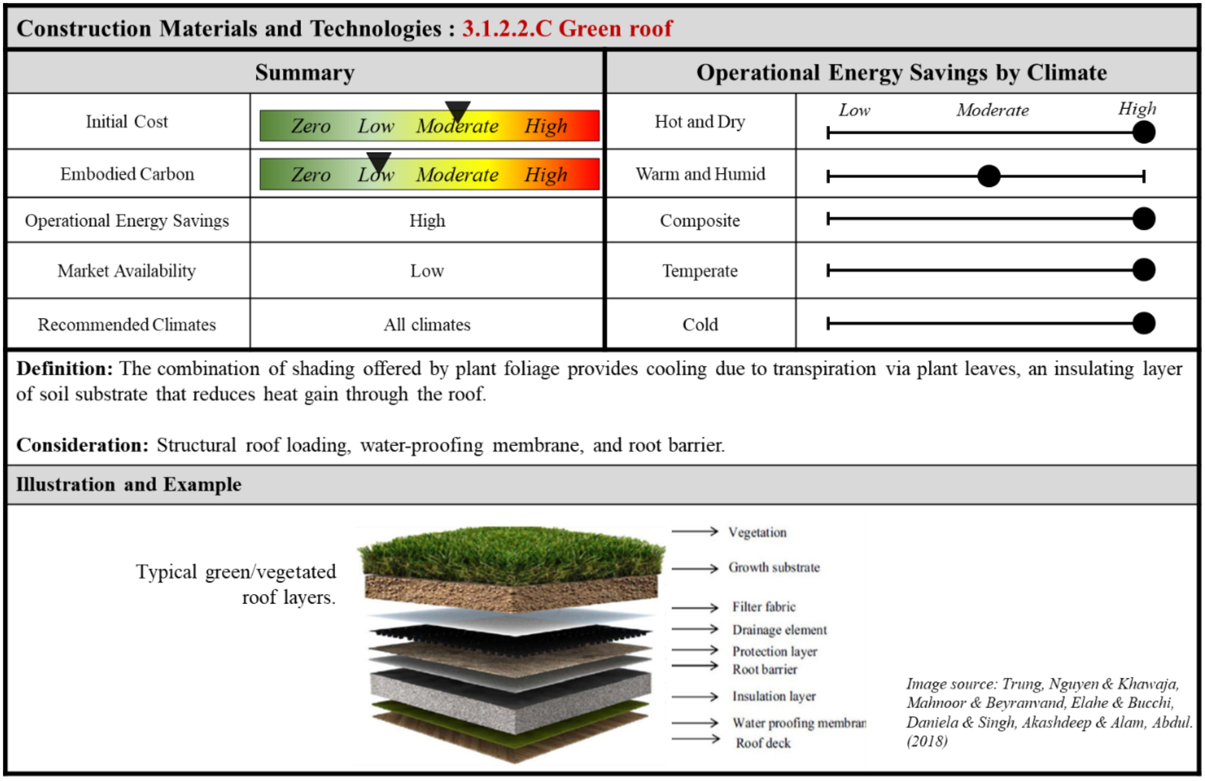


Image source: https://prohomemi.com/

Source: Author's analysis.

Figure 3.27. Construction materials and technologies: vegetated/green roof



Construction Materials and Technologies : 3.1.2.2.C Green roof

Summary		Operational Energy Savings by Climate	Low	Moderate	High
Initial Cost	Zero Low ▼Moderate High	Hot and Dry			●
Embodied Carbon	Zero ▼Low Moderate High	Warm and Humid		●	
Operational Energy Savings	High	Composite			●
Market Availability	Low	Temperate			●
Recommended Climates	All climates	Cold			●

Definition: The combination of shading offered by plant foliage provides cooling due to transpiration via plant leaves, an insulating layer of soil substrate that reduces heat gain through the roof.

Consideration: Structural roof loading, water-proofing membrane, and root barrier.

Illustration and Example

Typical green/vegetated roof layers.

Image source: Trung, Nguyen & Khawaja, Mahnoor & Beyranvand, Elahe & Bucchi, Daniela & Singh, Akashdeep & Alam, Abdul. (2018)

Source: Author's analysis.

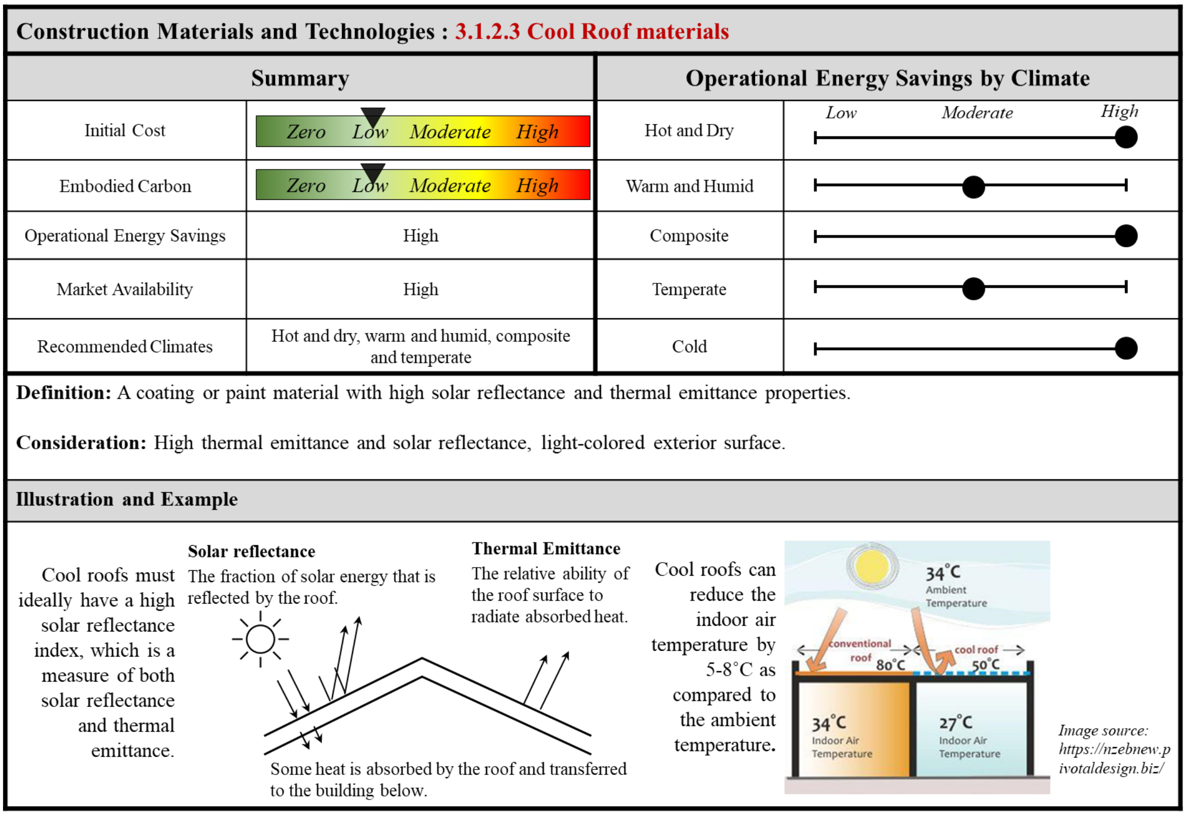
3.1.2.3 Cool Roof Materials

Cool roof materials reduce cooling loads and overheating in locations with high solar radiation and external air temperatures. Most cool roofs have high solar reflectivity leading to decreased roof surface temperatures. This benefits the building occupant by saving on energy bills and by reducing air-conditioning needs.

The effectiveness of a roof is influenced by its solar reflectance and thermal emittance, where solar reflectance is the ratio of solar radiation reflected by a surface to the solar radiation incident upon it. Solar reflectance is measured on a scale of 0 to 1. Thermal emittance is the relative ability of a material to reradiate absorbed heat as invisible infrared radiation. Emittance, measured from 0 to 1, is the ratio of the radiant flux emitted by a body to that emitted by a black body at the same temperature and under the same conditions.

Solar reflectance index (SRI) is a term that incorporates both solar reflectance and emittance in a single value and quantifies how hot a surface would get relative to standard black and standard white surfaces. The SRI of a standard black surface (of reflectance 0.05 and emittance 0.9) and a standard white surface (of reflectance 0.8 and emittance 0.9) is taken as 0 and 100, respectively. **Figure 3.28 shows the operating principle of cool roof materials and the factors to be considered when incorporating this passive measure.**

Figure 3.28. Construction materials and technologies: cool roof materials



Construction Materials and Technologies : 3.1.2.3 Cool Roof materials

Summary		Operational Energy Savings by Climate	Low	Moderate	High
Initial Cost	Zero ▼Low Moderate High	Hot and Dry			●
Embodied Carbon	Zero ▼Low Moderate High	Warm and Humid		●	
Operational Energy Savings	High	Composite			●
Market Availability	High	Temperate		●	
Recommended Climates	Hot and dry, warm and humid, composite and temperate	Cold			●

Definition: A coating or paint material with high solar reflectance and thermal emittance properties.

Consideration: High thermal emittance and solar reflectance, light-colored exterior surface.

Illustration and Example

Cool roofs must ideally have a high solar reflectance index, which is a measure of both solar reflectance and thermal emittance.

Solar reflectance The fraction of solar energy that is reflected by the roof.

Thermal Emittance The relative ability of the roof surface to radiate absorbed heat.

Some heat is absorbed by the roof and transferred to the building below.

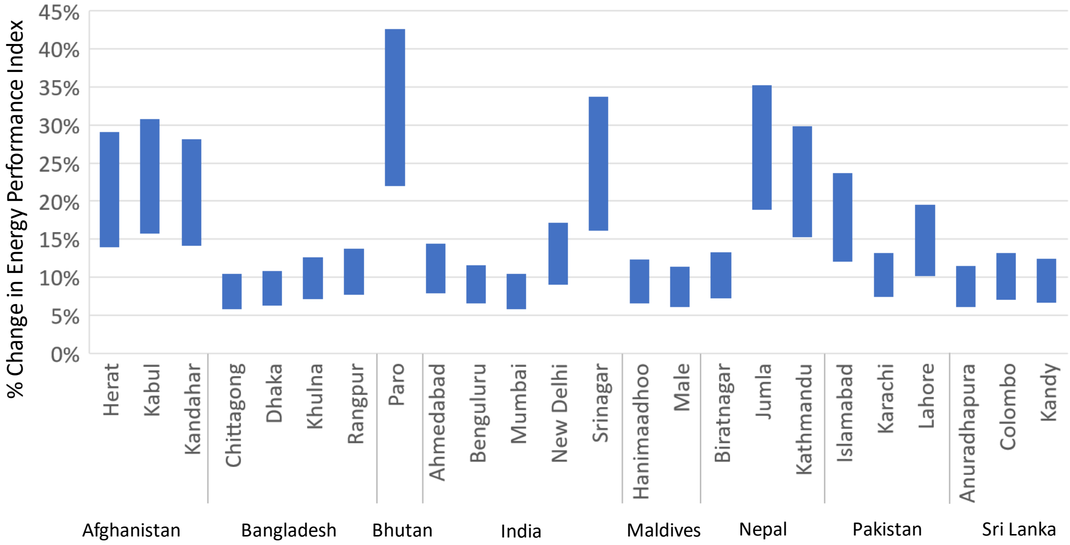
Cool roofs can reduce the indoor air temperature by 5-8˚C as compared to the ambient temperature.

Image source: https://nzebnew.pivotaldesign.biz/

Source: Author's analysis.

For cool roofs to be effective, roofs with slopes less than 20 degrees shall have an initial solar reflectance of at least 0.6 and an initial emittance of 0.9. Figure 3.29 shows the effect of improved roof assembly (an improved overall U-value by employing any of the roofing materials and technologies discussed here). Depending on the climate type, EPI savings of 12 to 42 percent can be achieved.

Figure 3.29. Percentage savings in energy performance index through roofing materials and technology



Source: Author's analysis.

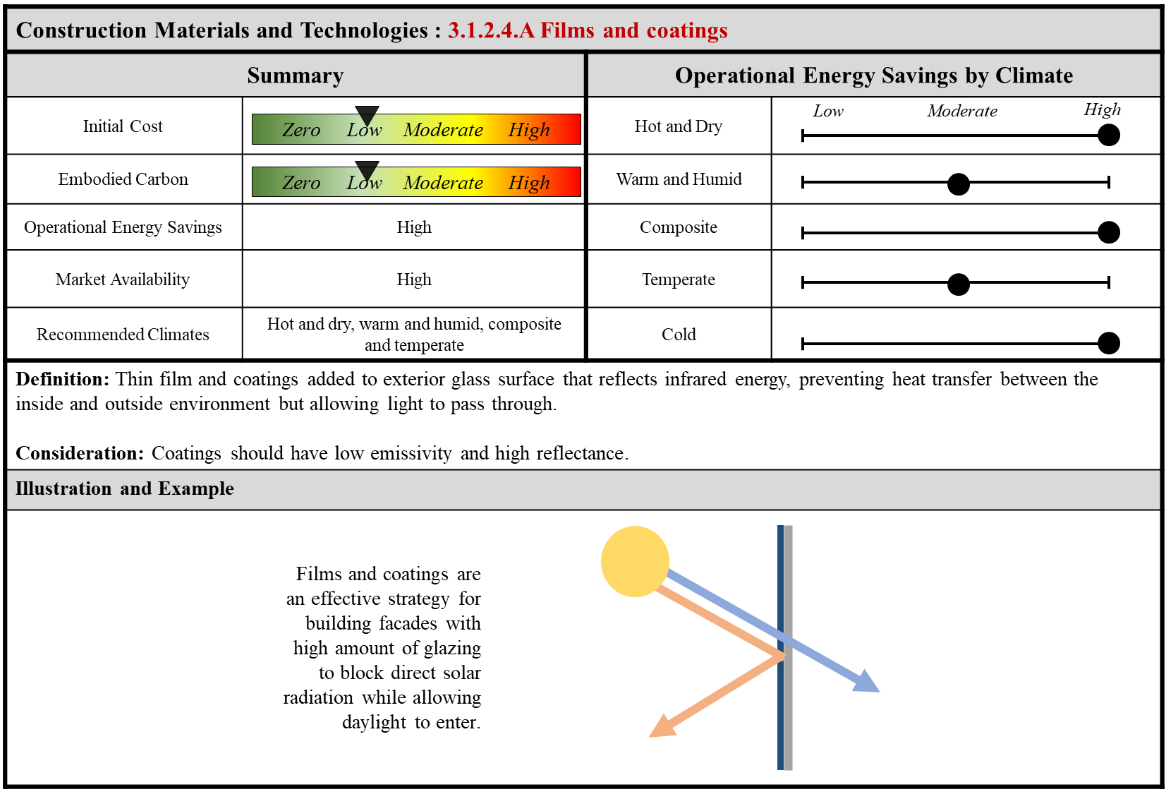
3.1.2.4 Fenestration Systems

Despite their high initial cost, efficient fenestration systems can significantly impact the building's energy consumption by reducing the operational cost of air-conditioning systems and providing daylight, which can positively impact the occupants' health and productivity.

A. Films and Coatings

The properties of glass can be altered by applying various coatings, films, or tints. Low-emissivity coatings can help dramatically lower the window U-value (which measures the rate at which heat is transferred through matter), thereby improving the thermal performance of the glass. A fenestration assembly with a low U-value (<3 W/m²K) and low solar heat gain coefficient (SHGC) values is preferred in hot and composite climates (<0.3) while, in colder climates, higher SHGC values are preferred (<0.51). High (<70 percent) glass visible transmittance is desirable for daylighting applications. SHGC is the fraction of solar radiation admitted through a window, door, or skylight either transmitted directly and absorbed or subsequently released as heat inside a home. The lower the SHGC, the less solar heat it transmits and the greater its shading ability. **Figure 3.30 shows the working of films and coatings and the key points that need to be considered for films and coatings to be incorporated into the building fenestration.**

Figure 3.30. Construction materials and technologies: films and coatings



Construction Materials and Technologies : 3.1.2.4.A Films and coatings

Summary		Operational Energy Savings by Climate	Low	Moderate	High
Initial Cost	Zero Low ▼ Moderate High	Hot and Dry			●
Embodied Carbon	Zero Low ▼ Moderate High	Warm and Humid		●	
Operational Energy Savings	High	Composite			●
Market Availability	High	Temperate		●	
Recommended Climates	Hot and dry, warm and humid, composite and temperate	Cold			●

Definition: Thin film and coatings added to exterior glass surface that reflects infrared energy, preventing heat transfer between the inside and outside environment but allowing light to pass through.

Consideration: Coatings should have low emissivity and high reflectance.

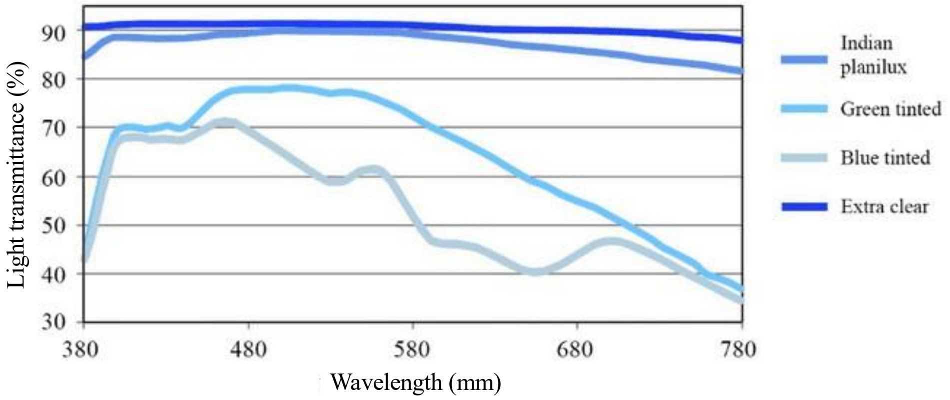
Illustration and Example

Films and coatings are an effective strategy for building facades with high amount of glazing to block direct solar radiation while allowing daylight to enter.

Source: Author's analysis.

Figure 3.31 shows the variation in transmission levels of different types of glasses at different wavelengths within the visible light spectrum. It can be observed that extra clear glass transmits nearly 90 percent of visible light, closely followed by Indian planilux or clear glass with 80-90 percent visible light transmission, while blue and green tinted glasses provide visual light transmittance (VLT) levels in the range of 35 to 80 percent.

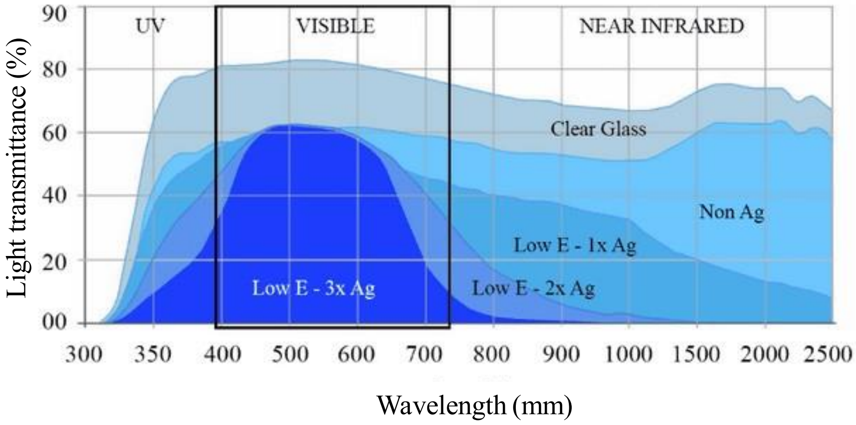
Figure 3.31. Visible light transmittance for different types of glasses



Source: Unnikrishnan.

Figure 3.32 presents the difference in the performance of simple, clear glass and advanced glazing systems with coatings, double glazed unit (DGU) with no coating (indicated as non-Ag), and DGU with one, two, or three low-e coatings (Low E).

Figure 3.32. Performance of different coating combinations in various spectrums

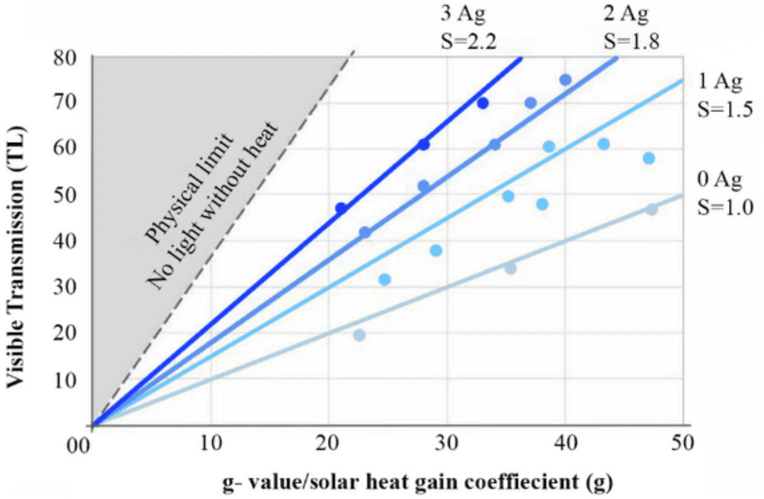


Source: Unnikrishnan.

Note: The abbreviated label 'non-Ag' shows the light transmittance values for a double-glazed unit with no coating, and 'Low E – 1x Ag, 2x Ag, and 3x Ag represent a double-glazed unit with one, two and three low-e coating(s), respectively.

Figure 3.33 compares the solar heat gain coefficients of clear glass without silver-based low-e coatings with those containing different numbers of coatings along with their visible light transmission levels. It also shows the theoretical limit of optimizing heat gain coefficient and VLT in a glazing material. Technological advancements such as low-e coatings make minimization of solar heat gains possible while allowing a higher amount of daylight to be experienced by the buildings. Spectral selectivity (S) is the ratio of visible transmittance to solar heat gain, which describes the total daylight penetration and associated heat gain into a space. A high spectral selectivity indicates high daylight penetration and low heat ingress, reducing the cooling requirement.

Figure 3.33. Selectivity, solar heat gain coefficient, and visible light transmission of different low-e coating combinations

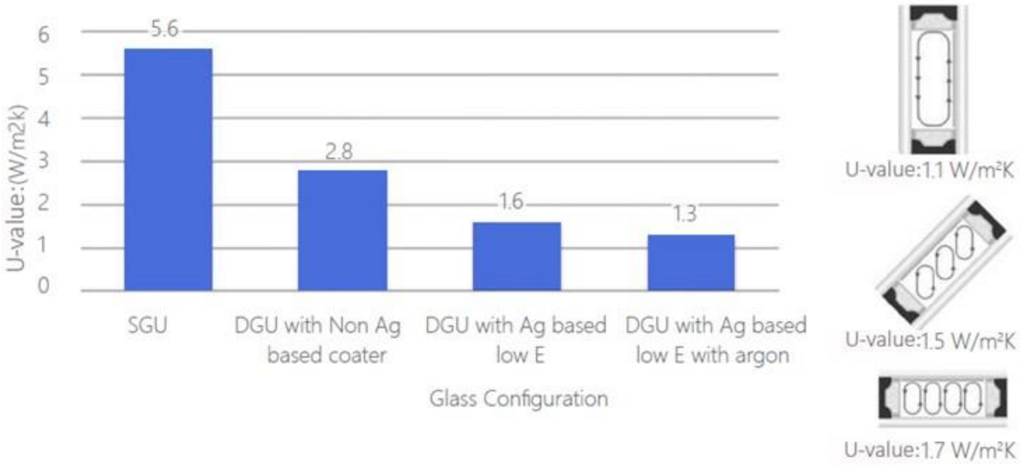


Source: Unnikrishnan.
Note: The abbreviation 'S' stands for selectivity, and the increasing values of 'Ag' represent the increasing number of low-e coatings as a combination.

B. Double Glazed Units

Double-glazed or insulated glass is two glass panes installed in a window frame. Air, or an inert gas such as argon, fills the two panes as an insulator. DGUs are an efficient fenestration component as they provide relief from high temperatures, direct solar heat gains, and reduce noise. The effects of DGUs can further be enhanced with films or coatings. Figure 3.34 compares a single-glazed unit with varying DGU configurations. It also shows the impact of orientation of the DGU on the overall assembly's U-value.

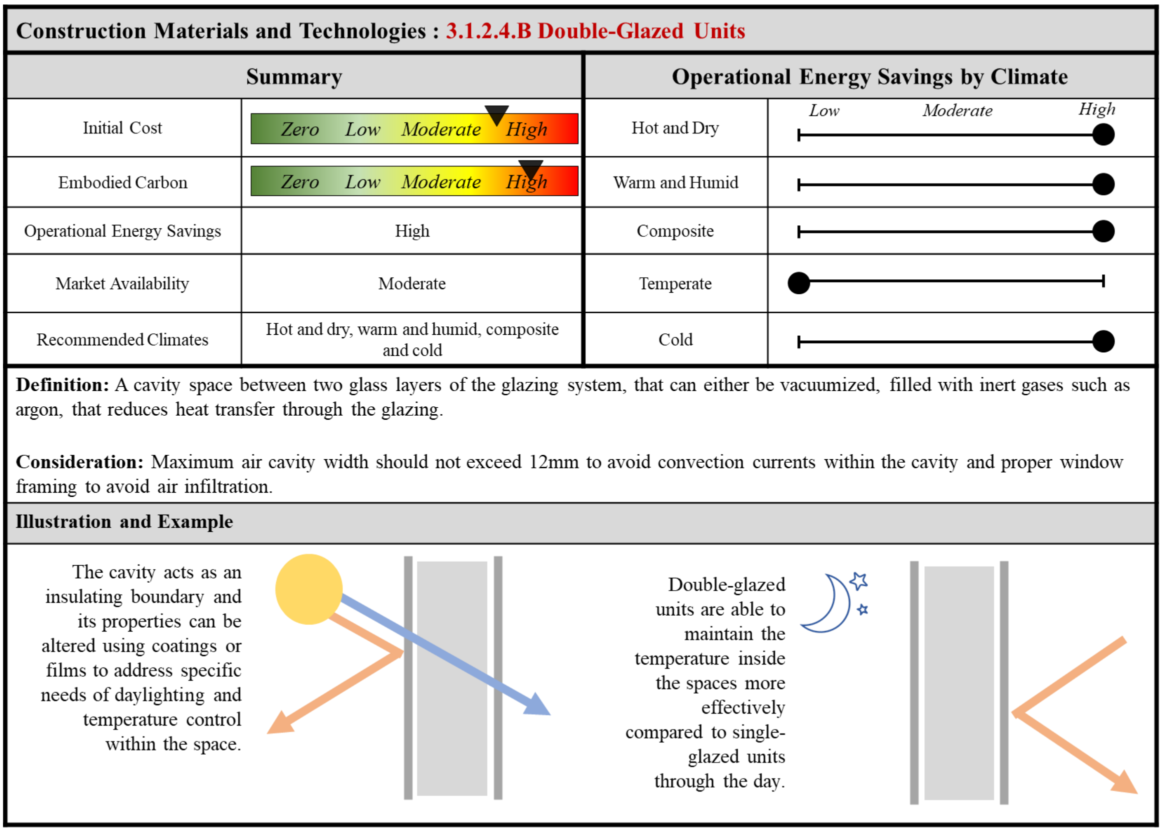
Figure 3.34. U-value based on window configuration and orientation



Source: CARBSE, 2022.
Note: SGU – Single Glazed Unit, DGU – Double Glazed Unit. 'Non-Ag based' represents no low-e coating, while 'Ag based' represents with low-e coating.

The example and illustration in Figure 3.35 summarize the operating and key points that must be considered when considering DGUs as a part of the building fenestration.

Figure 3.35. Construction materials and technologies: double-glazed units



Construction Materials and Technologies : 3.1.2.4.B Double-Glazed Units

Summary		**Operational Energy Savings by Climate**	
Initial Cost	*Zero Low Moderate* ▼ *High*	Hot and Dry	*Low Moderate High* |———————●
Embodied Carbon	*Zero Low Moderate* ▼*High*	Warm and Humid	|———————●
Operational Energy Savings	High	Composite	|———————●
Market Availability	Moderate	Temperate	●———————|
Recommended Climates	Hot and dry, warm and humid, composite and cold	Cold	|———————●

Definition: A cavity space between two glass layers of the glazing system, that can either be vacuumized, filled with inert gases such as argon, that reduces heat transfer through the glazing.

Consideration: Maximum air cavity width should not exceed 12mm to avoid convection currents within the cavity and proper window framing to avoid air infiltration.

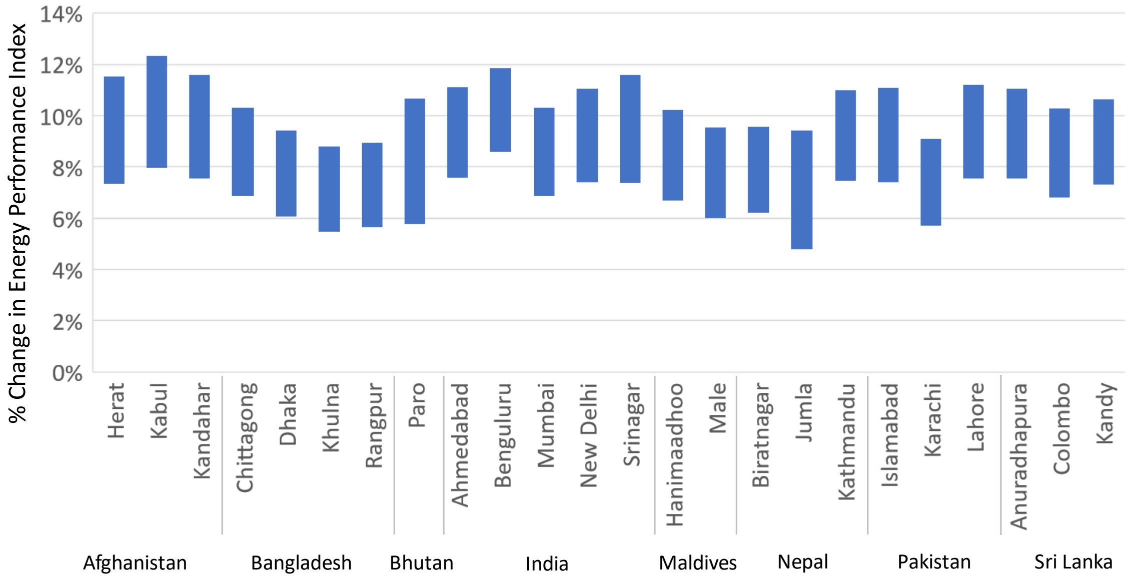
Illustration and Example

The cavity acts as an insulating boundary and its properties can be altered using coatings or films to address specific needs of daylighting and temperature control within the space.

Double-glazed units are able to maintain the temperature inside the spaces more effectively compared to single-glazed units through the day.

The results from the simulation, as shown in Figure 3.36, suggest that, for every climate type, DGU's EPI savings range from 9 to 12 percent when compared to a single-glazed building.

Figure 3.36. Percentage savings in energy performance index through efficient glazing

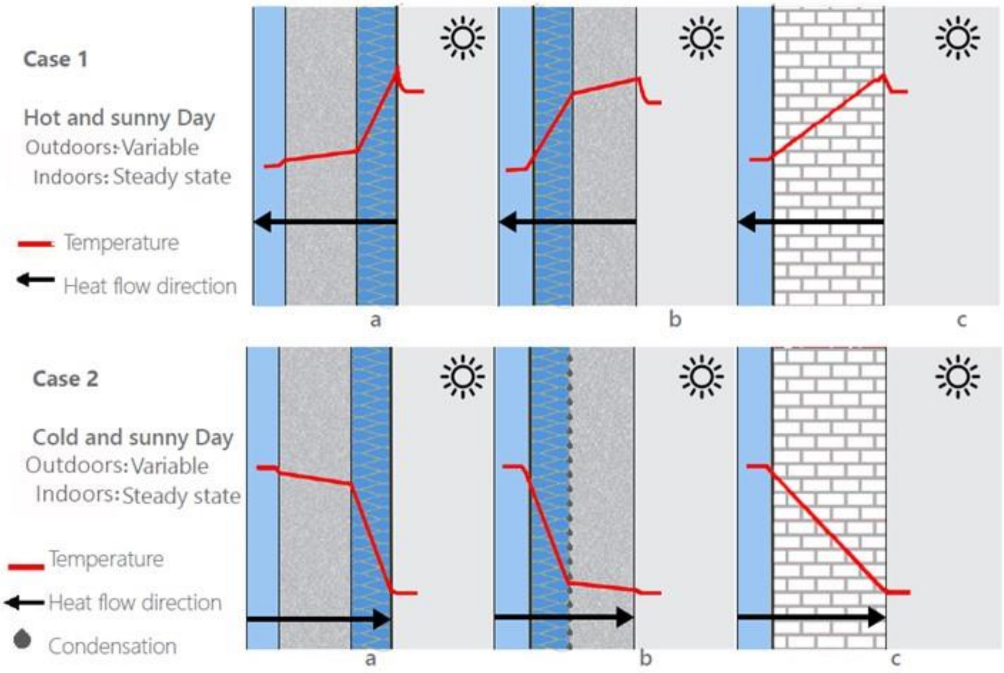


Source: Author's analysis.

3.1.2.5 Insulation Materials

Insulation refers to material used in building construction, in most cases as an add-on, that reduces heat transmission through walls, floors, and ceilings. Compared to thermal mass that relies on the ability of materials to absorb and store heat for later release, insulation creates a barrier that resists heat flow to reduce heat transfer in and out of a building. Under modern building codes, any reasonable thermal mass thickness cannot provide insulation equivalent to that achieved by thermal insulation materials while adhering to energy efficiency codes or standards. Another reason for adoption of insulation materials is that they reduce HVAC energy consumption while maintaining indoor temperatures for extended periods. In hot climates, insulating materials keep air-conditioned spaces cooler and, in cold climates, they keep heated spaces warm, reducing HVAC operation costs. Unlike thermal mass, insulating materials take up much less space depending on the type of insulation used. They can be broadly categorized as natural and synthetic (inorganic and organic). Some synthetic insulations offer extremely high insulation levels but require vast amounts of energy, while releasing emissions during manufacturing, such as glass wool and foamed glass (Dovjak et al., 2017). Natural insulation includes high- and low-density wood fiber boards, cellulose fiber, and cork, which have a lower environmental impact. Insulation materials can be installed in various ways, either as bats and rolls, sprayed foam, or part of the building structure, such as cores of the wall being filled with insulating material or placing together structurally insulated panels.

Figure 3.37. Temperature profile illustrations for various indoor and outdoor conditions



Source: Roulet, 2015.

In Figure 3.37, case 1 shows a steady-state indoors and variable outdoors when the outside air temperature is high while a constant, comfortable indoor temperature is maintained. Hence the direction of heat flow is from outdoors to indoors.

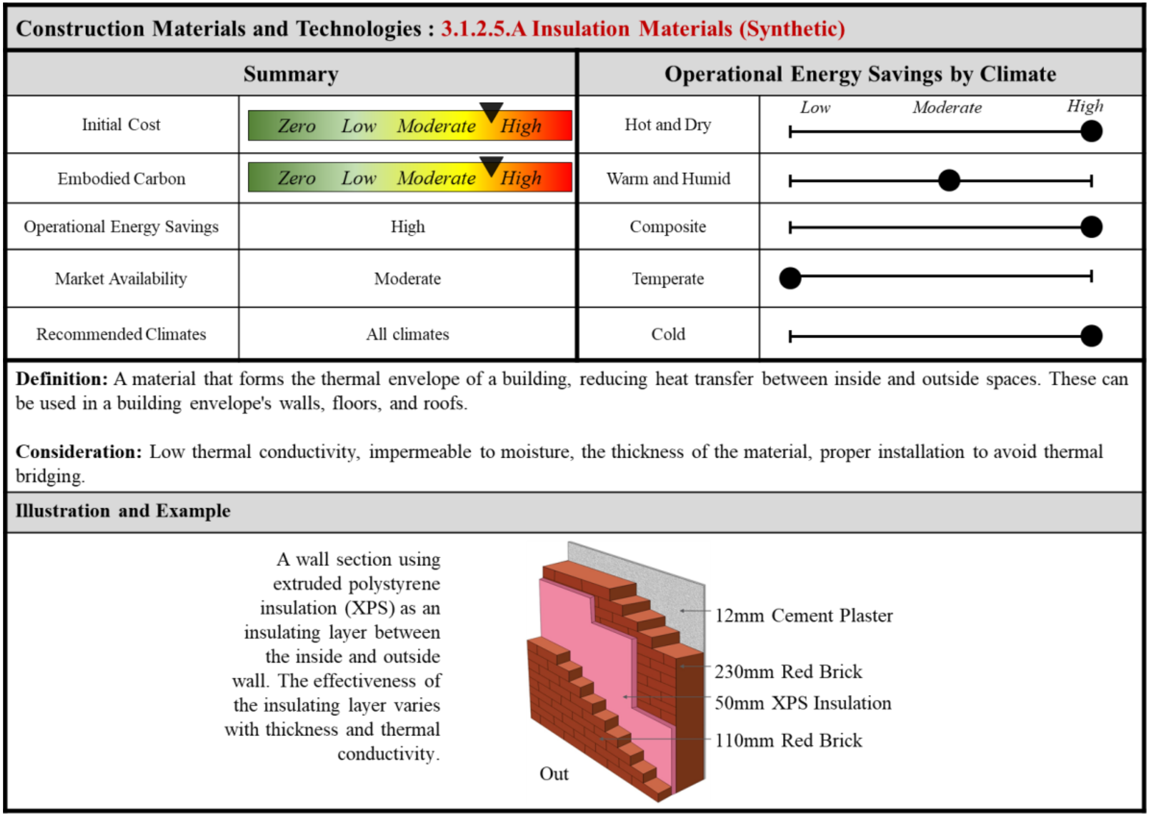
- **Case 1a:** Insulation is placed closer outdoors and finished with plaster. In this case, the insulation prevents maximum heat absorption, allowing the temperature to drop steeply across its exterior and interior surfaces. The slope of the temperature gradient may allude to the time taken for heat exchange between indoors and outdoors. In climates such as hot and dry ones, maximizing the time lag helps to maintain cooler indoor temperatures throughout the day;

- **Case 1b:** Insulation is placed closer indoors. In this case, the outermost layer of the wall allows for some thermal transmittance. Hence, although the temperature gradient across the insulating layer is high, it is still lower than in case 1a; and
- **Case 1c:** Insulation is absent, and a wall with high thermal mass is used. To maintain the indoor environment at a constant temperature, the thickness of the building material required when thermal mass is responsible for insulation may be greater than an assembly containing insulation. This can prove disadvantageous in terms of material costs incurred and space availability.

Case 2 shows a steady-state indoors and variable outdoors on cold sunny days. In this condition, the higher indoor air temperature dictates the direction of heat flow from indoors to outdoors. The placement of insulation in a situation where the indoor air temperature is higher than the outdoor air temperature is essential. In case 2b, the temperature profile across the insulating layer is steep. This can allow for the storage of moisture towards the layer's cooler surface, giving rise to the possibility of condensation where the insulating layers meet the RCC wall. The condensation issue can be resolved by introducing a vapor barrier between the insulating layer and the concrete wall. This is a suitable approach as placing insulation closer indoors helps to retain a comfortable temperature and thus reduces dependence on a cooling system to maintain a constant temperature.

Insulation materials should have a flame spread rating of 25 and a smoke density of not more than 450. The example in Figure 3.38 shows the wall assembly with a 50 mm XPS sheet sandwiched between two brick wall layers, resulting in an overall U-value of 0.42 W/m²K. It states the key points to ponder when considering insulating materials. Although the operational energy savings when using synthetic insulation are high, the embodied carbon footprint ranges from moderate to high.

Figure 3.38. Construction materials and technologies: insulation materials (synthetic)



Construction Materials and Technologies : 3.1.2.5.A Insulation Materials (Synthetic)

Summary		**Operational Energy Savings by Climate**	Low — Moderate — High
Initial Cost	Zero Low Moderate ▼ High	Hot and Dry	├──────────●
Embodied Carbon	Zero Low Moderate ▼ High	Warm and Humid	├─────●─────┤
Operational Energy Savings	High	Composite	├──────────●
Market Availability	Moderate	Temperate	●──────────┤
Recommended Climates	All climates	Cold	├──────────●

Definition: A material that forms the thermal envelope of a building, reducing heat transfer between inside and outside spaces. These can be used in a building envelope's walls, floors, and roofs.

Consideration: Low thermal conductivity, impermeable to moisture, the thickness of the material, proper installation to avoid thermal bridging.

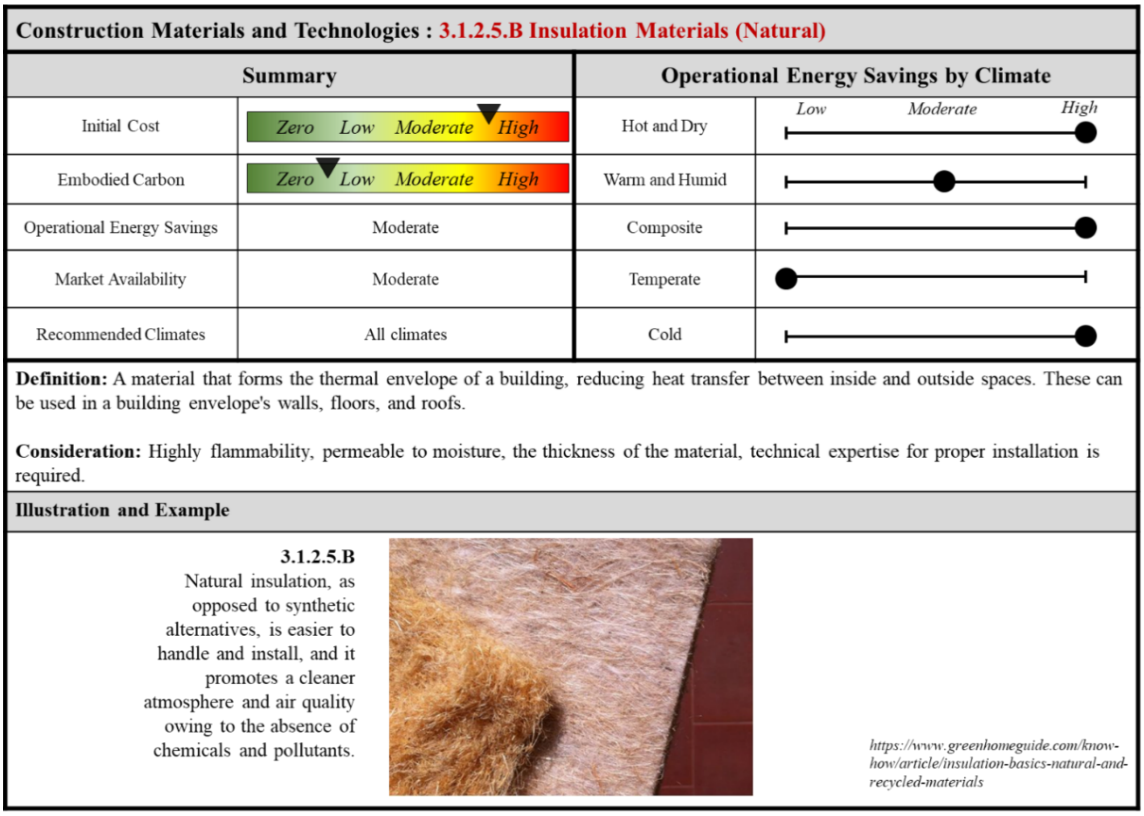
Illustration and Example

A wall section using extruded polystyrene insulation (XPS) as an insulating layer between the inside and outside wall. The effectiveness of the insulating layer varies with thickness and thermal conductivity.

Source: Author's analysis.

Natural insulation materials have lower embodied carbon than synthetic insulation materials. They are generally not harmful to health because they do not contain irritating fibers and hence require no precautions to be taken during installation. **Figure 3.39 highlights the key points to consider when opting for natural insulation materials.**

Figure 3.39. Construction materials and technologies: insulation materials (natural)



Construction Materials and Technologies : 3.1.2.5.B Insulation Materials (Natural)

Summary		**Operational Energy Savings by Climate**	
			Low *Moderate* *High*
Initial Cost	*Zero Low Moderate* ▼*High*	Hot and Dry	├──────────────●
Embodied Carbon	*Zero* ▼*Low Moderate High*	Warm and Humid	├───────●───────┤
Operational Energy Savings	Moderate	Composite	├──────────────●
Market Availability	Moderate	Temperate	●──────────────┤
Recommended Climates	All climates	Cold	├──────────────●

Definition: A material that forms the thermal envelope of a building, reducing heat transfer between inside and outside spaces. These can be used in a building envelope's walls, floors, and roofs.

Consideration: Highly flammability, permeable to moisture, the thickness of the material, technical expertise for proper installation is required.

Illustration and Example

3.1.2.5.B
Natural insulation, as opposed to synthetic alternatives, is easier to handle and install, and it promotes a cleaner atmosphere and air quality owing to the absence of chemicals and pollutants.

https://www.greenhomeguide.com/know-how/article/insulation-basics-natural-and-recycled-materials

Source: Author's analysis.

3.2 Active Cooling and Indoor Air Quality Systems

3.2.1 Active Cooling and Ventilation System Design

This section defines the basis of ventilation rates for IAQ and prescribes the ideal ventilation rates possible through passive and active means. It establishes the importance of active models of ventilation. Next, it introduces the design of active cooling systems in a regional context.

3.2.2 Ventilation Rates for Indoor Air Quality

Ventilation rate is defined as the air changes required per hour or the rate at which outdoor/fresh air is supplied into a building. Ventilation rates consider several factors, such as the number of persons, floor area, fresh air required per person, and ventilation effectiveness.

One key point to consider is that the introduction of fresh air into the space can take a heavy toll on energy consumption, as the outdoor air needs to be treated and cooled/heated from the occupant's comfort standpoint. Some common standards used are EN 15242 and American Society of Heating, Refrigerating, and Air-conditioning Engineers (ASHRAE) 62.1, which include prescriptive methods to calculate ventilation rates, considering people and building-related pollution sources while dealing with health and comfort issues. The National Building Code of India, 2016, also prescribes supply rates of acceptable outdoor air required for IAQ for different spaces; Nepal introduced the National Indoor Air Quality Standards and Implementation Guideline in 2009. On a global scale, WHO Guidelines on Indoor Air Quality, 2021, and ISO 16814:2008 (Building Environment Design – Indoor Air Quality) recommend thresholds for over 10 indoor pollutants based on the synthesis of peer-reviewed research.

According to the Indian Society of Heating, Refrigerating, and Air-conditioning Engineers COVID-19 guidance document, fresh air must be introduced into spaces that have no fresh air provision. A minimum fresh air volume of 8.5 m^3/hour per person and 1.1 m^3/hour per square meter is recommended. It also recommends the provision of a minimum efficiency reporting value (MERV) of 13 or higher filter fitted on air-handling units. Such filters can also be retrofitted into existing systems while ensuring that the fan and motor capacities are adequate to handle the pressure drop.

3.2.3 Design of Active Cooling Systems

Active cooling systems consume electricity or energy to cool/heat the building instead of passive measures such as natural ventilation or thermal mass. Determining the capacity of the system (also referred to as "sizing" the system) to be installed in the building requires consideration of the total heat load of the space, which is affected by factors such as the materials in the building envelope, glazing area, floor area, and building location.

An accurate calculation can size the system perfectly. However, oversizing can lead to higher power consumption and under sizing to reduced occupant comfort. Common active systems include split air conditioners requiring refrigerants between an external condensing unit and an indoor evaporative unit (s). While these units can address specific air-conditioning requirements, they consume much energy, which needs to be considered for the regions addressed in this report.

However, improvement in technology has resulted in these systems becoming more efficient over time. Considering that most of the population falls in the low-income category, the following section on low-energy cooling and ventilation systems addresses alternatives such as evaporative air conditioners, which use wet pads to cool the space, and air-circulation devices such as fans. While fans do not directly affect the air temperature, they elevate airspeed resulting in increased comfort and can also aid in night ventilation.

3.2.4 High-performance Cooling and Ventilation Systems

This section describes high-performance cooling and ventilation strategies used globally and in South Asia using relevant key performance indicators (based on comfort, IAQ, and disease resilience). These technologies prioritize provision of comfortable and disease-resilient indoor conditions over other factors, particularly relevant in the context of the COVID-19 pandemic. This section describes market-available products and their associated initial and operational costs.

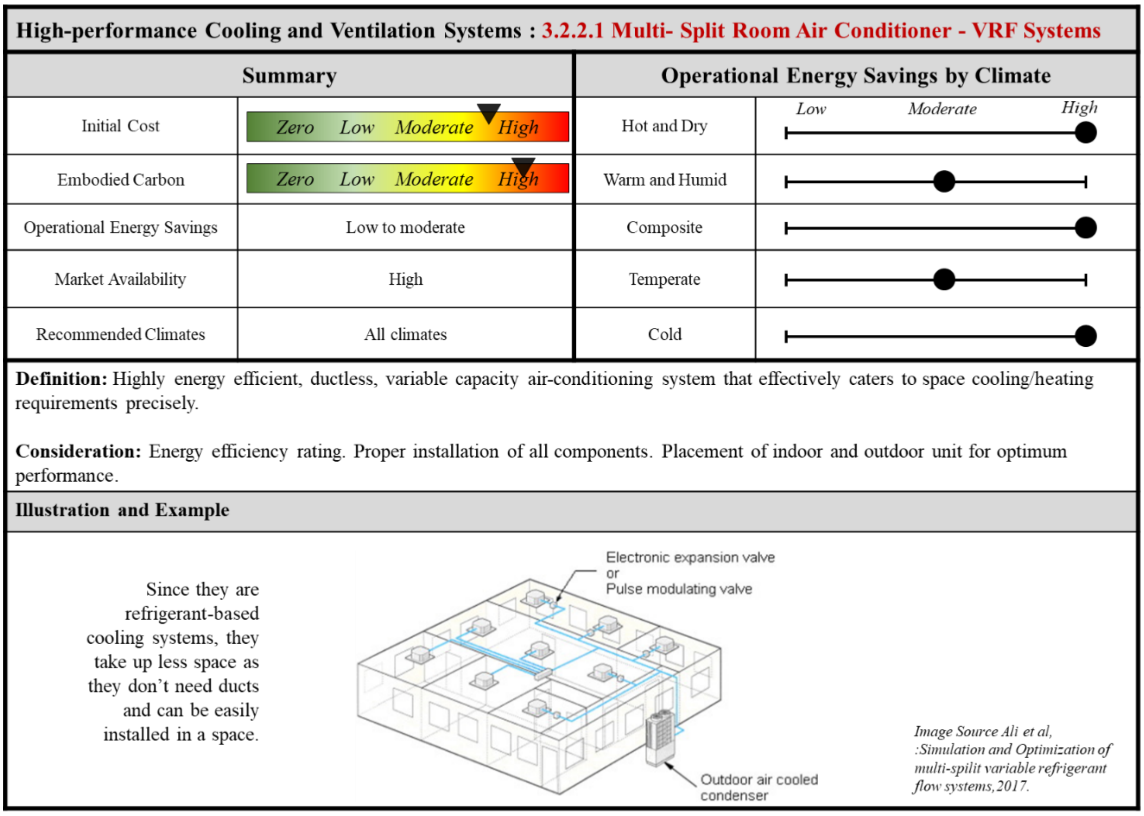
The section highlights the importance of flexible design in ventilation and cooling systems for efficient operation during the pandemic, pre-pandemic, and post-pandemic scenarios. Further, recommendations are provided for optimized air distribution systems to ensure occupants breathe clean air. The following high-performance cooling and ventilation systems are discussed: multi-split room air conditioners, portable air filters, and centralized air conditioners.

3.2.5 Multi-split Room Air Conditioner: Variable Refrigerant Flow Systems

Variable refrigerant flow is a technology that circulates only the minimum amount of refrigerant needed during a single heating or cooling period. Apart from its compactness and flexibility in terms of installation, an advantage of the system is that it can heat and cool different zones during the same mode of operation. This mechanism introduced the opportunity for end users to control several air-conditioned zones at one time individually. Their popularity is growing due to their high efficiency and low operational costs.

Figure 3.40 shows the key points to consider when considering multi-split room air conditioners to meet the space cooling/heating demands.

Figure 3.40. High-performance cooling and ventilation systems: multi-split room air conditioner–variable refrigerant flow systems



High-performance Cooling and Ventilation Systems : 3.2.2.1 Multi- Split Room Air Conditioner - VRF Systems

Summary		**Operational Energy Savings by Climate**	
Initial Cost	*Zero Low Moderate ▼High*	Hot and Dry	*Low Moderate High* ├──────────────●
Embodied Carbon	*Zero Low Moderate ▼High*	Warm and Humid	├───────●───────┤
Operational Energy Savings	Low to moderate	Composite	├──────────────●
Market Availability	High	Temperate	├───────●───────┤
Recommended Climates	All climates	Cold	├──────────────●

Definition: Highly energy efficient, ductless, variable capacity air-conditioning system that effectively caters to space cooling/heating requirements precisely.

Consideration: Energy efficiency rating. Proper installation of all components. Placement of indoor and outdoor unit for optimum performance.

Illustration and Example

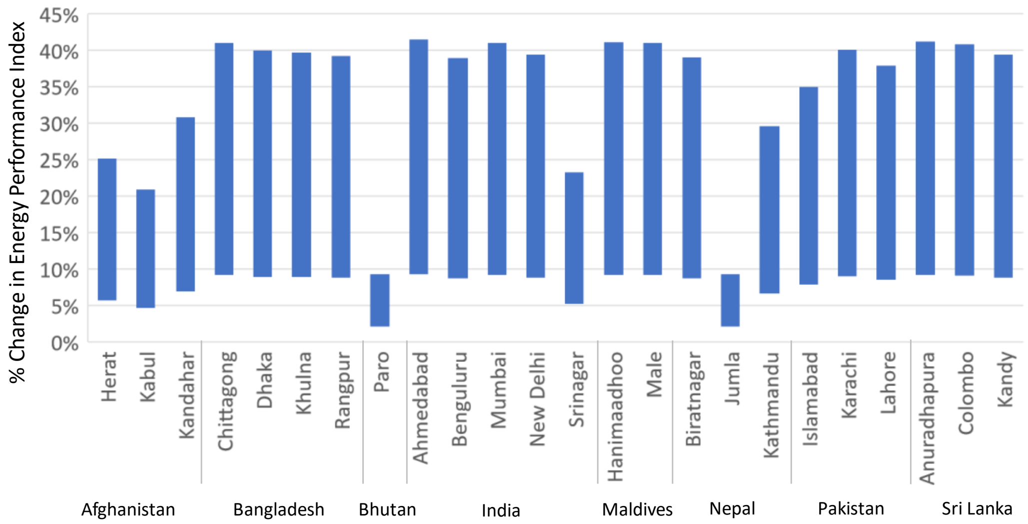
Since they are refrigerant-based cooling systems, they take up less space as they don't need ducts and can be easily installed in a space.

Image Source Ali et al, :Simulation and Optimization of multi-spilit variable refrigerant flow systems, 2017.

Source: Author's analysis.

Figure 3.41 shows a range of 3 to 40 percent EPI savings from using highly efficient multi-split variable refrigerant flow (VRF) air-conditioning systems.

Figure 3.41. Percentage savings in energy performance index through efficient air conditioning

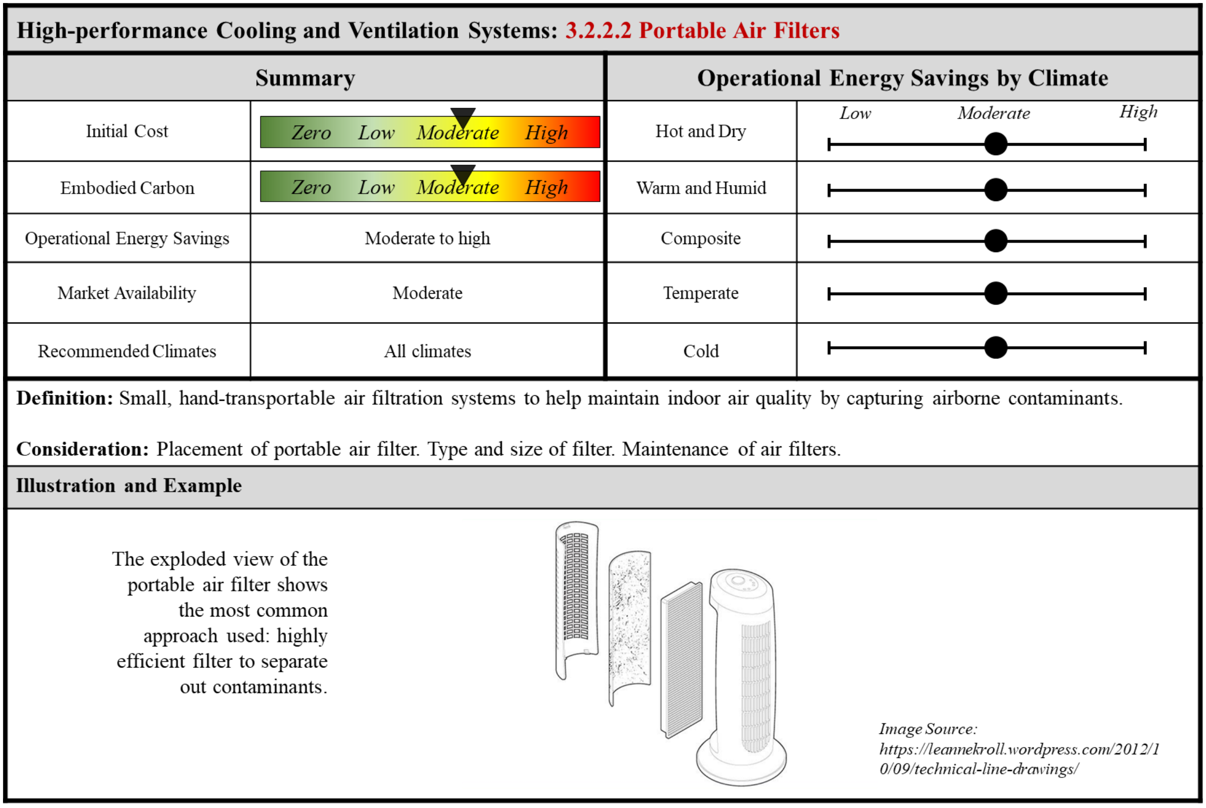


Source: Author's analysis.

3.2.6 Portable Air Filters

Portable air filters, also known as air purifiers or sanitizers, are designed to filter the air in a single room or area. A central furnace or HVAC filter filters the air throughout a home. Portable air cleaners can reduce indoor air pollutants, including airborne viruses.

Figure 3.42. High-performance cooling and ventilation systems: portable air filters



High-performance Cooling and Ventilation Systems: 3.2.2.2 Portable Air Filters

Summary		Operational Energy Savings by Climate			
			Low	*Moderate*	*High*
Initial Cost	*Zero Low ▼Moderate High*	Hot and Dry		●	
Embodied Carbon	*Zero Low ▼Moderate High*	Warm and Humid		●	
Operational Energy Savings	Moderate to high	Composite		●	
Market Availability	Moderate	Temperate		●	
Recommended Climates	All climates	Cold		●	

Definition: Small, hand-transportable air filtration systems to help maintain indoor air quality by capturing airborne contaminants.

Consideration: Placement of portable air filter. Type and size of filter. Maintenance of air filters.

Illustration and Example

The exploded view of the portable air filter shows the most common approach used: highly efficient filter to separate out contaminants.

Image Source: https://leannekroll.wordpress.com/2012/10/09/technical-line-drawings/

Source: Author's analysis.

For an air cleaner to effectively remove viruses from the air, it must be able to remove small airborne particles (in size range of 0.1-1 micrometer). Manufacturers report this capability in several ways. In some cases, they may indicate particle removal efficiency for specific particle sizes (for example, "removes 99.9 percent of particles as small as 0.3 micrometer"). Many manufacturers use the clean air delivery rating system to rate air cleaner performance. Others indicate they use high-efficiency particulate air (HEPA) filters. Selecting the right size for the space, positioning, and filter efficiency are key factors in determining its effectiveness. **Figure 3.42 shows the parameters to be considered when incorporating portable air filters.**

3.2.7 Centralized Air Conditioners

Centralized systems are those in which the cooling (chilled water) is generated in a chiller at one base location and distributed to air-handling or fan-coil units throughout the building spaces.

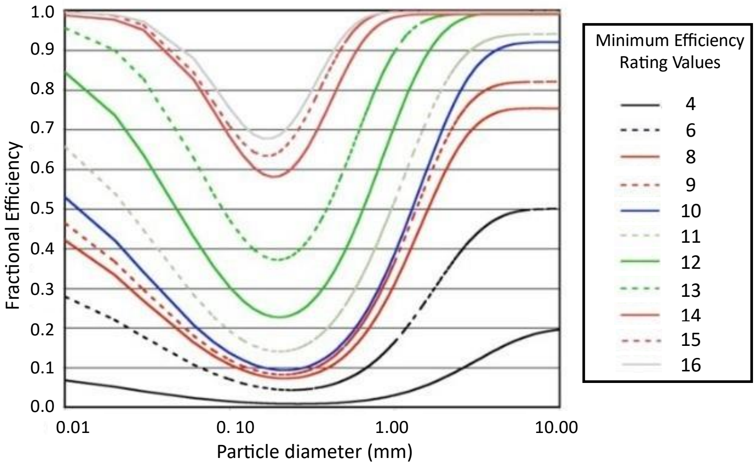
A. Variable Speed Systems

Variable speed system technology refers to the type of compressor in an air conditioner or heat pump. The compressor is the heart of the air-conditioning or heat pump system. It creates the cooling capacity for the system. Variable speed compressors allow a unit to run at virtually any speed between 30 and 100 percent.

B. Passive Filtration Systems

For passive filtration to be effective, it must essentially draw the pathogen, pollutant, or particulate matter through itself. The most popular passive air cleaning method uses a filter to capture the particulate. Various filters depend on the media type, washability, and pleating. Each filter has a MERV rating that determines its ability to capture particles. The clogging of these filters can affect the performance of the HVAC system. They must be cleaned and maintained regularly to avoid breeding bacteria and viruses, a potential hazard to occupant health and IAQ. Figure 3.43 shows the representative curves of particle removal efficiency for various MERVs.

Figure 3.43. Particle removal efficiency for various minimum efficiency rating value levels



Source: Kowalski et al., 2002.

C. Active Filtration Systems

As opposed to passive filtration, active filtration systems include ionization and photocatalytic oxidation technologies. These actively seek out pollutants rather than waiting for them by releasing air purifying agents that create a healthy atmosphere and improve IAQ. The advantage is that the systems cater to airborne particles and surface contamination. At the prefilter level, coarse and fine particulate matter is filtered out, including PM 10 (inhalable coarse particles smaller than 10 micrometers) and PM 2.5 (fine particles typically found in smoke and haze and less than 2.5 micrometers in size). The activated carbon or activated charcoal filter absorbs odors or colored substances from liquids and gases. HEPA filters remove 99.97 percent of contaminants in the air that are of size 0.3 microns. They can effectively capture microorganisms, bacteria, mold, dust mites, and pollen. In addition, the active filtration system can reduce the contamination of SARS-COV-2 in the air, as has been proved by studies conducted in the hospital ward environment (Morris et al., 2022).

D. Air Distribution Systems

An air distribution system includes several components, such as an air-handling unit, ductwork, and associated components for heating, cooling, and ventilating the building. It also caters to IAQ by providing pre-treated fresh air to offset the air-conditioning loads. The key components of air distribution systems are fans, coils, filters, dampers, and ducts. Unlike constant air volume (CAV) systems, which supply a constant airflow at a variable temperature, variable air volume (VAV) systems vary the airflow at a constant temperature. The advantages of VAV over CAV systems include more precise temperature control, reduced compressor wear, lower energy consumption by system fans, less fan noise, and additional passive dehumidification. Air supplied via ducts by a CAV or VAV system falls into two categories:

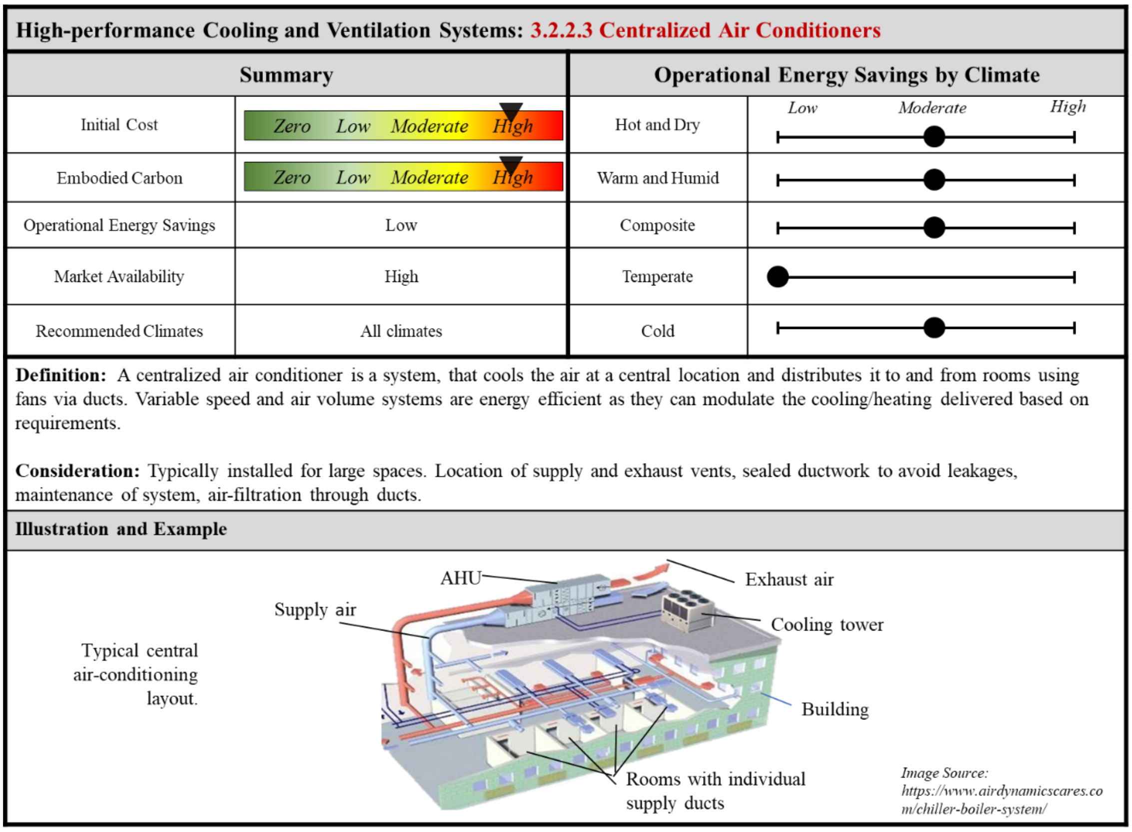
a. Overhead

Traditional methods introduce air into the enclosed space via ductwork placed above a suspended ceiling, as is still used in most buildings. The air enters from the supply duct and returns through air plenums in the ceiling. These systems are considered mixing ventilation systems designed to mix the entire air volume within the enclosed space to maintain the air volume at the same temperature.

b. Underfloor

The empty plenum space under a raised access floor is used to distribute air in underfloor air distribution. Conditioned air is introduced through diffusers at floor level, which rises naturally by thermal buoyancy and is collected by return air grills or plenums at ceiling level. Air currents force pollutants up and away from occupants, thus improving IAQ. Since underfloor air distribution is a displacement ventilation system, air can be supplied at higher temperatures. This, combined with a reduction in fan power consumption, results in energy and cost savings. **Figure 3.44 shows the parameters to consider when installing centralized air conditioners as an active measure to achieve thermal comfort and good IAQ.**

Figure 3.44. High-performance cooling and ventilation systems: centralized air conditioners



High-performance Cooling and Ventilation Systems: 3.2.2.3 Centralized Air Conditioners

Summary		Operational Energy Savings by Climate	
			Low *Moderate* *High*
Initial Cost	*Zero Low Moderate* ▼*High*	Hot and Dry	├──────●────┤
Embodied Carbon	*Zero Low Moderate* ▼*High*	Warm and Humid	├──────●────┤
Operational Energy Savings	Low	Composite	├──────●────┤
Market Availability	High	Temperate	●───────────┤
Recommended Climates	All climates	Cold	├──────●────┤

Definition: A centralized air conditioner is a system, that cools the air at a central location and distributes it to and from rooms using fans via ducts. Variable speed and air volume systems are energy efficient as they can modulate the cooling/heating delivered based on requirements.

Consideration: Typically installed for large spaces. Location of supply and exhaust vents, sealed ductwork to avoid leakages, maintenance of system, air-filtration through ducts.

Illustration and Example

Typical central air-conditioning layout.

Image Source: https://www.airdynamicscares.com/chiller-boiler-system/

Source: Author's analysis.

3.2.8 Low-energy Cooling and Ventilation Systems

This section discusses the low-energy cooling and ventilation strategies used globally and in South Asia. These technologies prioritize the aspect of energy efficiency over other factors. The section includes descriptions of market-available products with details on their initial and operational costs. Further, measures such as air circulation devices that provide opportunities to increase indoor thermal set points are also explained in this section.

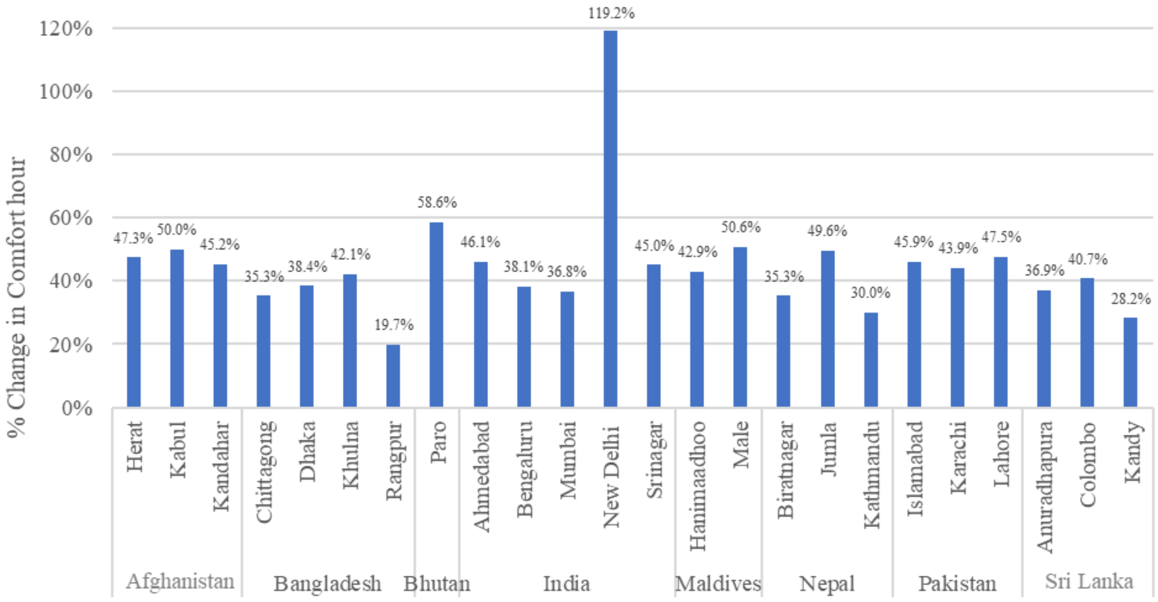
The use of hybrid cooling systems is also explained. The section highlights the applicability of these ventilation and cooling systems in pandemic, pre-pandemic, and post-pandemic scenarios. The following low-energy cooling and ventilation systems are discussed: air-circulation devices, mechanical ventilation systems, and evaporative coolers.

3.2.9 Air Circulation Devices

Air circulation devices, such as ceiling fans, are a reliable solution for reducing reliance on air conditioning in climates where passive solutions alone are insufficient. As they improve the air distribution within a space, they minimize temperature gradients, resulting in consistent temperature conditions throughout the space's volume. A study conducted at an air-conditioned office space in Singapore showed that occupants are more comfortable at 26°C with fans than at 23°C without fans, with no change in perceived productivity (Lipczynska t al., 2012).

Going one step further, personal comfort systems specifically target a space's occupied zones as a supplement to conventional HVAC systems. This provides individual-level, local control to the occupant without altering thermal conditioning at a zone or space level, thereby saving energy and cost (Rawal et al., 2020). Typical air circulation devices include ceiling, pedestal, table, wall-mounted, and tower fans. By improving air distribution, air circulation devices serve as an effective strategy for both cooling/heating-dominated scenarios. Figure 3.45 shows the effect of elevating the airspeed by 0.6 meter/second (m/s) within the residential building space, mimicking the effect of a fan resulting in increased comfort hours for all cities.

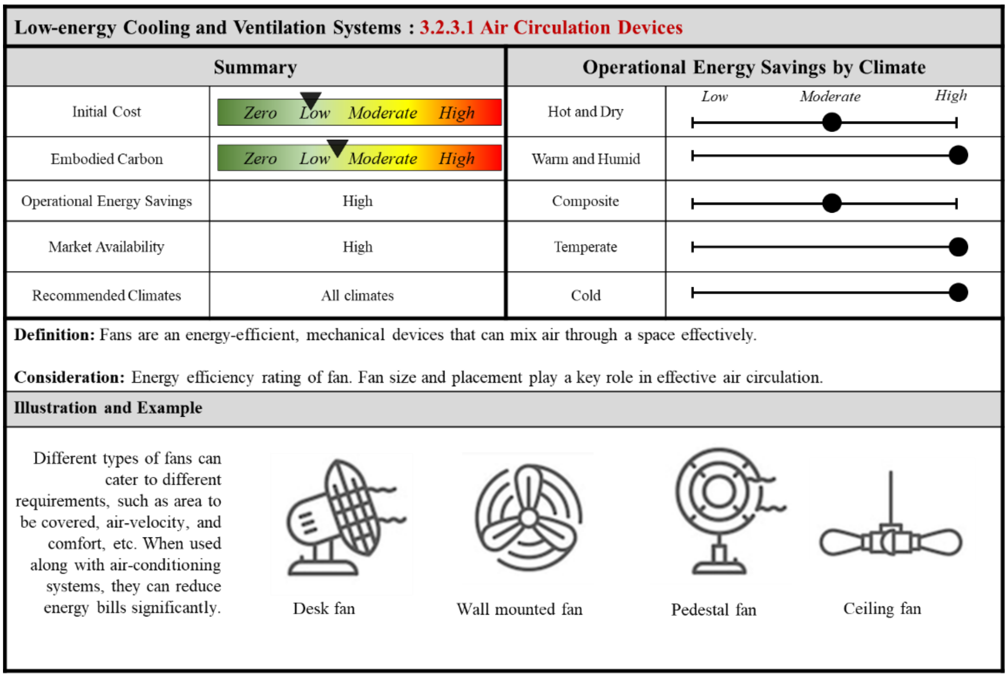
Figure 3.45. Effect of elevated airspeed (0.6 m/s) on comfort hours



Source: Author's analysis.

Figure 3.46 shows the various types of air-circulation devices that can be incorporated to induce air movement at a low initial cost leading to high operational savings.

Figure 3.46. Low-energy cooling and ventilation systems: air circulation devices



Low-energy Cooling and Ventilation Systems : 3.2.3.1 Air Circulation Devices

Summary		Operational Energy Savings by Climate	Low	Moderate	High
Initial Cost	Zero ▼Low Moderate High	Hot and Dry		●	
Embodied Carbon	Zero Low ▼ Moderate High	Warm and Humid			●
Operational Energy Savings	High	Composite		●	
Market Availability	High	Temperate			●
Recommended Climates	All climates	Cold			●

Definition: Fans are an energy-efficient, mechanical devices that can mix air through a space effectively.

Consideration: Energy efficiency rating of fan. Fan size and placement play a key role in effective air circulation.

Illustration and Example

Different types of fans can cater to different requirements, such as area to be covered, air-velocity, and comfort, etc. When used along with air-conditioning systems, they can reduce energy bills significantly.

Source: Author's analysis.

3.2.10 Mechanical Ventilation Systems

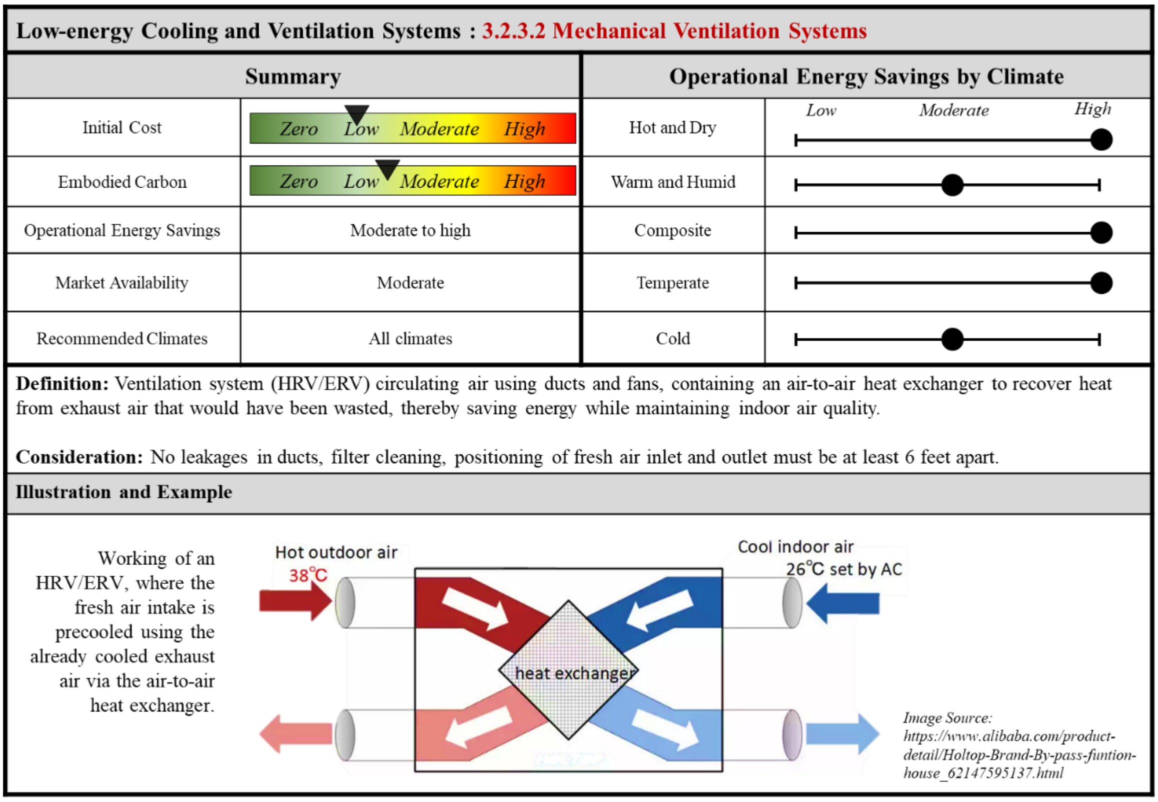
Ventilation, or introduction of outdoor/fresh air into the building by mechanical means such as fans or air-handling units (AHU), is not to be confused with air circulation devices, where no fresh air is introduced. Several factors in a building would lead to the requirement for mechanical ventilation, such as deep floor plans, poor air quality, internal building partitions, and dense urban structures obstructing wind flow. The system can be broadly categorized into four types:

- **Exhaust-only:** The basic principle involves exhausting air from the building, typically using a fan in a central exhaust point connected to ducts throughout the spaces within the building. This creates a low pressure inside, causing fresh air to be pulled through leakages in the building envelope. This kind of system is inexpensive and easy to install;
- **Supply-only:** The building is supplied with fresh/outdoor air, creating a high-pressure building, resulting in air leaking through the cracks in the building envelope and intentional vents, if any. The advantage of supply-only ventilation is that it inherently allows better control of quality of air quality introduced into the space. The air can be filtered as it minimizes the risk of outdoor pollutants and dehumidifies it with dehumidification systems;
- **Balanced:** A balanced ventilation system commonly uses two fans and two duct systems. Although fresh air supply and exhaust vents can be installed in any room, a balanced ventilation system is designed to provide fresh air to spaces where occupants spend most of their time. It also exhausts air from rooms that produce the greatest moisture and pollutants, such as the kitchen, bathrooms, and laundry room. Balanced ventilation systems do not pressurize or depressurize a building when correctly planned and installed. A balanced ventilation system introduces fresh outdoor air into a space at the same rate that stale indoor air is exhausted. As balanced systems directly supply outside air, some designs use a single-point exhaust. This allows for the use of filters to remove dust and

pollen. However, since these systems do not recover moisture or heat/cold from the exhaust air, they contribute to higher heating and cooling costs, unlike heat recovery ventilation/energy recovery ventilation (HRV/ERV); and

- **Flexible:** HRV/ERV are energy-efficient, flexible mechanical ventilation systems. They improve air quality and save energy and costs by recovering thermal energy and moisture from the exhaust air. The exhaust air preheats/precools the incoming fresh air based on climatic requirements. Proper ductwork and installation of a whole building HRV/ERV system can help improve air quality in all spaces without adding high operational HVAC costs. These are especially effective in airtight buildings. HRV/ERV systems can be used in all climates. **Figure 3.47 shows the operating principle of an HRV/ERV and factors that need consideration when incorporating the system into the building**.

Figure 3.47. Low-energy cooling and ventilation systems: mechanical ventilation systems



Low-energy Cooling and Ventilation Systems : 3.2.3.2 Mechanical Ventilation Systems

Summary		**Operational Energy Savings by Climate**	*Low* *Moderate* *High*
Initial Cost	*Zero* ▼*Low* *Moderate* *High*	Hot and Dry	├──────────────●
Embodied Carbon	*Zero* *Low* ▼ *Moderate* *High*	Warm and Humid	├───────●───────┤
Operational Energy Savings	Moderate to high	Composite	├──────────────●
Market Availability	Moderate	Temperate	├──────────────●
Recommended Climates	All climates	Cold	├───────●───────┤

Definition: Ventilation system (HRV/ERV) circulating air using ducts and fans, containing an air-to-air heat exchanger to recover heat from exhaust air that would have been wasted, thereby saving energy while maintaining indoor air quality.

Consideration: No leakages in ducts, filter cleaning, positioning of fresh air inlet and outlet must be at least 6 feet apart.

Illustration and Example

Working of an HRV/ERV, where the fresh air intake is precooled using the already cooled exhaust air via the air-to-air heat exchanger.

Image Source: https://www.alibaba.com/product-detail/Holtop-Brand-By-pass-funtion-house_62147595137.html

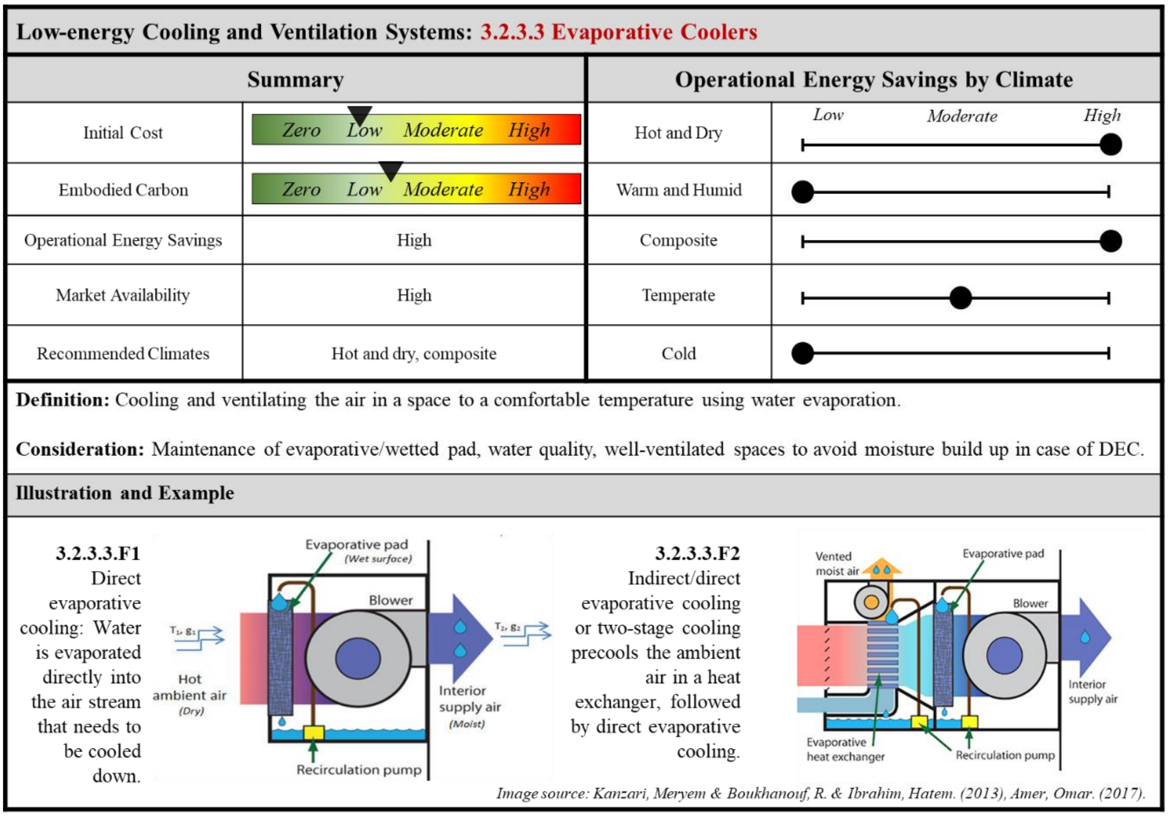
Source: Author's analysis.

3.2.11 Evaporative Coolers

Single-stage or direct evaporative cooling (DEC) (Figure 3.48, 3.2.3.3.F1) is the most effective way to cool a space where high temperatures and low humidity preside for most of the year. The cooling process involves water passing over a wet pad through which air is made to flow, where the heat is transferred from air to water. This results in cool air flowing out, although with a higher water vapor content with a resultant increase in humidity. The wet pad is the prominent factor impacting the effectiveness of the evaporative cooler. The pad's surface area, thickness, and size of perforations affect the overall performance. For example, a CelDek pad with a thickness of 0.4 m is 100 percent efficient up to an air velocity of 0.5 m/s, whereas a pad with a depth of 0.6 m can perform optimally up to an air velocity of 2 m/s.

Two-stage or indirect/direct evaporative cooling (Figure 3.48) can be used for climates with high humidity. In the first stage, the air is cooled via an air-to-air heat exchanger, where no moisture is added to the air, followed by the second stage, direct evaporative cooling. This can lead to a significant drop in moisture content added to the air and a more substantial drop in temperature. The Bihar Museum, Patna, India, used two-stage evaporative cooling in its public spaces, where indoor temperatures are expected to be 30 ± 5 °C during peak summers. Indirect/direct evaporative cooling can also be used with a combination of HVAC systems to precool air to reduce the load on the HVAC system for additional cost savings.

Figure 3.48. Low-energy cooling and ventilation systems: evaporative coolers



Low-energy Cooling and Ventilation Systems: 3.2.3.3 Evaporative Coolers

Summary		Operational Energy Savings by Climate	Low — Moderate — High
Initial Cost	Zero ▼Low Moderate High	Hot and Dry	———————●
Embodied Carbon	Zero Low ▼ Moderate High	Warm and Humid	●———————
Operational Energy Savings	High	Composite	———————●
Market Availability	High	Temperate	———●———
Recommended Climates	Hot and dry, composite	Cold	●———————

Definition: Cooling and ventilating the air in a space to a comfortable temperature using water evaporation.

Consideration: Maintenance of evaporative/wetted pad, water quality, well-ventilated spaces to avoid moisture build up in case of DEC.

Illustration and Example

3.2.3.3.F1 Direct evaporative cooling: Water is evaporated directly into the air stream that needs to be cooled down.

3.2.3.3.F2 Indirect/direct evaporative cooling or two-stage cooling precools the ambient air in a heat exchanger, followed by direct evaporative cooling.

Image source: Kanzari, Meryem & Boukhanouf, R. & Ibrahim, Hatem. (2013), Amer, Omar. (2017).

Source: Author's analysis.

3.3 Information Technology in Buildings

Energy demand management using information technology in buildings can lead to considerable energy savings, with solutions ranging from sophisticated advanced building energy management systems to simple programmable thermostats. These solutions enhance energy efficiency by optimizing temperature control based on real-time data and occupant preferences. Sensors and smart thermostats enable automatic regulation, resulting in significant energy savings and cost reduction. IT systems also enable remote monitoring and control, streamlining operations and facilitating proactive maintenance.

The simulations carried out for this report to assess the benefits of incorporating simple IT-based solutions such as scheduling of systems, demand-based ventilation systems, and variable capacity control indicated energy savings from 16% to 25% (with an average of 19% savings) for various combinations of these solutions. However, these estimates vary significantly depending on climate types, assumptions for operational hours, internal load, and occupant densities. For example, saving estimates due to operation modes or schedule algorithms vary based on the inherent assumption of inefficiencies due to manual operation hours. However, better control design and strategies could improve a building's energy performance.

This section offers simple IT-based solutions that are market-ready, affordable, cost-effective, and easy to operate; these solutions can be tangibly beneficial in addressing occupant well-being in the case of a significant reduction in outdoor air quality. Some simple and effective measures include: scheduling of systems, operation modes, demand-based ventilation systems, variable capacity control, and energy and IAQ information systems.

3.3.1 Scheduling of Cooling and Ventilation Systems

Ventilation-based cooling can significantly reduce, delay, or eliminate air conditioner operation, resulting in energy savings and peak demand reduction. These savings stem from the use of the fan to draw in outside air instead of the compressor, plus a fan to maintain indoor comfort. The amount of energy saved is a function of nighttime temperatures, airflow rate, effectiveness of thermal mass, amount of precooling, cooling below the thermostat setpoint, and thermal perception of the occupant.

HVAC scheduling can be broadly categorized into basic, conventional, and advanced. Basic scheduling is the time period when the HVAC system is switched on and off with fixed temperature set points. In conventional scheduling, precooling or preheating reduces peak demand while manipulating the temperature set point throughout the operational hours. Advanced scheduling combines basic and conventional scheduling for greater energy-saving potential (Haniff et al., 2013).

3.3.2 Operation Modes of Cooling and Ventilation Systems

All air-conditioning systems have three basic operational modes:

a) Cooling/ Heating Mode: This mode relies on the HVAC system to cool or heat the space and consumes the maximum amount of energy, as it requires the compressor to function as long as the set-point temperature of the conditioned space is not met;

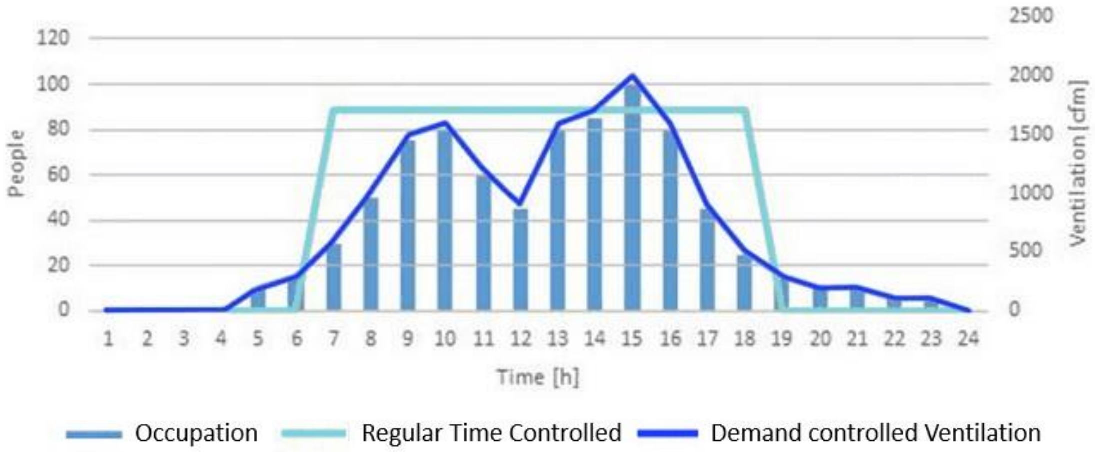
b) Dehumidification Mode: Dehumidification is a primary requirement for humid climates, as moisture in the air supplied to a space can add unnecessary latent load to the system. High moisture levels in the air can also cause discomfort to the occupants in the space; and

c) Fan Mode: This mode works when the set point of the conditioned space is met and can also be set when only ventilation or air circulation is required. It utilizes the system's fan only, resulting in higher energy savings.

3.3.3 Demand-based Ventilation Systems

Demand-based or demand-controlled ventilation (DCV) systems control the ventilation rate in a space to maintain certain air quality within the building. DCV is created by adding an IAQ control loop to an existing building management system (BMS), where the IAQ sensors continuously assess air quality. A DCV system is most effective in high-occupant-density spaces, where the occupancy levels constantly vary. These systems optimize fresh air supply, offsetting heating and cooling loads. Figure 3.49 shows the benefit of using a DCV instead of fixed-volume ventilation.

Figure 3.49. Comparison between conventional system and demand-controlled ventilation systems



Source: Strombom, 2019.

3.3.4 Variable Capacity Control Systems

Variable capacity control has a major advantage over constant capacity control: it is more efficient due to part load operation. It is more economical regarding operational costs for cases where space cooling/heating requirements are met at part load itself. Various studies have shown that chillers typically run at part load 99 percent of the time (AHRI, 2020). Capacity control can be employed within or outside the compressor, but the basic function is limited to varying the refrigerant flow rate in the refrigeration cycle. This easily offsets the higher initial costs of the system.

3.3.5 Energy and IAQ Control Systems

Accurate and timely information is integral to running an energy-efficient building. Information can bridge the gap between wasteful space cooling/heating and efficient HVAC systems. The information systems gather information about external weather conditions, occupancy, IAQ (measuring the concentration levels of carbon dioxide, particulate matter, volatile organic compounds, and so on), temperature and relative humidity of different zones/spaces, and performance of the HVAC system via strategically placed sensors, and then evaluates the energy consumption of the building and IAQ. The performance of the HVAC system is then optimized, which can either be automated or carried out by an operator.

3.4 Market Availability and Incremental Costs

This section provides an overview of the market availability and incremental costs of building-level cooling and ventilation measures. As the report focuses on the diverse regions of South Asia, quantitative and qualitative approaches are used to determine market availability and incremental costs.

Table 3.3 summarizes costs and market availability for all active and passive measures discussed in the report. Column 1 shows the incremental costs as a percentage of the building construction cost for each measure. Column 2 shows the incremental cost for each measure in South Asia based on stakeholder survey responses and is categorized as low, moderate, and high. Column 3 shows the payback period for each measure. The last column shows the market availability, which describes the efforts required to procure and implement the solution and is categorized as low, moderate, and high.

Table 3.3. Market availability and incremental costs of active and passive measures

Measures	Incremental cost	Payback period	Market availability
Active measures			
Air Circulation Devices	0–1%	< 1 year	High
Mechanical Ventilation	0–2%		Moderate
Evaporative Coolers	1–3%	1–2 years	High
High-efficiency Air conditioner	5–10%	> 3 years	
Passive measures			
Building Orientation	0%	< 1 year	High
Natural Ventilation	0%		
Shading	0–1%		
Cool Roof	0–1%		
Roofing Technologies	1–5%	2–3 years	Moderate
Fenestration Systems	1–5%		
Thermal Mass	3–5%		
Walling Technologies			

Source: Author's analysis.

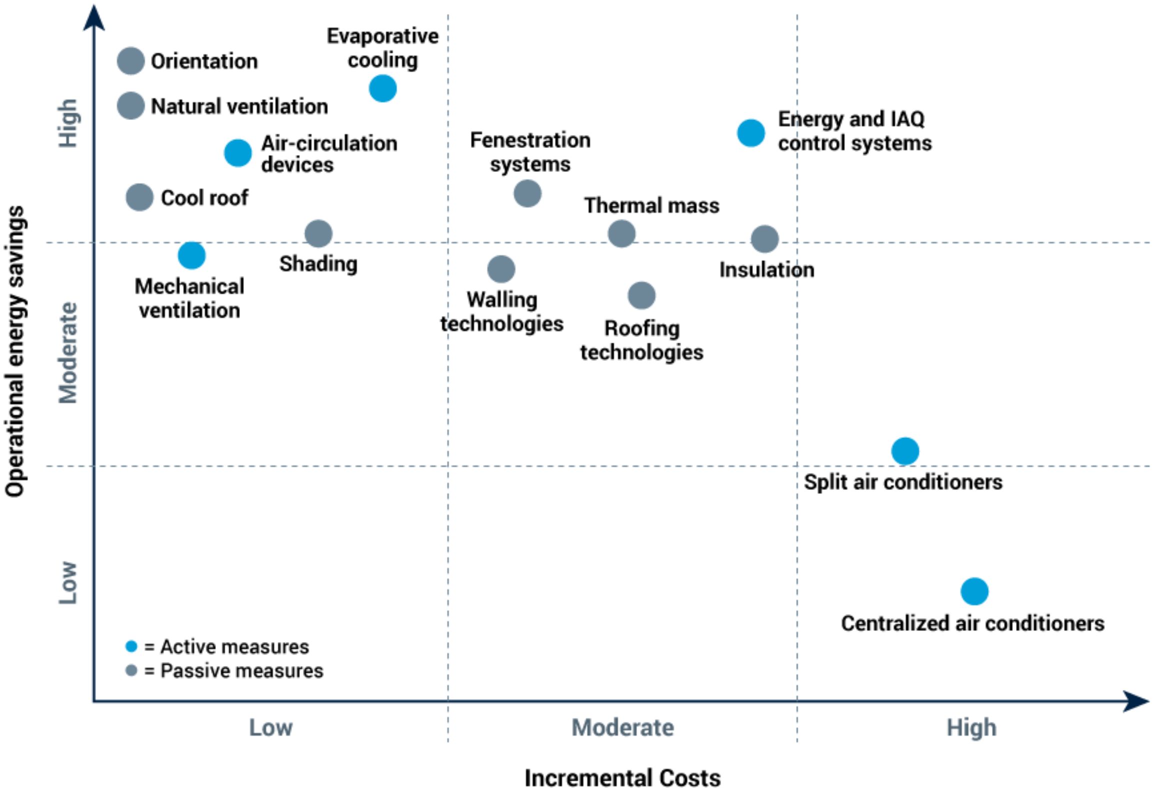
The incremental cost for each measure was derived for a residential building complex in Delhi using the city's schedule of rates. The schedule of rates provides government-approved rates for various building materials. Wherever the rates were not specified, commercial quotes from local vendors were used to estimate the cost of the measures.

A qualitative estimate of the expected incremental cost of building-level cooling and ventilation measures and their market availability was derived from a structured discussion with various stakeholders in South Asia (see Annex 8: Survey with Stakeholders), where stakeholders validated the ranges presented in 3.3 for other regions in South Asia. The stakeholders also indicated that efficient envelope material was available, but challenges may emerge during procurement and identification of qualified local installers for the small buildings. Availability and cost are significantly lower for large quantities where vendors from other countries, such as India, are willing to provide the materials and installers for the project.

Payback period estimates were derived from energy use results from simulations for the residential building model for Delhi (see Annex 7: Simulation Details). Table 3.3 categorizes the payback period as less than one year, one to three years, and more than three years. While specific measures are effective in one city, they may or may not have a quick payback period in other regions of South Asia.

While assessing market availability, it is essential to understand the efforts required to implement measures and incremental costs of the building-level ventilation and cooling solutions. Figure 3.50 shows the incremental cost and operational energy savings of all the measures discussed in the report.

Figure 3.50. Incremental costs and operational energy savings for measures



Source: Author's analysis.

Figure 3.50 shows that passive measures have a low incremental cost and lead to higher operational savings. For example, shading as a passive measure has a low incremental cost but provides higher operational savings, while split air conditioners exhibit a high incremental cost but lead to moderate operational energy savings. Adoption of measures with low incremental costs and high operational savings is highly desirable as opposed to measures with high incremental costs and low operational energy savings.

Although many passive measures have a low incremental cost and result in higher operational savings, the primary challenges include educating the designers, engaging the policymakers, and creating awareness among end users of the benefits. Regarding market availability, the challenge lies in developing a trained workforce that can integrate envelope solutions in construction processes while generating a business case for the vendors.

Chapter 3 References

AHRI. 2020. Performance Rating of Water-chilling and Heat Pump Water-heating Packages Using the Vapor Compression Cycle. AHRI 551/591 (SI/2020): Performance Rating of Water-chilling and Heat Pump Water-heating Packages Using the Vapor Compression Cycle (with Addendum 1) | AHRI (ahrinet.org)

Airtecnics. 2021. What Are HEPA Filters and How Do They Work? https://www.airtecnics.com/news/what-are-hepa-filters-and-how-do-they-work.

ASHRAE. ANSI/ASHRAE Standard 52.2-2017. 2017. Method of Testing General Ventilation Air-Cleaning Devices for Removal Efficiency by Particle Size. Atlanta: ASHRAE. https://www.ashrae.org/File%20Library/Technical%20Resources/COVID-19/52_2_2017_COVID-19_20200401.pdf.

Bhatia, A. 2012. HVAC – Overview of Underfloor Air-conditioning Systems, 217.

Bureau of Energy Efficiency. 2016. Design Guidelines for Energy-Efficient Multi-Storey Buildings: Warm-Humid Climates. New Delhi: Ministry of Power, Government of India,194. https://www.beepindia.org/wp-content/uploads/2013/12/Design-Guidelines-for-Energy-Efficient-Multi-Storey-Residential-Buildings-Warm-Humid-Climate_5.pdf.

Bureau of Energy Efficiency. 2016. Guidelines for Energy-Efficient and Thermally Comfortable Public Buildings in Karnataka. New Delhi: Ministry of Power, Government of India. https://www.beepindia.org/wp-content/uploads/2013/12/Guidelines-for-Energy-Efficient-and-Thermally-Comfortable-Public-Buildings-in-Karnataka_9.pdf.

Bureau of Energy Efficiency. 2017. Energy Conservation Building Code. New Delhi: Ministry of Power, Government of India. https://beeindia.gov.in/sites/default/files/BEE_ECBC%202017.pdf.

Bureau of Energy Efficiency. 2018. Eco-Niwas Samhita 2018. New Delhi: Ministry of Power, Government of India. https://www.beeindia.gov.in/sites/default/files/ECBC_BOOK_Web.pdf.

Bureau of Energy Efficiency. 2021. External Movable Shading Systems (EMSyS) Manual. New Delhi: Ministry of Power, Government of India. https://beeindia.gov.in/sites/default/files/EMSYS%20Manual_Web.pdf.

CARBSE. 2020. Low Energy Cooling And Ventilation For Indian Residences (LECaVIR) – (2017–2020). https://carbse.org/lecavir-3/.

Climate Smart Buildings: Training Program on Innovative Construction Technologies & Thermal Comfort in Affordable Housing Handbook. 2022. https:// Reports, Articles, and Guides - CARBSE

Doctor-Pingel, M., V.Vardhan, S. Manu, G. Brager and R. Rawal. 2019. A study of indoor thermal parameters for naturally ventilated occupied buildings in the warm-humid climate of southern India. Building and Environment, 151:1–14. DOI: 10.1016/j.buildenv.2019.01.026.

Dovjak, M., M. Kosir, L. Pajek and N. Iglic. 2017. Environmental impact of thermal insulations: How do natural insulation products differ from synthetic ones? IOP Conference Series: Earth and Environmental Science, 92:012009. DOI: 10.1088/1755-1315/92/1/012009.

EULEB. 2006. EULEB – European High Quality Low Energy Buildings. https://www.new-learn.info/packages/euleb/index.html.

Haniff, M.F., H. Selamat, R. Yusof, S. Buyamin and F.S. 2013. Ismail. Review of HVAC scheduling techniques for buildings towards energy-efficient and cost-effective operations. *Renewable and Sustainable Energy Reviews*, 27:94–103. DOI: 10.1016/j.rser.2013.06.041.

Kowalski, W.J. and W. P. Bahnfleth. 2002. MERV filter models for aerobiological applications. Air Media, 13–17.

Lipczynska, A., S. Schiavon and L. T. 2012. Graham. Thermal comfort and self-reported productivity in an office with ceiling fans in the tropics. *Building and Environment*, 135:202–212. DOI: 10.1016/j.buildenv.2018.03.013.

Material W, Assemblies W. 2020(June). Thermal Performance of Walling Material and Wall Technology.

Morris, A.C., K. Sharrocks, R.Bousfield, L. Kermack, M. Maes, E. Higginson, S. Forrest, J. Pereira-Dias, C. Cormie, T. Old, S. Brooks, I. Hamed, A. Koenig, A. Turner, P. White, R. A. Floto, G. Dougan, E. Gkrania-Klotsas, T. Gouliouris, S. Baker and V. Navapurkar. 2022. The removal of airborne severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) and other microbial bioaerosols by air filtration on coronavirus disease 2019 (COVID-19) surge units. *Clinical Infectious Diseases*, 75(1):e97-e101. DOI: 10.1093/cid/ciab933.

Rawal, R., M. Schweiker, O. B. Kazanci, V. Vardhan, Q. Jin and L. Duanmu. 2020. Personal comfort systems: A review on comfort, energy, and economics. *Energy and Buildings*, 214:109858. DOI: 10.1016/j.enbuild.2020.109858.

Rawal, R., Y. Shukla, A. Shah and G. Gowri. 2020. Thermal Performance of Walling Material and Wall Technology, Part-2. New Delhi/Ahmedabad: Shakti Sustainable Energy Foundation/CRDF. https://shaktifoundation.in/wp-content/uploads/2020/08/Thermal-performance-of-Walling-Material-and-Wall-Technology.pdf.

Roulet, C-A. 2015. Measuring Thermal Characteristics of Building Insulation Materials. New Delhi: Ministry of Power, Government of India. DOI: 10.13140/RG.2.2.31730.50881.

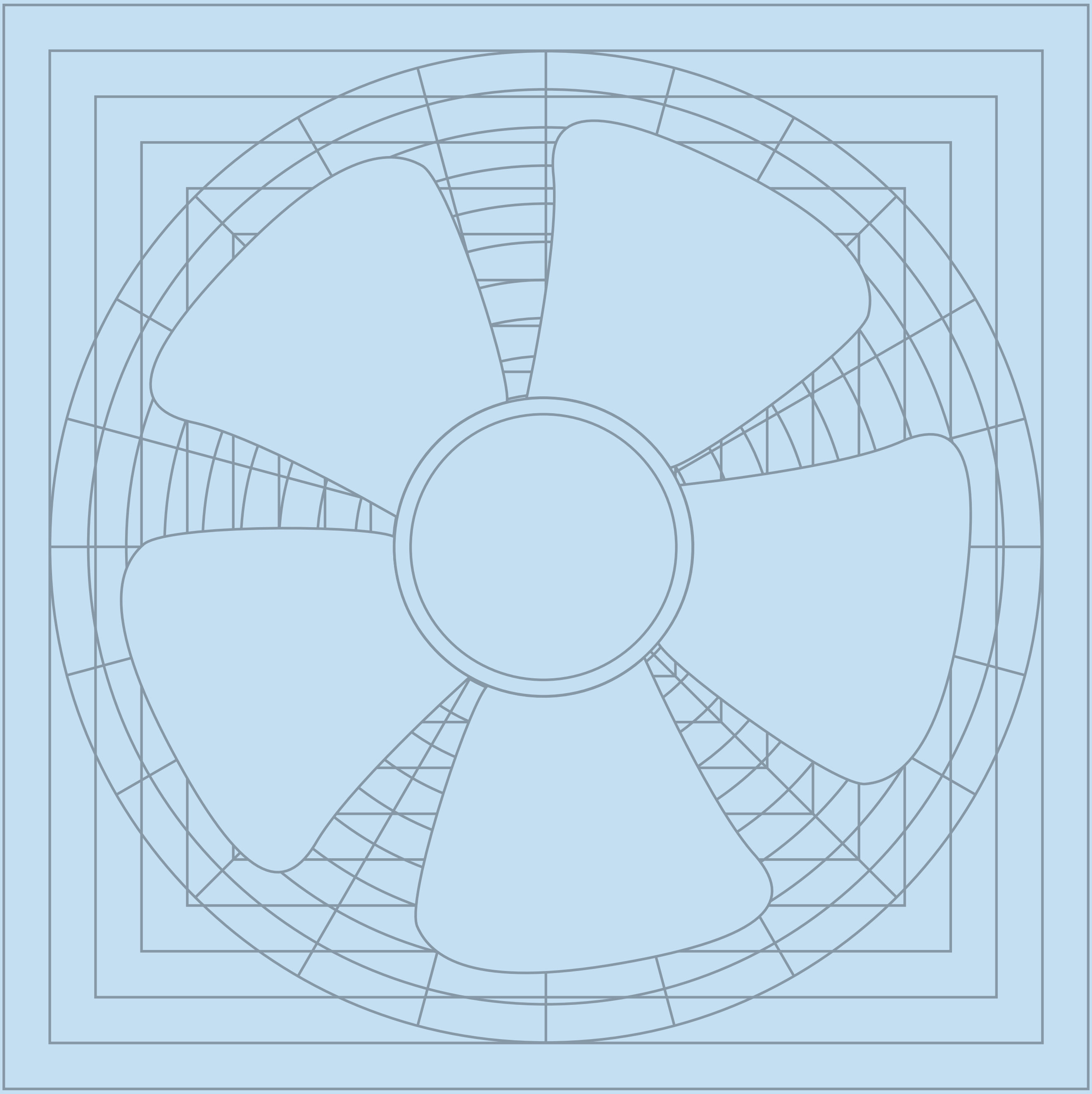
Strombom, L. 2019. Why Do We Measure CO_2 in HVAC Applications? Vaisala. https://www.vaisala.com/en/blog/2020-07/why-do-we-measure-co2-hvac-applications.

U.S. Department of Energy. Home Cooling. https://www.energy.gov/energysaver/heat-and-cool/home-cooling.

Unnikrishnan, A.R. VLT of different glasses. In: *Glasses Vod*, ed. Saint Gobain: Saint Gobain.

WGI. 2016. What Is a VRF Air Conditioning System? R410A Heat pump/multi split air conditioner/VRF system - Coowor.com

Recommendations



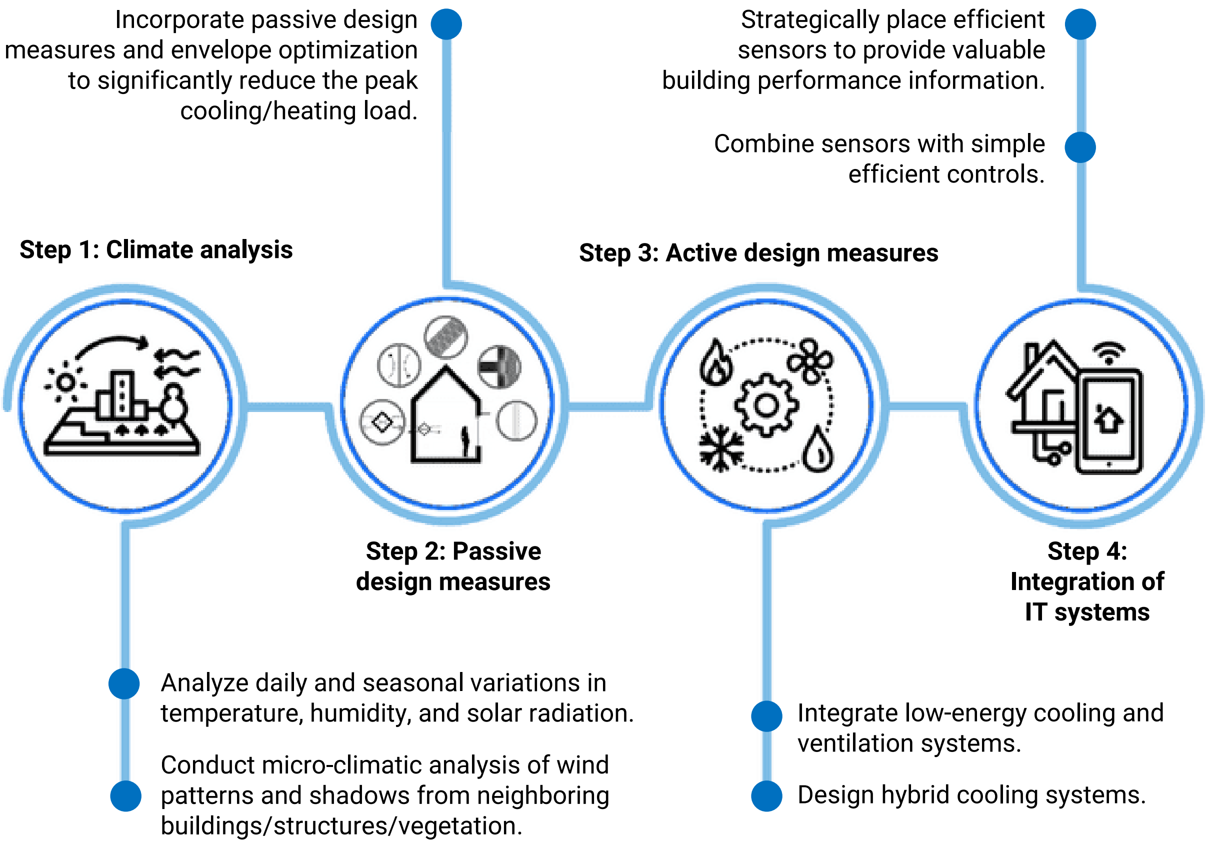
4 Recommendations

Concerted efforts are required to prepare South Asia for higher temperatures and extreme heat. Hence, it is essential to design, construct, and operate buildings that mitigate and adapt to the changing climate while sufficiently satisfying the cooling and ventilation needs of the region's growing population. This chapter builds on the information presented in previous chapters to make recommendations to improve building-level cooling and ventilation in South Asia. Case studies with examples of specific building-level interventions and estimated operational energy savings are in Annex 1.

Figure 4.1 shows the recommended process for selecting suitable design interventions for a new building in South Asia.

1. Conduct a climate and site analysis to identify the climate zone and location constraints.
2. Along with the climate zone, it is essential to determine the natural ventilation potential, wind direction and speed, temperature, and humidity variations, surrounding buildings, outdoor pollution, and neighborhood activities. This information helps assess the feasibility of recommended measures for a specific site.
3. Once the feasibility is determined, suitable active and passive measures should be selected based on the costs and applicability. As explained earlier, passive measures are always recommended before implementing active measures.

Figure 4.1. Steps to identify suitable design interventions for new buildings and retrofitting existing buildings in South Asia



Step 1: Climate analysis

Analyze daily and seasonal variations in temperature, humidity, and solar radiation.

Conduct micro-climatic analysis of wind patterns and shadows from neighboring buildings/structures/vegetation.

Step 2: Passive design measures

Incorporate passive design measures and envelope optimization to significantly reduce the peak cooling/heating load.

Step 3: Active design measures

Integrate low-energy cooling and ventilation systems.

Design hybrid cooling systems.

Step 4: Integration of IT systems

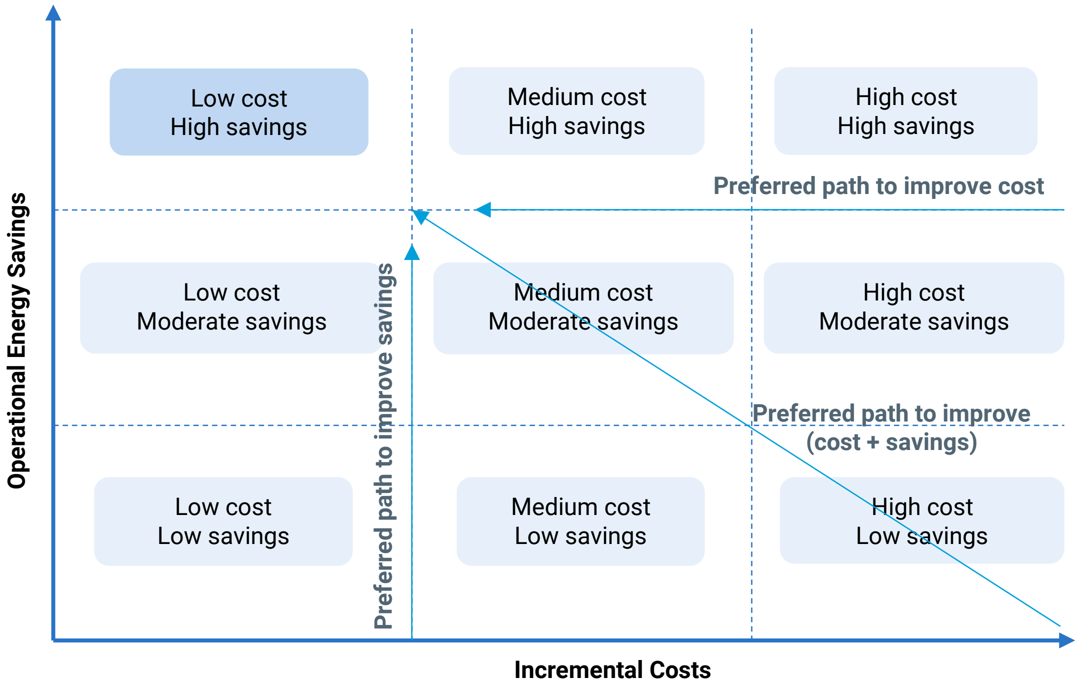
Strategically place efficient sensors to provide valuable building performance information.

Combine sensors with simple efficient controls.

Source: Rawal et al., 2017; Jain et al., 2021; and Philip et al., 2021.

Figure 4.2 shows how to evaluate options when assessing active and passive design measures to prioritize measures with low costs and high operational savings.

Figure 4.2. Recommendations to assess selected design interventions based on costs and operational energy savings



4.1 Key Recommendations for All Buildings in South Asia

This section identifies interventions suitable for all building types in South Asia. It provides essential information on various pragmatic measures that could be implemented to effectively cater to the cooling and ventilation needs of the buildings in South Asia while minimizing energy use. It is important to note that the energy benefits of these measures are estimated by retaining other building elements in a BAU scenario. Due to interdependency of the measures, cumulative savings of all measures combined may not be the same as the sum of individual measures.

1. Design building orientation and layout to minimize solar exposure.

Orientation and layout depend on several factors, such as the site's dimensions, building location concerning the adjacent roads, floor space index, and local regulations. Many factors are beyond the individual designer or practitioner's control. However, **it is recommended that a quick solar exposure analysis be conducted at the early design stage to determine the most suitable orientation and layout of a building**. The cost of running such an analysis is negligible, if any, but could reduce the energy needs of a building by 5-20 percent, depending on the building's location.

1.1 Orient the building to minimize solar exposure: The building should be oriented to reduce heat gain or loss through the envelope. In South Asia's cooling context, it is ideal to have a maximum wall and window area with a north orientation if possible.

1.2 Design the layout of the building to minimize solar exposure: As in orientation, the shape of the building should be selected to reduce solar gains, especially through walls and windows.

1.3 Use mutual shading of blocks or surrounding landscape: Mutual shading is a function of latitude (sun angle), the building's height, location, distance from other buildings, and surrounding trees or neighborhood buildings. Buildings to the north of the planned building provide minimal shading while those in the south provide shading during specific months.

1.4 Select an appropriate fenestration area and orientation: Selection of the fenestration area and orientation requires multiple considerations, such as daylight, prevailing wind direction (for natural ventilation), and heat gain through windows. It is recommended that a climate analysis and solar and wind exposure analysis, including solar radiation and wind patterns, be conducted to determine a suitable fenestration area and orientation (see Recommendation 2 for the aspect of natural ventilation). In South Asia's cooling context, fenestration located in the south gets maximum solar radiation, but with the south's higher sun angle, using an overhang is an effective strategy to cut down direct solar radiation. Fenestrations in the east and west get direct solar radiation from low sun angles and need a well-designed shading device to cut down direct solar radiation.

2. Maximize a building's natural ventilation potential.

Natural ventilation uses thermal buoyancy and prevalent wind movement to create air movement between indoor and outdoor spaces. It is a zero to low-cost design strategy to provide fresh air inside the building and obtain free cooling when outdoor conditions are comfortable. Further, it is considered one of the most effective measures, along with mechanical ventilation, to maintain indoor air quality. Natural ventilation systems can be designed to provide ventilation to a space level inside a building through windows or openings or the entire building through stairwells, elevators, atriums, and shafts. If incorporated early in the design process and used with automation, natural ventilation strategies do not necessarily add costs to the building's construction. Natural ventilation system design requires careful consideration of the wind direction throughout the year, site location (such as adjacent buildings), orientation, size, and operable area of ventilation openings, building dimensions, and weather analysis. It is recommended that a detailed analysis of the natural ventilation potential of the building be conducted at the early design stage**.** The natural ventilation strategy analysis should also consider local wind movements, sound levels in the adjacent area and if needed, mitigation approaches for noise pollution, outdoor pollution levels to estimate the benefits accurately. Climatic analyses of South Asian cities shows a high potential for utilizing natural ventilation as a design strategy (15-40 percent depending on the city), especially if the buildings are expected to operate during night hours (such as residential buildings).

3. Integrate external shading devices.

Fixed or portable external shading devices are an effective measure to significantly reduce heat gains through fenestrations, such as windows. Vernacular buildings in South Asia have often used shading as an essential strategy for building design as opposed to modern buildings The design of shading devices, including dimensions and shading technique, should be appropriate for the location and orientation of the building to maximize the benefits of shade. Well-designed shading devices can reduce the energy needs of a building by 5-6 percent, depending on the building's location and total area designed for fenestration. The cost of adding fixed shading devices in the building at the design stage is low (< 1 percent).

4. Minimize unwanted air leakage through the building envelope.

Envelope air leakage occurs when air exchange takes place through cracks and openings in the building envelope resulting in unplanned heat gains and losses from the building. It is essential to eliminate or minimize these unintentional air movements by sealing all joints, penetrations, and accidental openings using gaskets, caulking, and weather-stripping, especially at the windows and doors. A tight envelope, or envelope leakage sealing, often reduces the energy needs of a building by 5-10 percent in South Asia. Awareness about air sealing, basic training of workforce, and quality assurance processes must be built into the construction process to seal the building envelope properly. It is recommended that envelope sealing be integrated into building construction processes in South Asia. Air sealing is usually executed during construction at a low cost.

While the above passive design measures require minimal additional costs, their application and benefits depend on the building's location and site constraints. Passive design measures, recommended for all buildings in South Asia, translate into higher upfront costs, but with careful consideration, can result in significant long-term energy savings and lower operating costs.

5. Select efficient materials for building envelopes.

A building envelope is typically considered efficient when it allows low heat transfer rates between indoor and outdoor spaces. Using efficient building envelope materials can significantly reduce heat gains in the buildings, create comfortable conditions inside, and often, substantially reduce the energy needs of the building. The cost of materials to achieve an efficient envelope is a moderate (1–5 percent) increase in building costs depending on material selection. For example, hollow brick walls add marginal resistance to heat transfer (U-value of 1.83 W/m²K for 230 mm hollow brick with plaster) compared to traditional brick construction (U-value of 2.41 W/m²K for 230 mm brick with plaster) at minimal incremental costs. However, insulation materials provide significant resistance to heat transfer (U-value of 0.5–0.6 W/m²K for 230 mm brick with 50 mm of extruded polystyrene) at moderate incremental costs. Using more efficient building envelope materials and technologies could reduce the energy needs of a building by 10–30 percent, depending on the location of the building in South Asia.

6. Use high thermal mass in buildings.

A building's higher thermal mass reduces indoor temperature fluctuations compared to outdoor temperatures. Many vernacular buildings in South Asia have effectively used this strategy by incorporating very thick walls and roofs in the building design. Due to the pressure to maximize floor area and minimize costs of envelope materials, modern buildings do not use thick walls and roofs. However, in modern buildings, the benefits of high thermal mass can be achieved by utilizing specific building materials in envelopes that absorb and store heat. While designing the envelope, it is essential to place the materials, such as insulation, closer to outside in the wall or roof assembly to achieve the most effective use of higher thermal mass. A high thermal mass strategy, supplemented by nighttime ventilation, can reduce the energy needs of a building by 5–10 percent in hot and dry climates. It is thus recommended that higher thermal mass materials be used in buildings in South Asia. The thermal mass strategy can complement the benefits of an efficient envelope while reducing the project's overall cost. A high thermal mass can be achieved at a moderate (3–5 percent) increase in building costs. If the structural elements are used for thermal mass, the cost of thermal mass can be slightly reduced.

Success stories in South Asia highlight the importance of individual leadership of architects or building stakeholders, such as developers or owners, who consciously aim to integrate passive measures into the building design. An integrated design process is collaborative, inclusive of all stakeholders, architects, contractors, and consultants who make coherent design decisions that increase the selected interventions' effectiveness. An integrated design process from the beginning provides an opportunity to achieve higher building performance with minimal costs. For example, shading design is best combined with proper building and fenestration orientation. The cost of such an effort is minimal but requires a significant change in the approach to working collaboratively with other stakeholders. It is essential to highlight the importance of an integrated design process to achieve the desired thermal comfort and indoor air quality inside buildings.

7. Design and operate buildings as per adaptive thermal comfort models.

Many modern buildings in South Asia with mechanical systems are designed to achieve an indoor temperature of 24 degrees Celsius. However, in the last few decades, significant research has been conducted to better understand the thermal comfort preferences of building occupants in South Asia, with findings supporting the application of the adaptive thermal comfort model in designing and operating buildings in the region. The model recognizes that the thermal comfort preferences of occupants vary based on contextual and historical factors and on the cooling opportunities available, such as operable windows or pedestal fans. It also recognizes that occupants actively interact with their environment, which leads to behavioral, physiological, and psychological thermal adaptation.

The adaptive model is based on international standards, including ASHRAE Standard 55-2020, that defines acceptable thermal environmental conditions for human occupancy. Recent studies in tropical countries have also extended the applicability of the adaptive thermal comfort model in mixed-mode buildings. Mixed mode is a hybrid approach to space conditioning that combines natural ventilation and mechanical systems to achieve desired environmental conditions inside the building. In a zoned mixed-mode building design, different residential spaces, such as a bedroom or a living room, have different ventilation strategies based on the space's needs. In a change-over mixed-mode design, the building switches between natural ventilation and mechanical systems based on the prevalent environmental conditions manually (opening a window) or automatically (through a central system). Adaptive thermal comfort studies show that occupants in South Asia are comfortable at a higher temperature (>27 degrees Celsius in summer when the outdoor temperature is higher than 35) than traditionally assumed by building designers. The adaptive comfort model challenges the existing approach to design that aims to maintain a lower constant temperature (22 or 24) inside buildings. The application of the model often leads to more responsive environmental control, enhanced levels of occupant thermal comfort, and reduced energy use in buildings. Studies have also demonstrated that each degree Celsius increase in the cooling setpoint could lead to a 6–10 percent reduction in energy use in buildings located in a hot climate, and even higher energy savings when combined with additional measures, such as the use of air circulation devices. While applying the adaptive thermal comfort model, it is essential to maintain temperatures below the upper limit as defined in the model to avoid heat stress inside the buildings.

8. Increase the use of air circulation devices to minimize temperature gradients within spaces.

Air circulation devices, such as ceiling or pedestal fans, effectively improve occupants' thermal comfort by elevating air speed in the space. However, modern buildings have significantly reduced the use of air circulation devices for aesthetic reasons while also decreasing ceiling heights. Thermal comfort standards, including ASHRAE Standard 55-2020, also recognize the benefits of elevated air speeds and allow an increase of operative temperature limits by 1.2–2.2 degrees Celsius when the average air speed is 0.6-1.2 m/s inside occupant-controlled naturally ventilated spaces. It is recommended that the use of air circulation devices in buildings in South Asia be increased. Air circulation devices, if properly designed, can also improve air distribution within a space, minimizing the temperature gradients and resulting in consistent temperature conditions throughout the space. They can also reduce the energy needs of a building by 5–10 percent by allowing the adjustment of the temperature set points. The cost of adding air circulation devices in buildings is low, especially in the context of ample availability in the market.

9. Use mechanical ventilation, especially during cooler night hours.

Mechanical ventilation uses energy to operate mechanical systems. However, it is a cost-effective approach, especially in buildings with more stringent ventilation rate requirements or when the building constraints (such as deep floor plan buildings or locations) do not allow for air movement through natural ventilation. It brings in a higher quantity of air (or ventilation rates) inside the buildings and can be designed to filter outdoor air to maintain IAQ. Mechanical ventilation systems should be increased in buildings in South Asia. Mechanical ventilation also offers the opportunity of higher utilization of outdoor air, especially during night hours. Mechanical ventilation systems using ducts and fans can be added to building with low costs as they are readily available.

10. Use low-energy cooling systems and apply an adaptive comfort thermal model.

With rising temperatures, mechanical systems are increasingly required across South Asia to maintain safe and comfortable building conditions, especially during extreme weather events. In such cases, it is vital to utilize low-energy cooling and ventilation systems, wherever feasible, instead of traditional vapor compression systems that consume significant energy to deliver comfort. Application of the adaptive thermal comfort model allows maintenance of wider temperature conditions and opportunities to install alternative (such as evaporative or dry) cooling systems inside the buildings. For example, a combination of evaporative coolers and vapor compression-based cooling systems provides comfortable conditions with minimum energy use in hot and dry climates. The application of the adaptive thermal comfort model along with hybrid cooling systems could lead to 20–25 percent energy savings in various cities of South Asia. The incremental cost of incorporating hybrid technologies is moderate based on the type of technology. For example, the cost of evaporative cooling systems is moderate, but the cost of air filters, such as HEPA, is high.

Along with incorporating passive and active measures in buildings, operating them efficiently after construction is also essential. It is also vital to integrate flexibility in buildings so that operating modes can be changed during extreme weather or pandemic events.

11. Use simple IT to enhance building operations.

The pandemic has highlighted the need to design our buildings with the necessary flexibility to adapt to different scenarios. Simple information technology solutions such as carbon dioxide, temperature, and humidity sensors can help quickly modify ventilation and cooling processes according to real-time needs. The cost of incorporating information technology in buildings varies considerably based on the type of technology. For residences, simple automated systems may suffice. For commercial buildings, sophisticated integrated technologies, such as centralized systems with built-in algorithms based on specific building requirements, could lead to moderate capital cost (5-7 percent) increases while producing energy savings of 16-25 percent. With the increasing availability of low-cost sensors, the feasibility of integrating information technology in buildings will significantly increase over the coming years and become affordable for a larger share of the population.

12. Building occupants should be educated in proper day/night building operations to minimize thermal extremes.

Maximizing free natural cooling, either by window operation or mechanical systems, can result in significant energy savings and improved indoor air quality, as well as reduced peak temperatures for buildings without air conditioning. Depending on the location of the building, natural ventilation can be used for about 15-40 percent of the day. Cooling buildings using lower outdoor temperatures at night enhances occupant thermal comfort through higher radiant and convective heat exchange with cool surfaces. Efficient night cooling requires access to the thermal mass of the building structure. Window or attic fans can enhance air exchange in open-plan buildings at low energy consumption rates.

4.2 Recommendations for Residential and Commercial Buildings

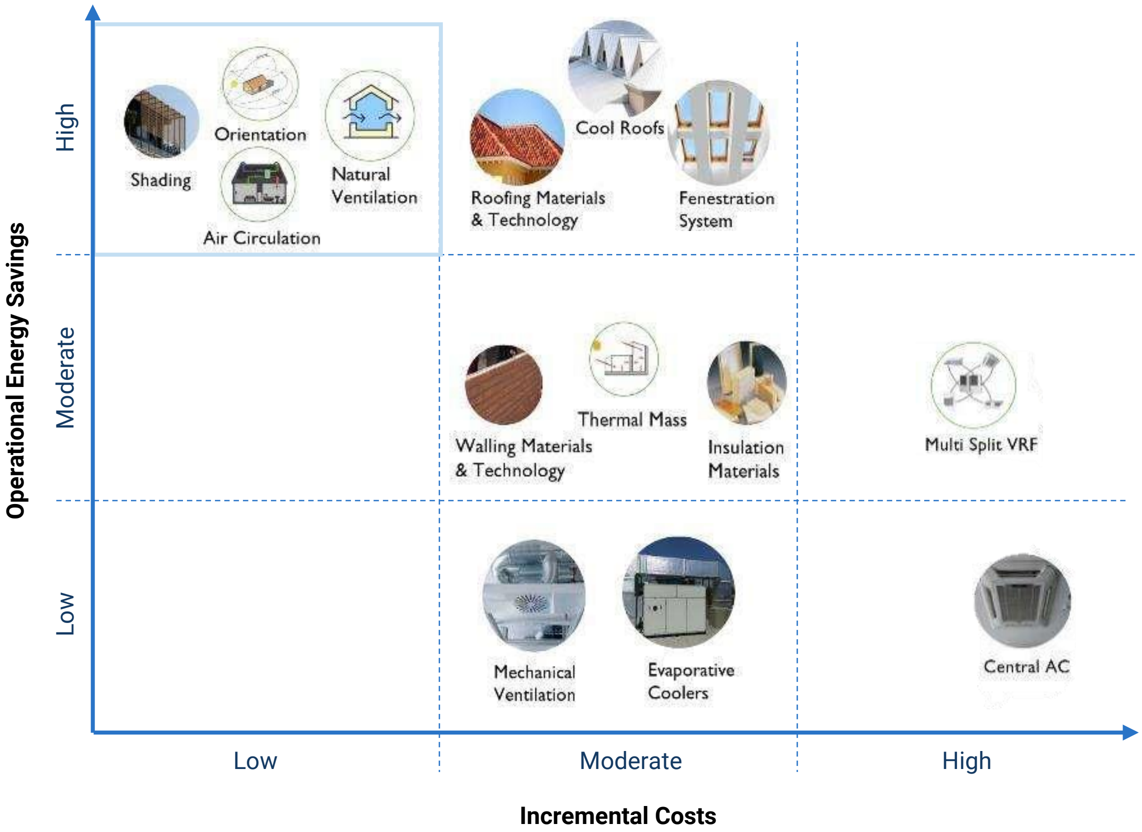
4.2.1 Recommendations for Residential Buildings

For the context of this report, a residential building is defined as a building in which most of its floor area is used for dwelling. Among many residential building typologies, the primary focus of the report is to propose recommendations for affordable residential buildings and apartment complexes. Apartment complexes, where multiple families stay in dwellings in an apartment block, are becoming prevalent in cities of South Asia.

Figure 4.3 demonstrates the key recommended interventions for residential buildings in South Asia based on the cost involved in implementing the measures.

As seen in Figure 4.3, the recommended measures are categorized by their incremental costs (low, moderate, and high) and their operational energy savings (low, medium, and high). The combination of measures with high operational energy savings and low incremental costs will provide comfortable indoor temperatures even during peak periods of heat stress.

Figure 4.3. Recommended measures for residential buildings in South Asia



Source: Author's analysis.

Currently, most affordable residential buildings and apartment complexes in South Asia are designed to operate in natural or mixed-mode ventilation modes. It is recognized that due to more frequent extreme weather events, residential buildings may need to use some form of mechanical systems, traditional, or low-energy cooling systems, to achieve comfortable conditions, especially during extreme climatic conditions.

1. To be more resilient to climate extremes, future residential buildings in South Asia should use zoned and change-over mixed-mode building design.

The mixed-mode design approach significantly reduces the energy consumption of a residential building, leads to higher occupant satisfaction, and provides the ability to adapt operation modes during a pandemic or extreme climatic conditions. The size (or capacity), design, and operation hours of mechanical systems can be significantly reduced by incorporating passive measures in the residential building design.

2. Orient buildings with maximum fenestration facing north.

Envelope loads primarily drive cooling load in residences. Hence, it is recommended that the maximum number of walls and fenestrations be oriented towards the north and south (with shading devices on the south fenestrations). It is also important to focus on the direction of the residential apartments' living rooms and bedrooms, primarily used during the daytime and nighttime. It is best to utilize self-shading of adjacent apartment blocks, use the tunnel effect between them to generate wind movement, and make use of adjacent vegetation for shading as feasible.

3. Design a floor plan layout that facilitates stack ventilation.

For urban residencies, a natural ventilation opening area design should be considered based only on stack ventilation, as wind effects may not be reliable due to the compact nature of urban settlements. External noise and privacy concerns are expected in urban residential complexes. In this case, they can be alleviated by a design that provides well-designed openings to replace windows, or building-level natural ventilation systems (shafts or an atrium). Whenever natural ventilation is not feasible, mechanical ventilation, at a space or building level, can be an important alternative to utilize free cooling in residential buildings.

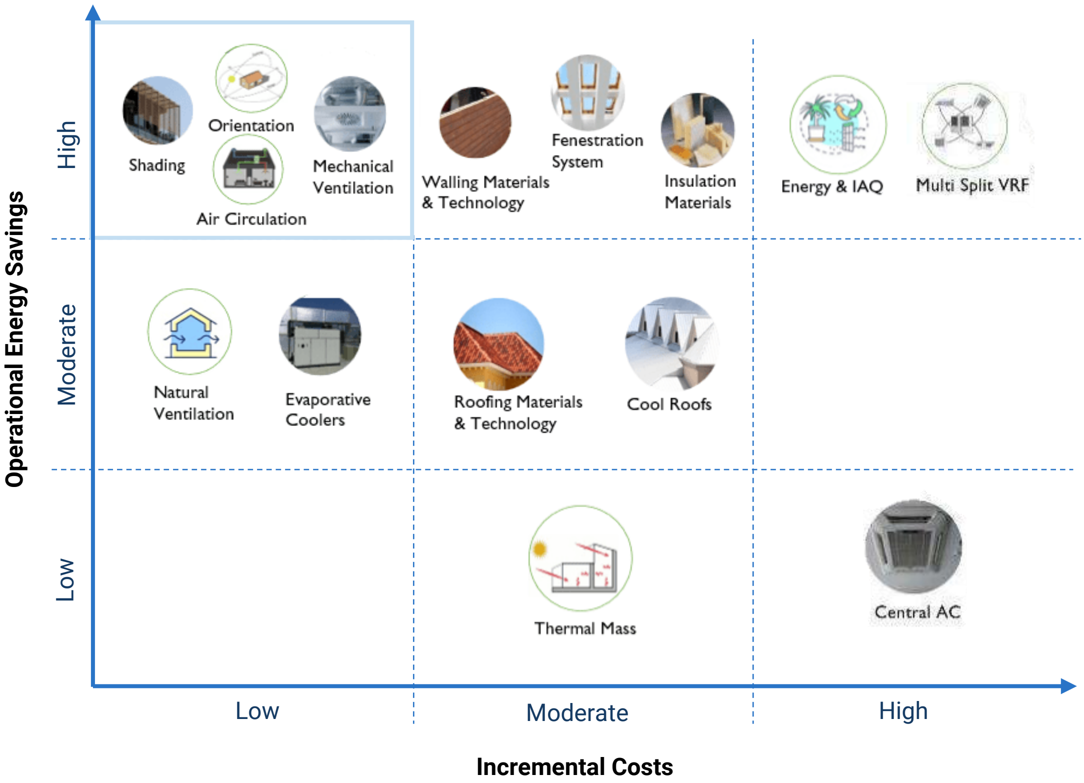
A narrow floor plan layout is recommended in residential buildings, wherever feasible, to design more effective natural ventilation systems. Two-sided cross-ventilation is much more effective than single-sided ventilation. Further, within residential buildings, the bedrooms should be mainly assessed for natural ventilation as night-time occupancy aligns with the high potential of free cooling.

Most of South Asia’s standards, literature, and guidelines focus on specifying window openings to achieve the desired ventilation rates inside residential buildings. However, ventilation rates should be calculated using equations or design charts to verify if the ventilation rates meet the ASHRAE 62.2-2019 standard specifications. If natural ventilation cannot provide the necessary ventilation rates, designing mechanical ventilation systems to meet the specifications would be advisable. In the case of a pandemic, it is recommended that the ventilation risk assessment tool provided by the Representatives of European Heating and Ventilation Associations (REHVA) be used to determine suitable ventilation rates for the space.

4.2.2 Recommendations for Commercial Buildings

For the context of this report, a commercial building is defined as a building that contains small to medium-sized office spaces on all floors, with small-sized air-conditioning and ventilation systems. **Error! Reference source not found.**4 presents the recommended measures for commercial buildings with incremental costs and operational energy savings.

Figure 4.4. Recommended measures for commercial buildings in South Asia



Source: Author's analysis.

1. Design and use high-efficiency or hybrid cooling systems.

High-efficiency mechanical systems or hybrid cooling systems, when feasible, are recommended for commercial buildings in South Asia. Well-designed and highly efficient cooling systems can help achieve comfortable building conditions with minimum energy use.

2. Maintain IAQ in the buildings using localized and centralized air filters.

It is recommended IAQ of commercial buildings located in South Asia be verified and maintained as per WHO guidelines. A combination of localized or centralized filters and ventilation rates will need to be used to achieve the desired IAQ inside the buildings. Calculation of ventilation rates, primarily mechanical ventilation, is recommended to meet the ASHRAE 62.1-2019 standard specifications. Like residential buildings, in the case of a pandemic, it is recommended that the ventilation risk assessment tool provided by REHVA be used to determine suitable ventilation rates for the space. The ventilation system design should also allow free cooling through mechanical systems when outside conditions are favorable.

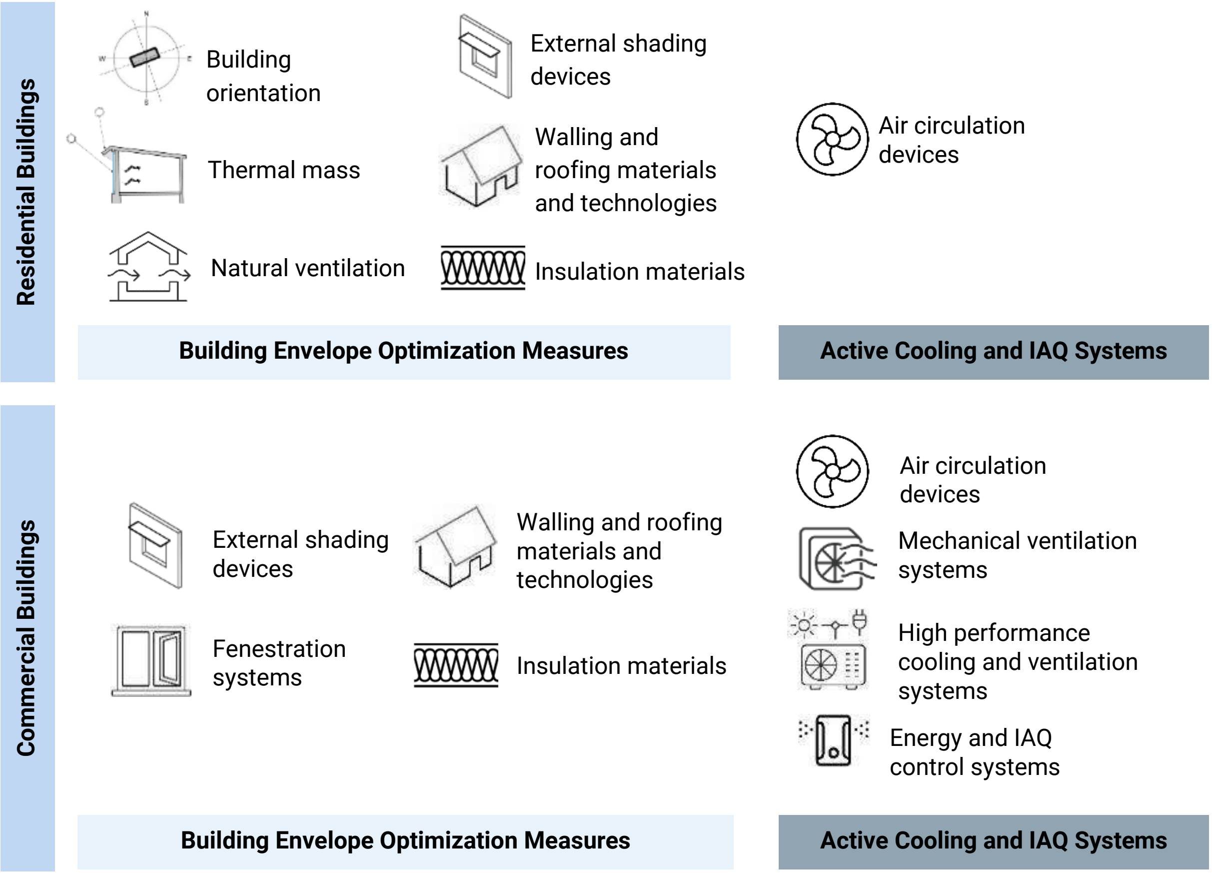
3. Use and maintain low-energy cooling and ventilation systems.

Hybrid cooling systems, where multiple complementary technologies are used in tandem, are recommended for commercial buildings located in South Asia. Well-designed hybrid cooling systems can help achieve comfortable conditions inside the buildings with minimum possible energy use. Further, the combination of technologies in hybrid systems should be changed based on the climatic locations. These systems require building controls developed explicitly for them. For example, a building in a warm and humid climate would require a different combination of technologies and controls in hybrid cooling systems than in a hot, dry, or temperate climate. Proper operation of such systems requires careful building commissioning and training of the building management staff.

4. Use simple IT for building operations.

For commercial office spaces with centralized air-conditioning systems, it is important to have building management systems, even if they contain only a few sensors and controllers that can modulate the building operations. This technology allows the building to monitor and adapt operation modes, especially during extreme climatic conditions or pandemic scenarios. Figure 4.5 shows how recommended measures vary for residential and commercial buildings.

Figure 4.5 Measures with largest impacts based on building type



4.3 Policy Recommendations

The following policy recommendations aim to further mainstream low-cost and energy-efficient building-level ventilation and cooling systems in South Asia:

1. Better document existing buildings: A review of case studies across South Asia demonstrates significant gaps in the detailed documentation of buildings, especially those for low-income families. The information in academic and non-academic literature is sparse. The documentation needs to be strengthened in collaboration with designers and professionals to highlight critical ventilation and cooling features and design decisions made during the design process. Documentation will help designers and owners make key decisions to prepare for extreme heat and learn from existing success stories and best practices.

2. Deploy demonstration buildings: The review of case studies also highlighted the fact that suitable technologies are currently applied in outstanding facilities that meet specific guidelines or achieve certain points in rating systems. However, additional case studies are required to demonstrate the benefits of building-level ventilation and cooling systems and climate-responsive design in affordable housing and apartment complexes. These demonstration buildings would illustrate the feasibility with specific examples that can be replicated in other buildings. It is important to include actual operating data of energy use and associated costs.

3. Increase stakeholder engagement: While awareness of building-level ventilation and cooling has increased in the last few years, especially during the pandemic, significant efforts are needed to better engage stakeholders in implementing these technologies. There is also an urgent need to engage policymakers and practitioners to foster adoption of existing ventilation and cooling technologies. Design charettes to support future-ready demonstration buildings for climate extremes, as well as focused training on implementation, will significantly help expand the application of ventilation and cooling technologies available in the region.

4. Expand training and awareness-raising campaigns for occupants: The lack of awareness among occupants is an important area requiring significant capacity-building in the region. Information on what people can do during extreme events and generally to enhance thermal comfort within their buildings plays a vital role in reducing overall energy consumption.

5. Incentivize low-carbon cooling and ventilation solutions: Governments can provide financial incentives such as tax credits, grants, subsidies, and low-interest loans to incentivize the use of innovative low-carbon solutions in South Asia. By doing so, governments can increase the adoption of low-carbon solutions and help to reduce emissions in the region.

6. Upgrade building codes to reflect newer cooling and ventilation technologies: The application of building-level ventilation and cooling solutions is currently limited to a few exemplary buildings where consultants and designers are aware of international practices, standards, and benefits of these practices. However, many facilities located in South Asia, especially in the residential or small commercial building sectors, do not professionally engage building design experts. Building codes need to be updated to reflect newer technologies, along with proper enforcement of these codes, to scale up building-level ventilation and cooling solutions in these sectors.

7. Utilize integrated design processes: One of the key benefits of an integrated design process is that it can ensure that energy efficiency and environmental performance are considered from the earliest stages of the building design process. By involving all relevant stakeholders from the outset, the design team can consider various factors that may impact the building's thermal comfort and energy performance, such as site orientation, building envelope design, and mechanical systems. The integrated design process would ensure that the selected interventions are complementary. For example, combining higher thermal mass, adequate window openings, and a proper night cooling schedule increases the effectiveness of natural ventilation in residential buildings.

Chapter 4 References

Bureau of Energy Efficiency. 2016. Case Study: “Green” Affordable Housing: Smart Ghar III, Rajkot. New Delhi: Ministry of Power, Government of India. https://www.gkspl.in/publication/case-study-smart-ghar-iii-rajkot/.

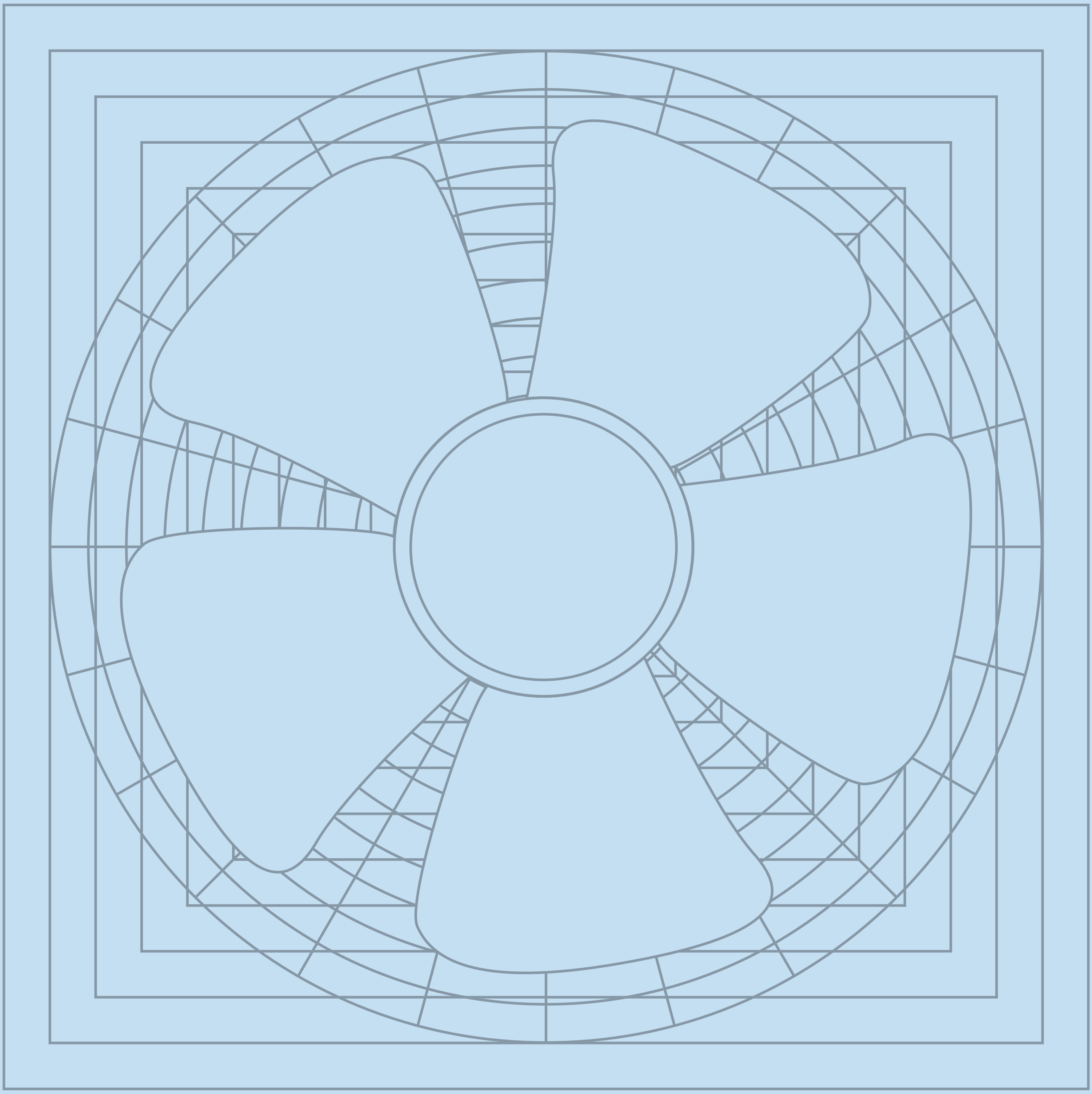
Chetia, S., S. Maithel, P. Jaboyedoff, A.Lall, P. Bhanware and A. Gupta. 2020. A Case Study on Design of Thermally Comfortable Affordable Housing in Composite Climate: Simulation Results & Monitored Performance. Energise 2020 Energy Innovation for a Sustainable Economy Paper Proceedings,91–97. https://aeee.in/wp-content/uploads/2020/07/Energise-2020-Paper-Proceedings.pdf.

Jain, M., A. Agrawal, J. Chopra, D. Gami, U. Shah, A. Mishra, A. Parakh, Uma P. and R. Trivedi. 2021 Multi Family Housing for Savvy Infrastructures Pvt Ltd: Final Design Report. https://solardecathlonindia.in/wp-content/uploads/2021/05/1_D4_MFY_0.0.0.pdf.

Philip, A., A. Santiago, H. Modi, I. Shaji, M. Bhargav, N. Khatri, G.V.S. Raghavendra Rao, S. S. Shanbhag, Snowy S. and S. Goyal. 2021. Final Design Report, Office Building: KillBill 4.0. https://solardecathlonindia.in/wp-content/uploads/2021/05/1_D4_OFF_KillBill4.pdf.

Rawal, R., S. Manu and A. Shah. 2017. Net Zero Energy Building: A Living Laboratory, CEPT University, Ahmedabad.: https://carbse.org/wp-content/uploads/2019/06/NZEB-Report.pdf.

Annexes



Annexes

Annex 1: Case Studies

Case studies discussed in the report have been compiled in this section for the reader's benefit. Measures incorporated into these buildings and their estimated operational energy savings are also presented.

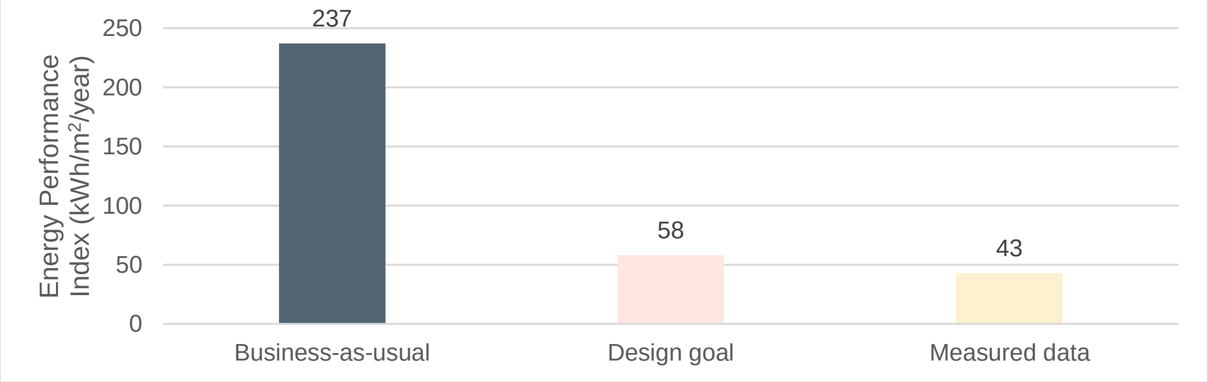
1. Net Zero Energy Building at CARBSE, CEPT University, Ahmedabad, India

Net zero energy building, CEPT University, Ahmedabad (source: nzeb.in).

Building information

The net zero energy building (NZEB) constructed within the CEPT University campus demonstrates that a net zero design can be propagated in the region with proper design and execution of market-ready interventions. During the design phase, an integrated design process was adopted to identify and incorporate suitable active and passive measures in the building. The NZEB has a site area of 386 m^2 and a built-up area of 800 m^2. The building has been operational since March 2015.

Figure A1.1. Energy performance index of the net zero building



Source: nzeb.in

Location and Climate

The building is located in Ahmedabad, India (23.03 °N and 72.58 °E). The city falls under India's hot and dry climate zone, with maximum temperatures reaching 45°C in summer and dropping to a minimum of 15°C in the winter.

Passive Measures

Building orientation and massing: The building is designed with a 3:1 aspect ratio (length-to-width ratio, length of the building parallel to the east-west axis) to minimize incident solar radiation and heat gains from the envelope. No windows are provided on the east and west façade to reduce direct solar radiation at lower sun angles. Most windows are located on the north façade of the building (that has minimum incident solar radiation).

External shading devices: Overhangs are provided on the south windows to reduce unwanted solar heat gain inside the building. Overhangs also shade east- and west-facing glass doors.

Natural ventilation: The building has adopted a mixed-mode ventilation strategy in which the occupants can open the windows when conditions are favorable. The building has a slanted high ceiling to maximize the stack ventilation effect. The window location and area have been designed with simulation tools, such as computational fluid dynamics, to maximize the benefits of natural ventilation inside the building.

Walling materials and technology: Walls have been constructed with U-value 0.42 W/m^{2}K (outermost layer of 0.05 m XPS insulation has been sandwiched between 0.11 m thick exposed brick and 0.23 m thick cement plastered brick masonry wall). Thermal bridging around windows and other critical structural areas has been minimized using construction details.

Roofing material and technology: The building uses an in-situ RCC roof with 32 percent fly ash content. The roof also has 0.045 m rigid polyurethane foam (PUF) insulation with a U-value of 0.38 W/m^{2}K to minimize conductive heat gains from the roof. White roof paint, highly reflective with a solar reflective index of 103, has been applied as the last layer on the roof.

Fenestration systems: Based on extensive simulation models, the building's WWR has been optimized to 20 percent. The building has installed an insulated DGU with Low-E glass and unplasticized polyvinyl chloride (uPVC) frame to reduce unwanted heat gains through the windows. DGU has to be selected to achieve VLT of 39 percent (to maximize daylighting benefits), SHGC of 0.29, and U value of 1.7 W/m^{2}K.

Active Measures

High-performance air-conditioning systems: The building has been designed to operate with primary (radiant) and secondary (VRF) cooling systems to maximize energy savings. The primary system continuously maintains indoor conditions through radiant cooling throughout the year. The secondary system, a high-efficiency VRF, operates only during peak cooling periods to cater to latent loads during humid seasons. The building has a high-efficiency VRF system with an efficiency (COP) of 6.1–3.8 at different part load conditions from 25 percent to 100 percent, respectively.

Air circulation devices: Pedestal fans are provided to occupants with adjustable direction and fan speed to achieve a personalized environment (for air velocity).

Mechanical ventilation systems: Exhaust fans have been strategically located on the first and second floors to provide fan-assisted ventilation inside the building. A dedicated outdoor air system with a heat recovery wheel has been installed in the basement conference rooms to provide clean and conditioned air.

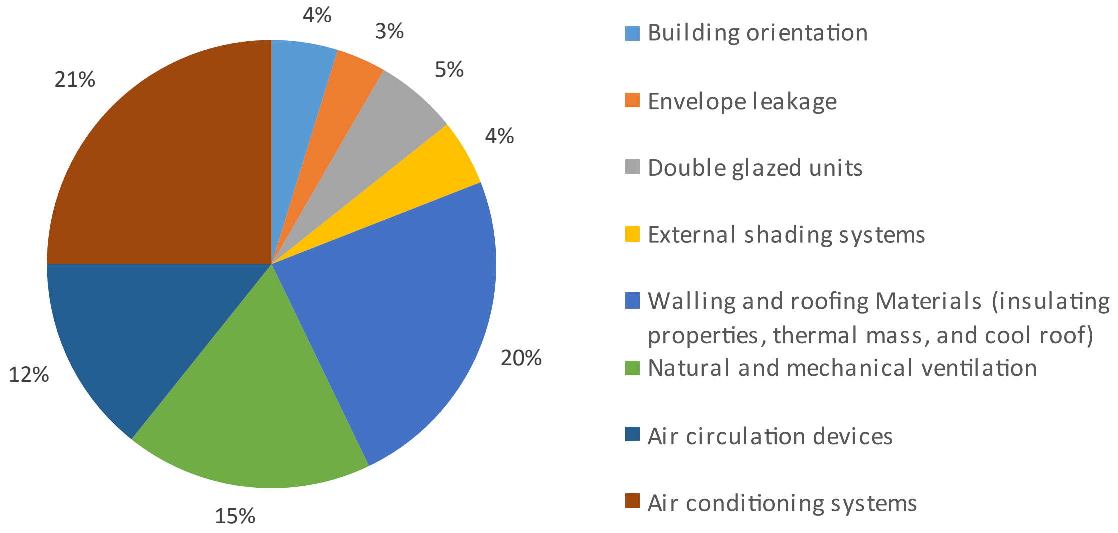
Energy and IAQ control systems: Temperature, humidity, carbon dioxide, and particulate matter (PM 2.5 and 10) sensors are installed to control and monitor the indoor environment with the help of a BMS. The building is operated to maintain indoor conditions per the region's adaptive thermal comfort models. BMS modulates the ventilation rates of the building based on occupancy using the demand control ventilation strategy.

Other strategies in the building include roof-integrated solar photovoltaic (SPV) panels (of 30-kilowatt kW) peak) to achieve net zero energy. The SPV panel structure has also incorporated a 0.45 m ventilated air cavity to increase photovoltaic panel efficiency and reduce heat gain impact.

Energy performance and indoor conditions

The NZEB has been operating with an EPI value of 42.5 kWh/m^2/year while maintaining indoor air temperature between 25-28°C and 30-70 percent relative humidity. Post-occupancy thermal comfort survey indicates that more than 90 percent of the occupants find the indoor environment comfortable. Monitored building energy consumption is 86 percent lower than BAU buildings in the university. Figure A1.2 shows the estimated operational energy savings of various passive and active measures in the building. The energy impacts have been estimated using simulation models developed for the building.

Figure A1.2. Estimated operational energy savings for the building



Source: Author's analysis.

2. RNA Multi-purpose Office/Residence, Pelawatte, Sri Lanka

RNA multi-purpose office/residence (source: nzeb.in)

Building Information

The multi-purpose RNA office/residence building was redeveloped from a residential building. The ground floor is a residential unit, while the first floor was developed into an office unit. It has a site area of 470 m^2 and a built-up area of 312 m^2 and has been operational since 2014.

Location and Climate

Pelawatte, Sri Lanka (6.89° N, 79.92° E) has a tropical climate; the maximum average temperature is 31°C, and the minimum average is 25°C throughout the year. During monsoons, the relative humidity floats between 80 to 85 percent throughout the rest of the year.

Passive Measures

Natural ventilation: The lower floor or multi-use space is naturally ventilated. A gable roof with extended eaves and a steep angle helps to cool the interior spaces by facilitating natural ventilation through the stack effect.

Walling materials and technology: It incorporates stabilized soil blocks, which consist of 70 percent clay as the primary element for new walls constructed, making it cost-effective for building construction and life-cycle cost.

Fenestration systems: The coated single-glazed units minimize heat gain, with perforated blinds controlling glare and radiation without compromising visual comfort and views.

Active Measures

High-performance air-conditioning systems: The building has installed high-efficiency split air-conditioners on the first floor.

Air circulation devices: Ceiling and wall-mounted fans are provided on both building levels.

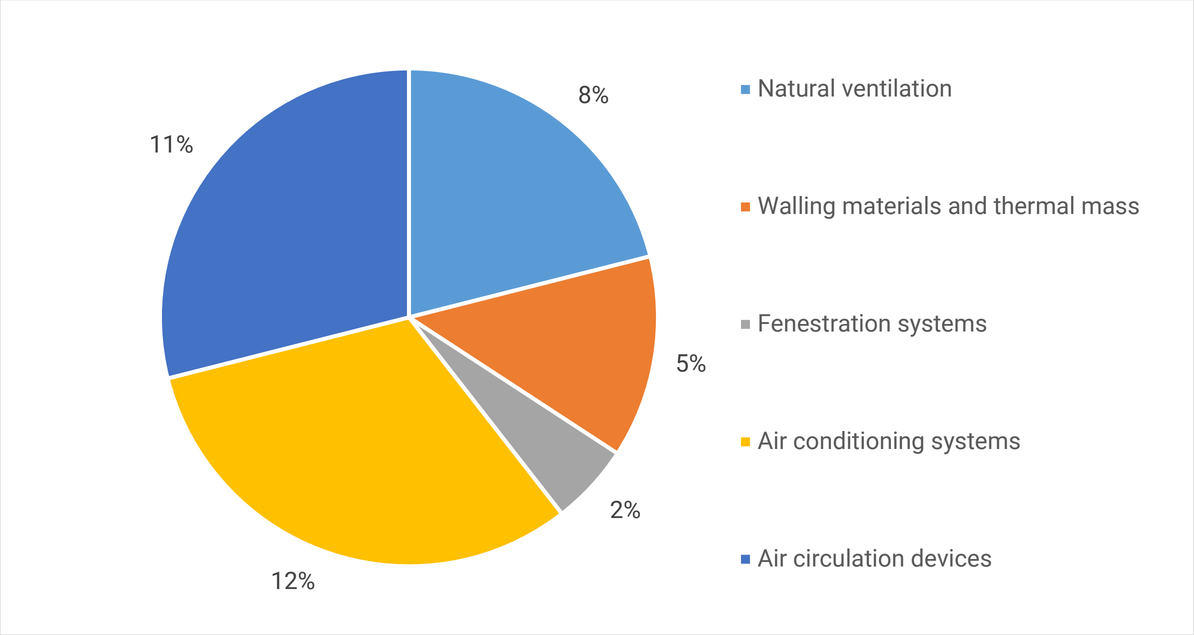
Other strategies in the building include solar powered and sensor-operated lights to minimize usage during daylit hours.

Light fixtures with low-energy bulbs are provided for each workstation with individual switches. Reuse of existing building materials is an essential factor, and the shading from an existing tree canopy was considered in the redesign of the building.

Energy performance and indoor conditions

The energy impacts of individual measures have been estimated using the simulation model developed for a typical building with the same area and climatic conditions of Pelawatte. The building has an estimated EPI value of 35 kWh/m^2/year. The indoor air temperature ranges from 25ºC and 27ºC, based on simulated data. **Figure A1.3** shows the estimated operational energy savings of various passive and active measures in the building.

Figure A1.3. Estimated operational energy savings for the building



3. Ministry of Environment, Forest and Climate Change, New Delhi, India

Indira Paryavaran Bhawan, Ministry of Environment, Forest, and Climate Change (source: nzeb.in).

Building Information

The Indira Paryavaran Bhawan building houses the Ministry of Environment, Forest and Climate Change and has a five-star GRIHA (Green Rating from Integrated Habitat Assessment) and a LEED India Platinum rating from the Indian Green Building Council rating. It has a site area of 9,565 m^2 and a built-up area of 32,000 m^2, which span over two blocks, seven-story structure, and three-level basements. The building has been operational since 2013.

Location and Climate

Delhi, India (28.70° N, 77.10° E) falls under the composite climate zone of India, where the maximum temperature in summer reaches 41 C and drops to a minimum of 7°C in the winter.

The building has also incorporated light shelves for optimized daylighting and shading. As the HVAC system uses functional zoning, the air-conditioning loads are significantly reduced. Regarding active measures, the building has a central air-conditioning system with water-cooled chillers, which utilize a variable frequency drive.

Building orientation and massing: The length of the building is parallel to the east-west axis to reduce solar heat gain with an optimized WWR.

External shading devices: Overhangs are provided on the south windows to reduce unwanted solar heat gain inside the building. Overhangs also shade east- and west-facing glass doors.

Natural ventilation: The central courtyard with natural vegetation helps with air movement due to the stack effect. Adequately sized windows and jaalis aid in cross-ventilation. The central atrium between the two blocks allows natural air movement due to the stack effect. The provision of windows further enhances the process of cross-ventilation.

Walling materials and technology: The use of products having low embodied energy and recycled materials have been prioritized. These include AAC blocks with fly ash for walling, fly ash-based plaster and mortar, and local stone flooring.

The external wall consists of a 0.3 m thick AAC) block, 0.07 m thick mineral wool insulation, 0.12 m wide air gap, and 0.12 m thick 'Fal-G' (proprietary blend of fly ash (Fa), lime (L) and gypsum (G)) block brick and has a U-value of 0.221 W/m^{2}K.

Roofing material and technology: The external roof of the building consists of 0.02 m thick clay tile, 0.06 m thick cement mortar, 0.04 m thick PUF insulation, 0.06 m thick brick bat coba, 0.06 m thick cement mortar, 0.10 m thick concrete. High reflectance terrace tiles are installed on the building roof as a cool roof leading to low heat ingress, high strength, and durability.

Fenestration systems: Windows installed in the building with uPVC frames are hermetically sealed DGUs with gas filling with a U-value of 0.26 W/m^{2}K and SHGC of 0.32 and aluminum frame.

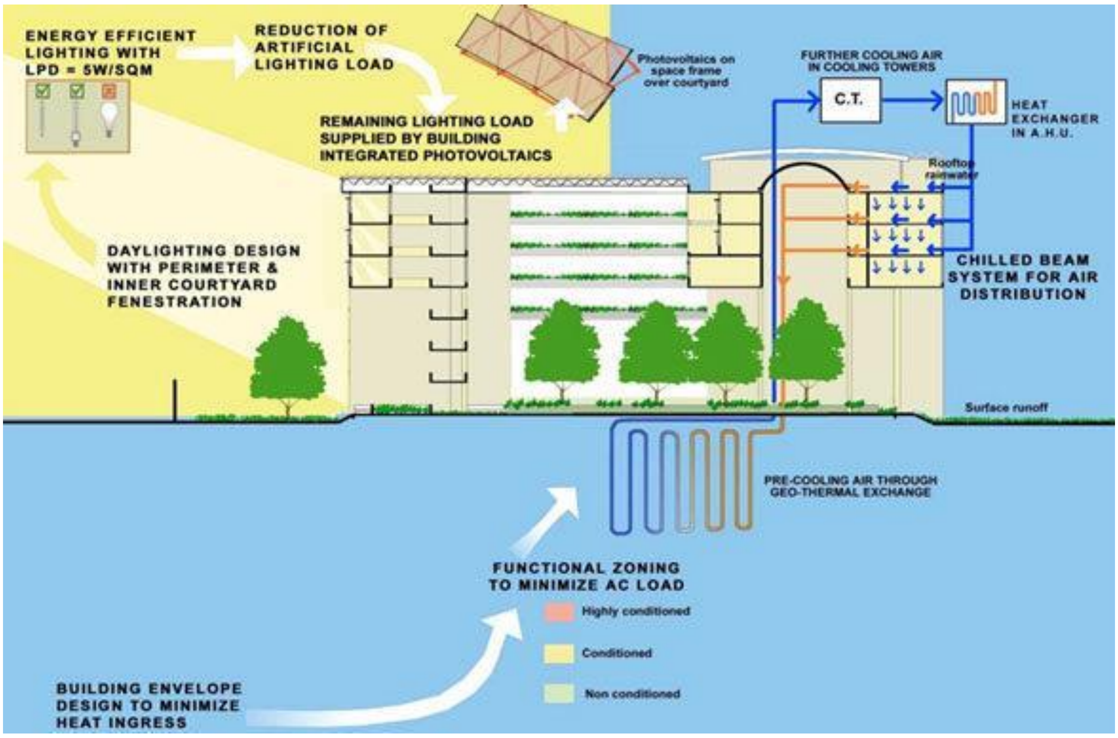
Active Measures

High-performance air-conditioning systems: The building has installed a chilled beam system to meet 160 TR of air-conditioning load, which reduces the energy use by 50 percent compared to a conventional system by saving AHU fan power consumption by approximately 50 kW.

Variable air volume-controlled fans are provided to each of the AHUs supplying air to the area where a chilled beam system at the zone is not provided. In all the other areas, where the chilled beam system is provided at a zone level, constant volume AHUs cater to individual spaces. AHU meets the latent load of the space, and the chilled beams cater to sensible load.

A geothermal system is installed in the building (**Figure A1.4.**), which consists of 180 vertical bores to a depth of 80 m with a minimum of 3 m distant all over the building premises. By using this system, 160 TR of heat rejection is achieved without the use of a cooling tower.

Figure A1.4. Active and passive design measures incorporated in building design



Source: nzeb.in.

Mechanical ventilation systems: Sensible and latent heat energy recovery wheel is used to precool fresh supply air from toilet exhaust air.

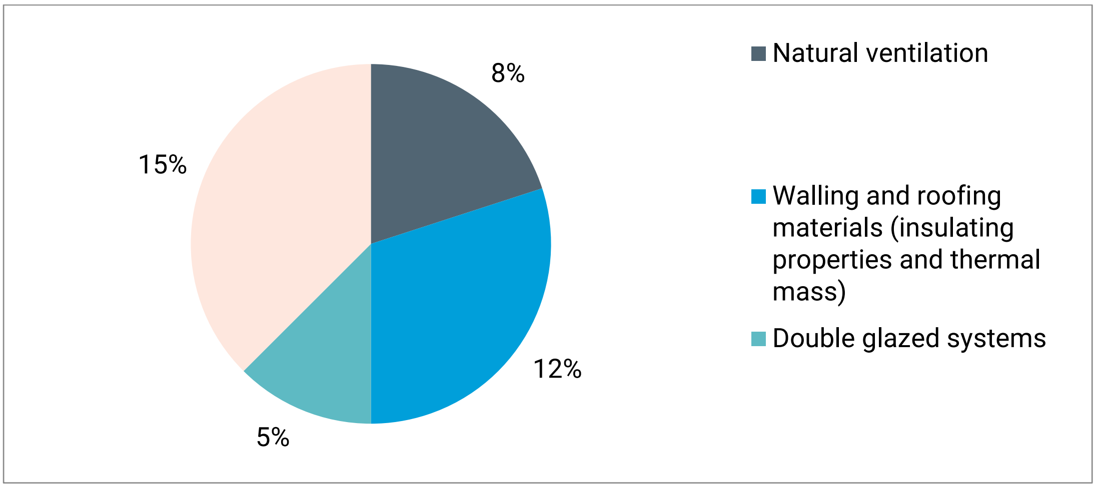
Energy and IAQ control systems: All HVAC equipment is controlled and monitored through a BMS.

Other strategies in the building: The lighting power density is maintained close to 5 W/m^{2,} which is 50 percent more efficient than the Energy Conservation Building Code 2007 requirement (11 W/m^2). The building-integrated photovoltaic power plant supplies the lighting load. A 930-kW rooftop photovoltaic system has been installed in the building. The annual electricity generation is approximately 1,430,000 kWh (units).

Energy performance and indoor conditions

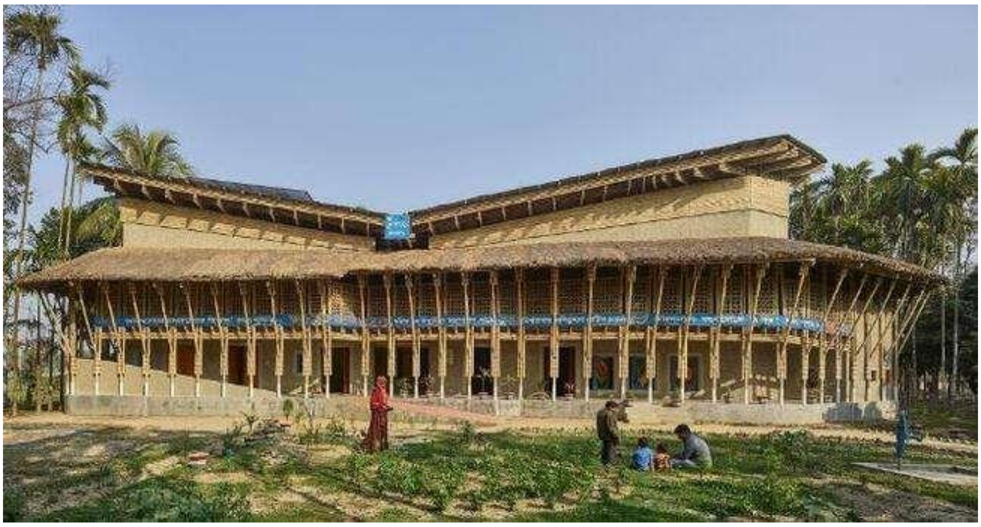
Compared to a conventional design, which would consume 22,00,000 kWh, Indira Paryavaran Bhawan consumes only 14,00,000 kWh, resulting in 40 percent energy savings. The building achieved an IEP value of 24 kWh/m^2/year (based on measured data). The indoor temperature for summer was maintained at 28°C, and during winters at 22°C. **Figure A1.5** shows the estimated operational energy savings of various passive and active measures, estimated using the simulation model for a typical building with the same area and climatic conditions of Delhi.

Figure A1.5. Estimated operational energy savings for the building



Source: Author's analysis.

4. Anandaloy Building, Dinajpur, Bangladesh



Anandaloy building (source: nzeb.in).

Building Information

This building is a community center and workshop, which takes inspiration from its location for design, materials, and construction methods.

Location and climate: Dinajpur, Bangladesh (25.62° N, 88.64° E) falls in the warm and humid climate type, where the maximum temperature peaks at 36°C and minimum temperatures dip to 10°C. During monsoons, the average relative humidity levels are at 85 percent.

Building orientation and thermal mass: The length of the extended facade along the north-south orientation reduces the envelope heat gains. It has been constructed using a mud construction technique called "cob," which does not require any formwork.

External shading devices: The architectural design of the building provides natural shading. It has also been appropriately shaded using a bamboo framework and straw bales on all sides.

Walling technology and material: Thick mud walls with bamboo are the primary material.

Natural ventilation: It is naturally ventilated most of the year, with high ceilings facilitating the stack effect.

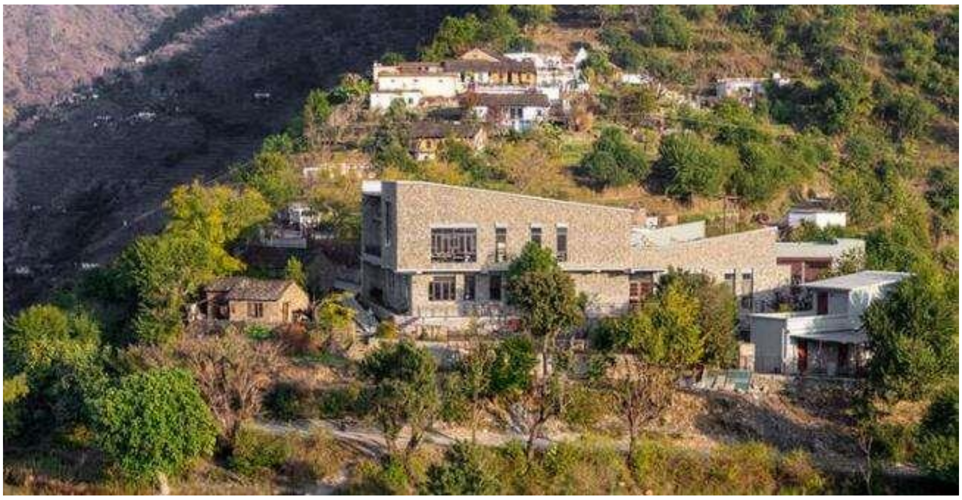
Air-circulation devices: Ceiling fans with adjustable air speeds are provided.

Other strategies in the building: The entire building is powered by solar energy.

Energy performance and indoor conditions

Savings resulting from individual measures could not be estimated for the building due to a lack of information on construction materials and air-conditioning systems. However, using a typical building model with the same area and climatic conditions of Dinajpur has an estimated EPI value of 45 kWh/m^2/year.

5. Lodsi Project, Rishikesh, Uttarakhand, India



Lodsi community project, Uttarakhand, India (source: nzeb.in).

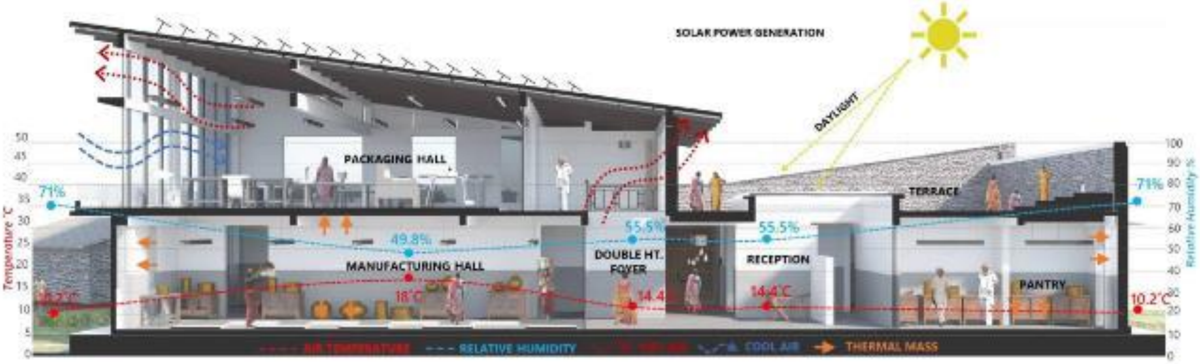
Building Information

The Lodsi Community Project is a manufacturing assembly for a modern skincare product company. The building is designed based on an extensive review of site location, topography, and climate, using indigenous construction techniques and locally available materials. It is a free-running production unit with a built-up area of 929 m². The building has been in operation since 2019.

Location and climate: Rishikesh (30.08 °N, 78.26 °E) falls in the cold climate zone of India, where the maximum temperature peaks at 35°C and minimum temperatures dip to 5°C. During monsoons, the average relative humidity levels are at 80 percent.

Building orientation and thermal mass: A rectilinear volume oriented along the east-west axis has been planned with a central entry that divides the facility into two parts, as seen in Figure A1.6.

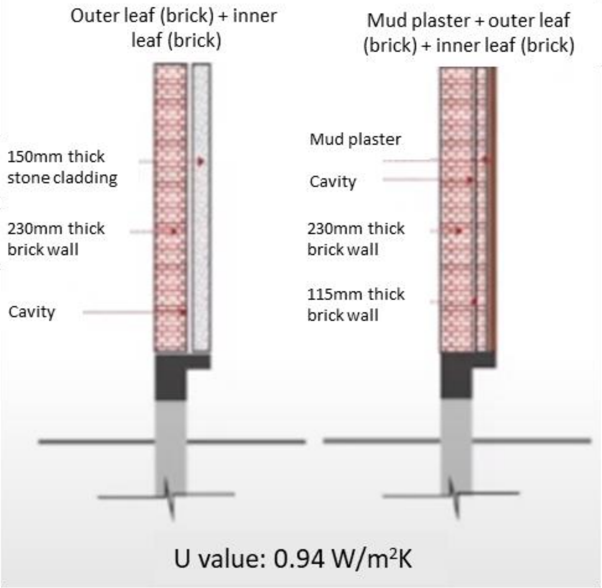
Figure A1.6. Sectional view of the facility



Source: nzeb.in.

Walling technology and material: The walls combine thermal mass and cavity walls. Two types of double-leaf wall assemblies were used. The first was a 0.15 m thick stone cladding (outer leaf), a 0.23 m thick brick wall (inner leaf), and a cavity between them, as shown in **Figure A1.7.**, and the second constituted a 0.23 m brick wall (outer leaf) with mud plaster, and a 0.115 m brick wall (inner leaf). The assemblies achieved a U-value of 0.94 W/m^{2}K.

Figure A1.7. Walling assemblies used in the building



Source: Abdel, 2019.

Natural ventilation: The north-south oriented butterfly roof form allows large openable windows that allow the prevailing north-east and south-east winds to support ventilation. The high volume of space with operable clerestory windows enforces Bernoulli's principle and moderates indoor temperatures.

Fenestration systems: The building has installed DGUs with a U-value of 2.8 W/m^{2}K.

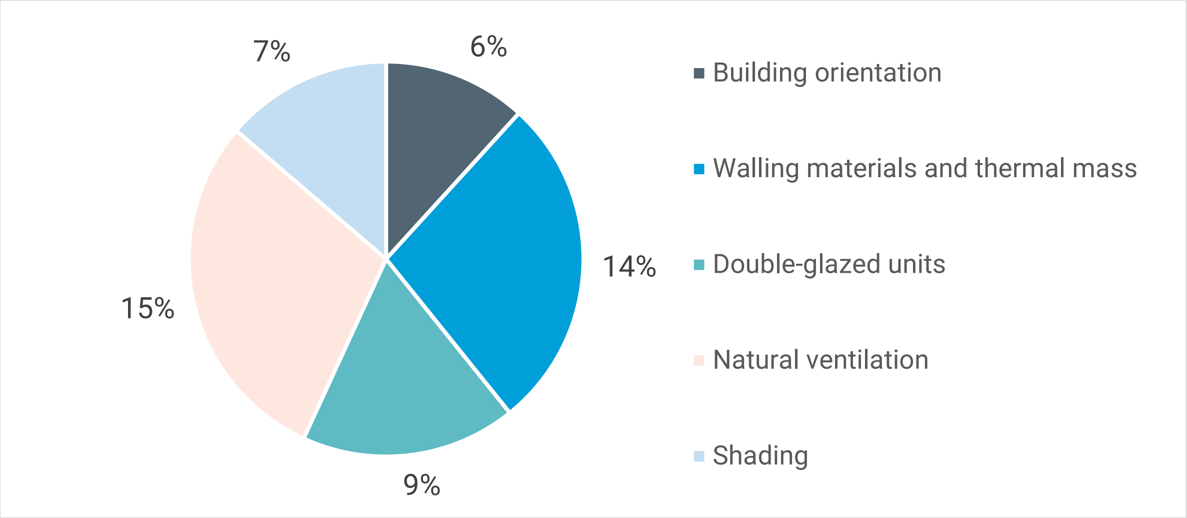
Other strategies in the building include a solar roof generating 50 kWp (as shown in the photograph) that offsets the facility's requirements but generates a surplus. About 80 percent of the building spaces are naturally daylit throughout most of the day. A central light well is provided to create a well-lit area for the workforce.

A 50 kWp Solar Roof installed on the building (source: Abdel, 2019).

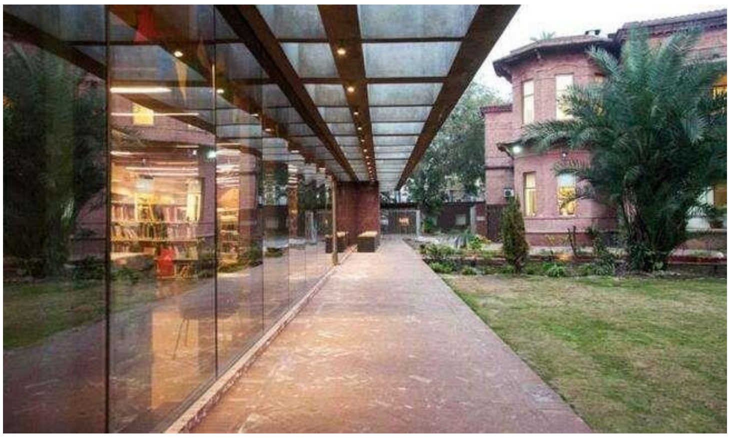
Energy performance and indoor conditions

A simulation to estimate the energy performance of a typical building with the same area and climatic conditions of Lodsi shows an EPI of 35-38 kWh/m²/year. Passive measures achieved thermal comfort for 80 percent of the year, with indoor air temperature ranging from 20ºC and 25ºC. The estimated operational energy savings of individual measures are presented in Figure A1.8.

Figure A1.8. Estimated operational energy savings for the building



6. British Council Library, Lahore, Pakistan



British Council Library, Lahore (source: divisare.com).

Building Information

The LEED-certified British Council Library building has a built-up area of 5121 m^2 and has been operational since 2016.

Location and climate: Lahore, Pakistan (31.52° N, 74.35° E) falls in the composite climate type, with peak summer temperatures reaching 42°C and dropping to 6°C during winters.

Roofing technology and material: A green roof on the building was built into the design to offset heat gains and water runoff.

Fenestration systems: High-quality laminated safety glass with extra fire protection on top of the energy-efficient, highly reflective glass with a low solar heat gain coefficient unit was installed throughout the building.

High-performance air-conditioning systems: High-efficiency air-conditioning systems with heat recovery were installed to improve resource efficiency and complement design features.

Energy and IAQ control systems: Temperature and daylight sensors were integrated to reduce energy use during low occupancy.

Other strategies in the building: The building uses 20 percent recycled building materials (of which 10 percent is salvaged, refurbished, or reused) to reduce the carbon footprint. The building is designed to allow daylight into 75 percent of the occupied space (as shown in the photograph). It also achieved a 40 percent reduction in water use and a 50 percent reduction through wastewater regeneration. Energy-saving fixtures are used to minimize water use.

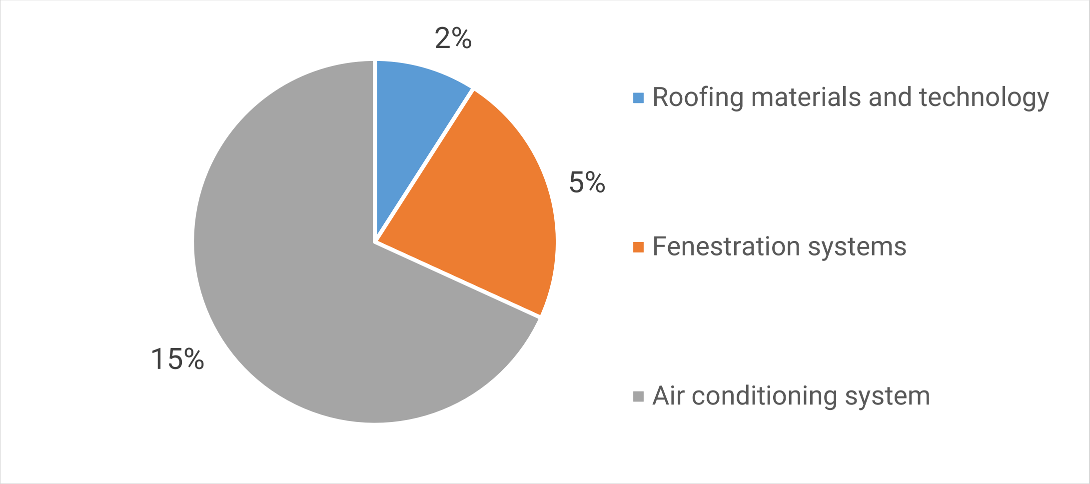
Energy performance and indoor conditions

It has an estimated energy performance value of 75 kWh/m^2/year. With a selection of materials, design features, and renewable technologies, the building uses 30-35 percent less energy than the typical reference building at the location. The estimated operational savings are derived from the simulation of a typical building model with the same floor area and climatic conditions of Lahore. Several assumptions, such as those noted below, had to be made to estimate the savings benefit of each measure in the building (Figure A1.9):

- Estimated higher insulation of roof due to implemented strategy to estimate savings.

- Assumed glass with low transmittance to estimate savings; and
- **Assumed COP of air conditioning system as 3.5, with demand control ventilation and setback of 2°C.**

Figure A1.9. Estimated operational energy savings for the building



7. Smart Ghar III: Residential Building, Rajkot, India

Smart Ghar III, Rajkot: Residential building (source: BEE, 2016).

Building Information

Smart GHAR III is an affordable housing project constructed under the Pradhan Mantri Awas Yojana and executed by the Rajkot Municipal Corporation. It has 1,176 dwelling units spaced over 11 towers, each of seven floors. The Smart Ghar III project has a site area of 17,593 m^2 and a built-up area of 57,408 m^2. The buildings have been occupied since 2019. A design charrette was conducted during the project's design phase to analyze the impact of implementing active and passive measures. Without any interventions, on a typical summer day, the peak indoor air temperature reached 38 ºC.

Location and Climate

Rajkot (22.30° N, 70.80° E) falls in the composite climate zone of India, with peak summer daytime temperature reaching 43°C and dropping to a minimum of 13 °C in the winter.

Passive Measures

Building orientation and thermal mass: The length of the project site is parallel to the east-west axis to reduce solar heat gain.

Walling materials and technology: The walls are constructed of 0.23 m AAC blocks, with a U-value of 0.8 W/m^{2}K, thus allowing less conduction heat gains through the wall. Walls on the southern side are cavity walls, constructed of 0.23 m AAC blocks on both sides with an air cavity of 0.05 m achieving a U-value of 0.3 W/m^{2}K.

Roofing material and technology: The roof has external insulation (0.04 m polyurethane foam), achieving a U-value of 0.56 W/m^{2}K. The roof also has a high-reflective China mosaic finish.

Fenestration systems: Taller, partially glazed casement windows were installed with a 90 percent openable area to facilitate higher ventilation rates. The window shutters are two-thirds opaque, with the glazing area reduced to 30 percent to avoid excess heat gain through glazing and provide adequate daylight.

Active Measures

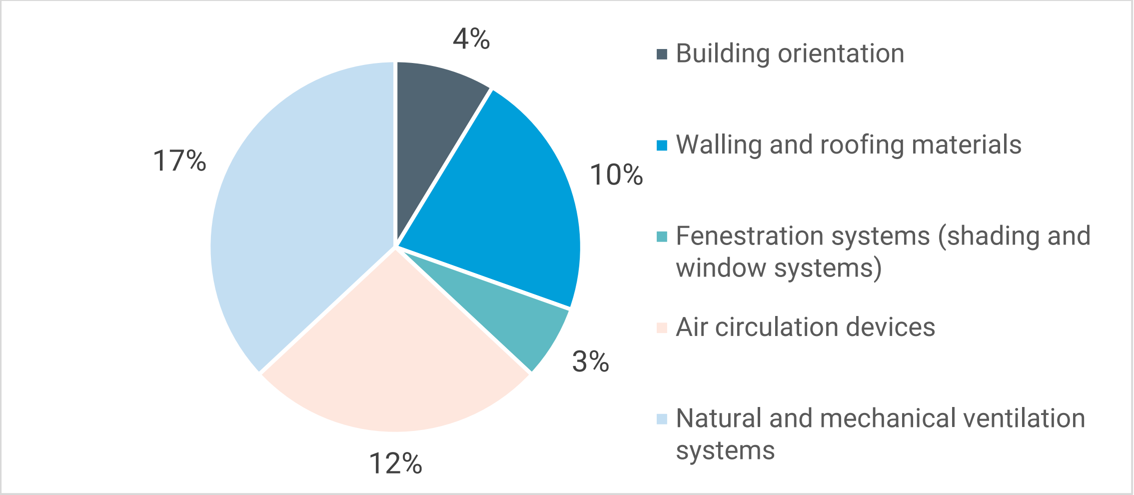
Natural and mechanical ventilation systems: A provision has been made to ensure adequate ventilation (ACH of 10) through all flats using the existing service shaft between two towers. This assisted ventilation has a roof feature and a fan on top of the shaft, creating negative pressure in the shaft (with/without wind) and improving air change through the dwelling units.

Energy performance and indoor conditions

Adopting the energy efficiency measures finalized after the design charrette, indoor room air temperature was brought down to 33°C during peak summer. The 5°C reduction in indoor room temperature increases comfortable hours from 2600 to 6300.

Figure A1.10 shows the estimated operational energy savings for a typical residential apartment with the same floor area and climatic conditions of Rajkot, with a split air-conditioning system in the bedroom to calculate estimated benefits in energy use.

Figure A1.10. Estimated operational energy savings for the building



Source: Author's analysis.

It has an estimated energy performance index value of 20 kWh/m^2/year and indoor temperatures between 26°C and 30°C.

8. Mobil House, Dhaka, Bangladesh

Building Information

The Mobil House is the head office of MJL Bangladesh Limited. The building is LEED Platinum certified with a built-up area of 6,673m^2. It has been operational since October 2019.

Mobil House, Dhaka, Bangladesh (source: nzeb.in)

Location and Climate

Dhaka, Bangladesh (23.8° N, 90.4° E) has a warm and humid climate type, with maximum temperatures touching 32°C and dipping to a minimum of 12°C during winters. The average humidity during the monsoon period floats around 85 percent and at 68 percent during the rest of the year.

Passive Measures

Building orientation and thermal mass: The building mass has been oriented such that circulation elements like the lift core and staircases are situated along the West façade. This shields the regularly occupied spaces such as offices and reception from solar gains through the west façade. The northeast façade incorporates large windows to allow daylight and outdoor views.

Walling materials and technology: The envelope is made of 0.3 m thick concrete walls leading to high thermal mass and reducing heat ingress during the daytime.

Fenestration systems: Double-glazed panels with low emissivity and a U-value of 1.1 W/m^{2}k also significantly reduce heat gain. The glazing has a shading coefficient of less than 0.25, reducing solar heat gain.

Active Measures

High-performance air conditioning systems: An efficient chilled water system with a chiller coefficient of performance of 6.3, low approach cooling tower with VFD significantly reduce the cooling energy consumption.

Mechanical ventilation systems: An energy recovery wheel is incorporated into the HVAC design to reduce the cooling load due to fresh air intake.

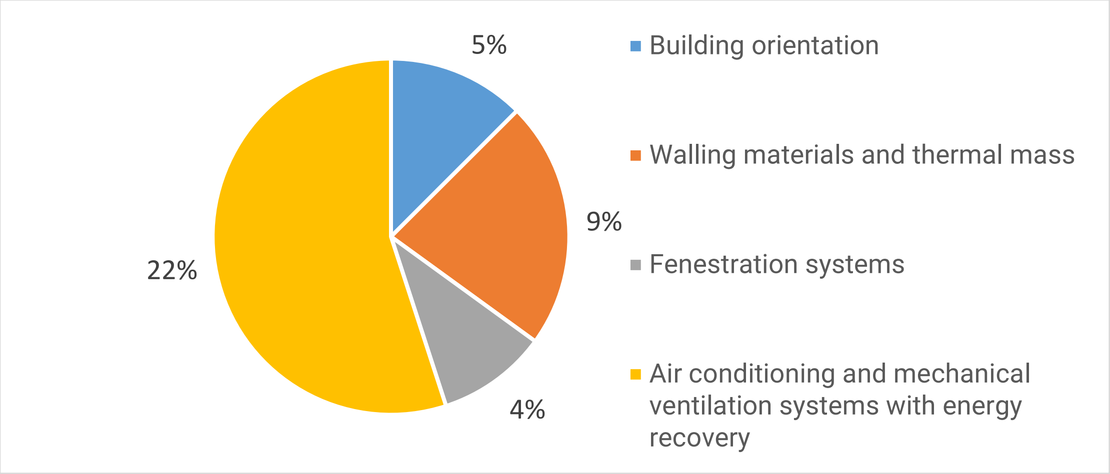
Energy and IAQ control systems: Occupancy and daylit sensors are installed to provide optimum lighting levels and reduce lighting loads in unoccupied spaces.

Other strategies in the building include sizable courtyards and building cut-outs populated with foliage and vertical gardens. The deep building terraces and courtyards enhance biophilia and create shaded outdoor breakout spaces that remain cool throughout the day. The building has an 18 kWp grid-tied solar system on its roof to offset its electrical consumption and generates 24,000 kWh annually. The building uses 30 percent less energy and 50 percent less water compared to conventional office buildings in the region.

Energy performance and indoor conditions

It has an energy performance index of 58 kWh/m^2/year based on measured data. Figure A1.11 provides estimated operational energy savings from individual measures incorporated in the building by simulating a typical building with the same floor area and climatic conditions of Dhaka.

Figure A1.11. Estimated operational energy savings for the building



Source: Author's analysis.

9. Bayalpata Hospital, Achham, Nepal

Bayalpata Hospital, Achham, Nepal (source: nzeb.in).

Building Information

Bayalpata Hospital is a medical complex with a built-up area of 4,225 m^2. It includes five medical buildings that house outpatient, inpatient, and antenatal units, along with emergency facilities for 70 beds. Built from onsite materials using low-tech construction methods, the building has minimized the cost-prohibitive transportation of materials in the mountainous region. The hospital has been operational since 2019.

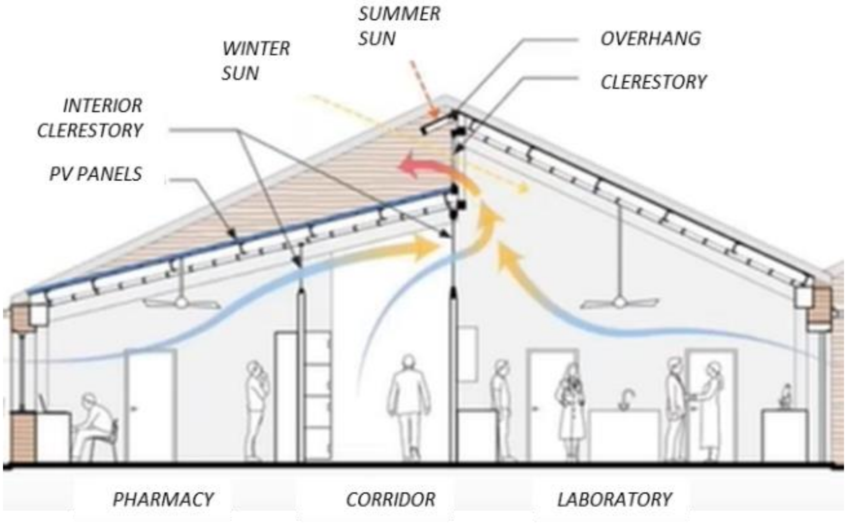
Location and Climate

Achham, Nepal (29°N, 81°E) has a subtropical climate type, with average temperatures during summers at 25°C and winter average temperatures at 15°C.

Passive Measures

Natural ventilation: Material with thermal mass retains daytime heat gain in winter while keeping the interiors cool by preventing overheating during summer. The cross-ventilation facilitated due to courtyards, aided by clerestory ventilation and ceiling fans (Figure A1.12), promotes natural ventilation and improves comfort conditions.

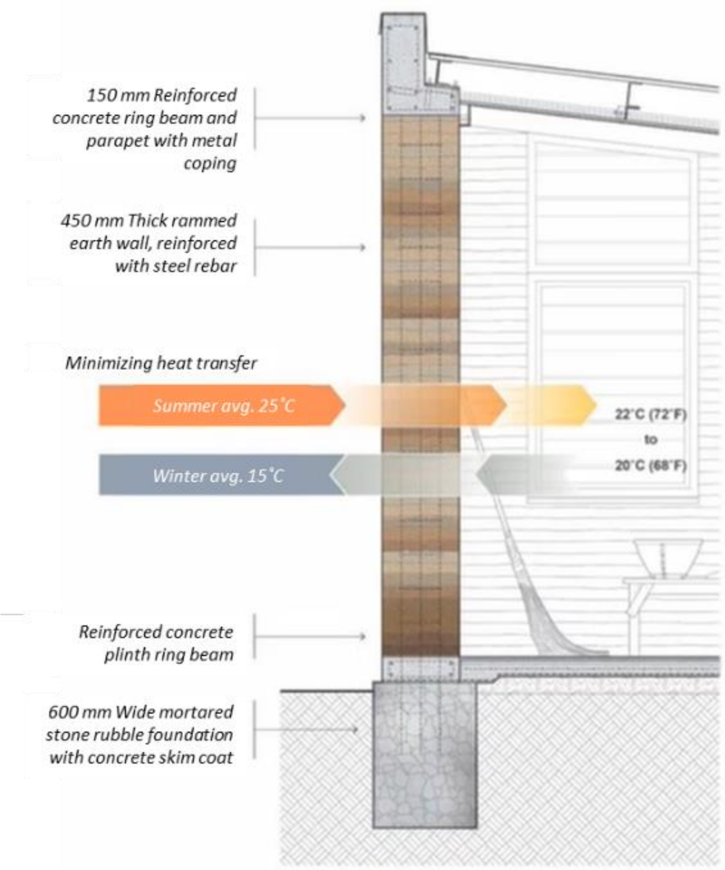
Figure A1.12. Building design elements facilitating natural ventilation



Source: nzeb.in

Walling materials and technology: Soil from the site was mixed with 6 percent cement content to stabilize the earth for better durability and seismic resistance. Local stone was used for foundations, pathways, and retaining walls. Figure shows the cross-sectional view of the walling assembly.

Figure A1.13. Details of walling assembly



Source: nzeb.in

Fenestration systems: Tall narrow windows and south-facing series of glazed clerestories bring in natural daylight, reducing the need for artificial lighting.

Active Measures

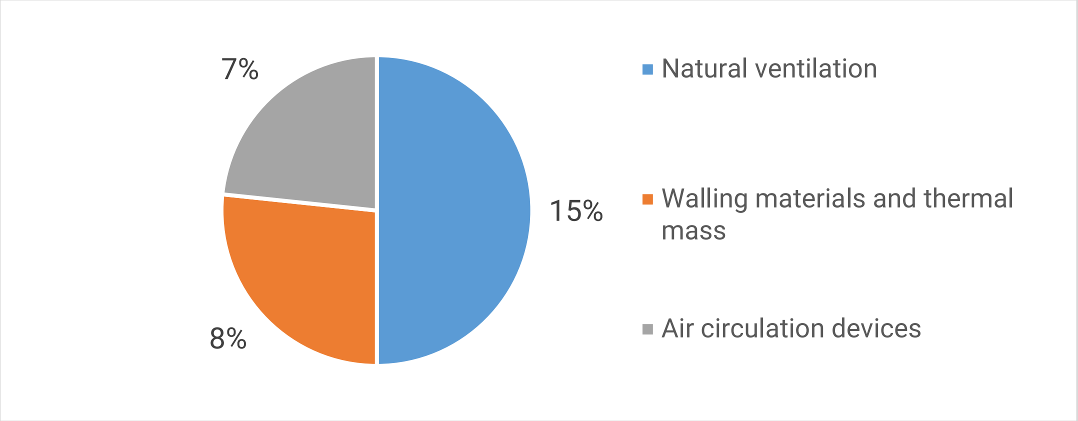
Air circulation devices: Ceiling fans have been provided, aiding natural ventilation.

Other strategies in the building include a 100-kW solar array integrated into the south-facing roofs. A solar-powered water heating system heats up to 3,300 liters daily for medical and staff use.

Energy performance and indoor conditions

Th building has an EPI of 10 kWh/m^2/year based on measured data. **Figure** A1.14 provides the estimated operational energy savings from individual measures incorporated in the building by simulating a typical building with the same floor area and climatic conditions of Achham.

Figure A1.14. Estimated operational energy savings for the building



10. Star Garment Innovation Center, Katunayake, Sri Lanka

Star Garment Innovation Center, Katunayake, Sri Lanka (source: nzeb.in)

Building Information

The Star Innovation Center, a garment manufacturing factory, was retrofitted in 2018 and has been carefully designed and engineered for sustainability, energy efficiency, and worker comfort. The manufacturing building has been modified to fulfill the Passive standard, making it Sri Lanka's first certified Passive House building. It has a built-up area of 3,675 m^2.

Location and Climate

Katunayake, Sri Lanka (7° N, 80° E) falls in the tropical climate type, with maximum average temperatures reaching up to 32°C and a minimum of 24°C throughout the year, with average relative humidity at 80 percent.

Passive Measures

External shading devices: Roof eves and shading devices reduce heat gain through the glazing.

Walling materials and technology: The most critical strategy implemented is the installation of the highly efficient airtight, insulated envelope. A fluid-applied thermal break is used at strategic connections to seal the envelope carefully to minimize thermal bridging.

An exterior insulated finish system continuously wraps existing and new structural components in insulation with minimal thermal bridging. Low absorption or highly reflective exterior surfaces helps to reduce the cooling energy demand of the building.

The exposed steel frame is partly filled with concrete masonry units, made efficient using a thermal insulation composite system made from expanded polystyrene (EPS). The exterior wall is a concrete masonry unit wall assembly consisting of a masonry wall (0.203 m), a cement board (0.012 m), EPS (graphite enhanced, 0.08 m), and stucco (0.006 m), resulting in a U-value of 0.329 W/m^{2}K.

Roofing materials and technology: A new metal prefabricated roof consists of 0.120 m thick sandwich panels with a polyurethane rigid foam insulating core and an outer heat-reflecting coating. The roof assembly has a thermal transmittance U-value of 0.182 W/m^{2}K, largely contributing towards keeping the tropical heat away from the interior.

Fenestration Systems

The exposed steel frame is filled with extensive floor-to-ceiling insulating glass elements. A high-performing curtain wall with double glazing and a solar heat gain coefficient of 0.22 allows only 22 percent of solar radiation to enter the building, thus significantly reducing the heat transfer into the interior and further reducing cooling loads. The window assembly has a U-value of 1.81 W/m^{2}K.

Active Measures

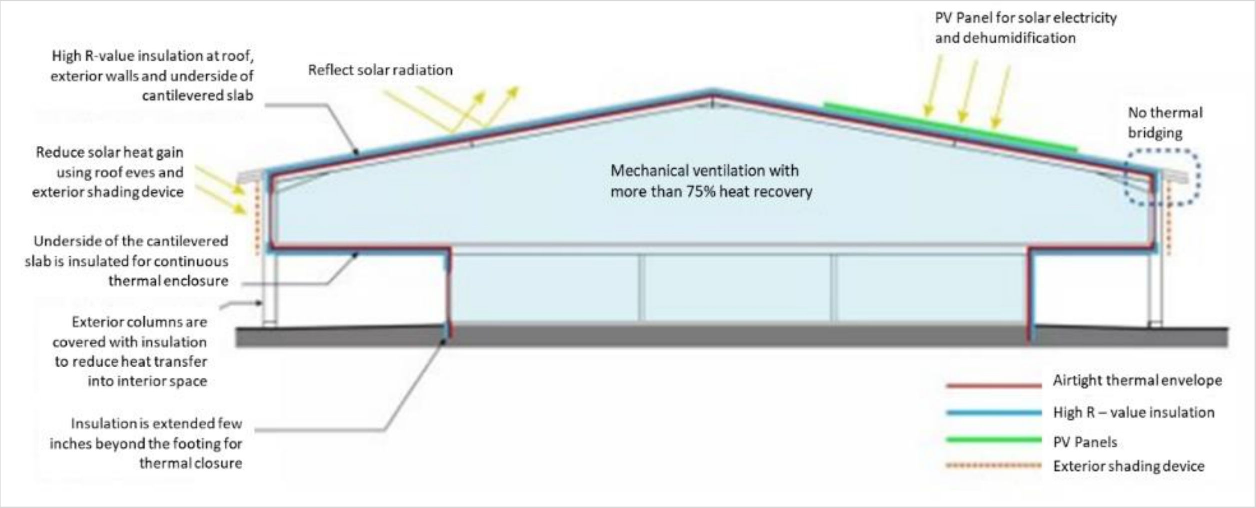
High-performance air conditioning systems: A highly efficient VRF system has been installed for enhanced dehumidification capacity. The heat pipes work in collaboration with the solar panels on the roof, which saves costs compared to the usual electrical reheat systems.

Mechanical ventilation systems: Five heat and humidity recovery units have been installed. Average electric efficiency of 0.7 Wh/m^3 results in 72 percent heat and 70 percent humidity recovery.

Other building strategies include installing rooftop solar photovoltaics that generate approximately 11 percent of the energy requirement of the building. The existing steel skeleton and the concrete slab have been reused to reduce the carbon footprint of the building.

The estimated generation is approximately 48,340 kWh/yr, 19 kWh/m^2/year, based on the projected area of 2,549 m^2. Figure shows all the measures incorporated into the garment factory building.

Figure A1.15. Active and passive measures incorporated into the building



Source: nzeb.in.

Energy performance and indoor conditions

The building provides year-round comfort in the workspace, abundant natural light, low humidity, filtered fresh air, maintaining temperatures near a constant 24°C. The benefit of these features is reflected in the reduced annual energy use of around 54 percent. It has a current EPI of 164 kWh/m^2/year. The operational energy savings resulting from individual measures could not be estimated due to a lack of information regarding the internal loads of the building.

Annex 1 References

Abdel, H. 2019. The Lodsi Community Project for Forest Essentials / Morphogenesis. ArchDaily.https://www.archdaily.com/958594/the-lodsi-community-project-for-forest-essentials-morphogenesis.

Bureau of Energy Efficiency. 2016. Case Study: “Green” Affordable Housing: Smart Ghar III, Rajkot. New Delhi: Ministry of Power, Government of India. https://www.gkspl.in/publication/case-study-smart-ghar-iii-rajkot/.

Divisare. 2017. Raza Ali Dada: British Council Library. https://divisare.com/projects/342036-raza-ali-dada-british-council-library.

NZEB. Anandaloy: Centre for People with Disabilities & Dipdii Textiles Studio. https://nzeb.in/case-studies/south-asia-case-studies/south-asia-list/#row_15.

NZEB. Bayalpata Hospital, Achham, Nepal. https://nzeb.in/case-studies/south-asia-case-studies/south-asia-list/bayalpata-hospital-achham-nepal/

NZEB. CEPT, A Living Laboratory. https://nzeb.in/case-studies/nzebs-in-india/nzebs-in-india-case-studies-list/cept-case-study/.

NZEB. Indira Paryavaran Bhawan, Ministry of Environment and Forest (MoEF). https://nzeb.in/case-studies/nzebs-in-india/nzebs-in-india-case-studies-list/ipb-case-study/.

NZEB. Mobil House, Dhaka, Bangladesh. https://nzeb.in/case-studies/south-asia-case-studies/south-asia-list/mobil-house/

NZEB. RNA Multi-purpose Office/Residence. https://nzeb.in/case-studies/south-asia-case-studies/south-asia-list/#row_9.

NZEB. Star Garment Innovation Center, Katunayake, Sri Lanka. https://nzeb.in/case-studies/south-asia-case-studies/south-asia-list/star-garment-innovation-center-case-study/

Annex 2: Country-specific Recommendations

This section provides a list of country-specific recommendations for buildings in South Asia. These recommendations are derived from a review of existing literature in the specific country, prevalent policy, identified case studies, climatic analysis of the city, and simulations performed to assess the benefits of recommended measures. The following sections categorize each measure into high, moderate, and low applicability for each city. The applicability (or suitability) indicates how appropriate or suitable the measure is for the city.

Bangladesh

This section provides an additional list of recommendations for buildings in Bangladesh. Table provides the recommended measures for various cities in Bangladesh, along with the measures' expected incremental costs and applicability.

Table A2.1. Specific interventions for cities in Bangladesh

Incremental Cost	Interventions	Khulna, Rangpur (Warm-humid)	Dhaka (Composite)
None	Building Orientation	⬜	🟩
	Natural Ventilation	⬜	🟩
Low	Shading	🟩	🟩
	Cool Roof	⬜	🟩
	Air Circulation Devices	🟩	🟩
	Mechanical Ventilation	⬜	🟩
	Evaporative Coolers	🟥	⬜
Moderate	Thermal Mass	🟥	⬜
	Walling Technologies	🟩	🟩
	Roofing Technologies	🟩	🟩
	Fenestration Systems	🟩	🟩
High	High-efficiency air conditioners	⬜	⬜

🟩 High applicability ⬜ Moderate applicability 🟥 Low applicability

As shown in A2.1, orientation, shading, and efficient envelope significantly reduce the cooling needs of buildings in Dhaka. While located in a composite climate, Dhaka experiences considerably lower temperatures than some other cities in South Asia. Ventilation strategies are very effective for part of the year (six to seven months) to create comfortable building conditions. However, mechanical ventilation with filtration is more suitable for buildings in Dhaka due to high outdoor air pollution. Air circulation devices, requiring low incremental costs, should be included in the buildings.

Shading and efficient envelope measures significantly reduce the cooling needs of the buildings located in Khulna and Rangpur. Further, the potential for ventilation is very moderate due to high outdoor humidity during the year. Air circulation devices are one of the most effective strategies to increase occupant heat loss through perspiration. The low-energy air-conditioning systems that primarily reduce moisture loads in the space are effective.

Only one green rating system currently serves Bangladesh and encourages sustainable design and construction use. While thermal comfort, energy efficiency, and IAQ are only cursory requirements of the rating system, designing buildings to comply with the green building rating systems is recommended.

Bangladesh National Building Code, a code adopted by the government of Bangladesh and revised in 2021, guides the design of various building typologies in different climate zones of the country. The regulation specifies envelopes, window opening area, ventilation requirements, and system efficiency to design code-compliant buildings. The code is the only national code in Asia that specifies IAQ thresholds inside buildings. Use this code is recommended in designing commercial buildings in Bangladesh.

India

This section provides an additional list of recommendations for buildings in India. Table A2.2 provides the recommended measures for various cities in India, along with the expected incremental costs and applicability of the recommended measures.

Table A2.2. Specific interventions for cities in India

Incremental Cost	Interventions	Ahmedabad (Hot-dry)	Mumbai (Warm-humid)	Delhi (Composite)	Bengaluru (Temperate)	Srinagar (Cold)
None	Building Orientation	🟩	⬜	🟩	🟥	🟩
	Natural Ventilation	⬜	⬜	⬜	🟩	⬜
Low	Shading	🟩	🟩	🟩	⬜	🟥
	Cool Roof	🟩	⬜	🟩	⬜	🟥
	Air Circulation Devices	🟩	🟩	🟩	🟩	🟥
	Mechanical Ventilation	⬜	🟥	⬜	🟩	⬜
	Evaporative Coolers	🟩	🟥	⬜	🟥	🟥
Moderate	Thermal Mass	🟩	🟥	⬜	🟥	🟩
	Walling Technologies	🟩	🟩	🟩	⬜	🟩
	Roofing Technologies	🟩	🟩	🟩	⬜	🟩
	Fenestration Systems	🟩	🟩	🟩	⬜	🟩
High	High-efficiency air conditioners	🟩	⬜	🟩	🟥	🟩

🟩 High applicability ⬜ Moderate applicability 🟥 Low applicability

As shown in Table A 2.2, building orientation, shading, and efficient envelope significantly reduce the cooling needs of buildings in Delhi. Air circulation devices, requiring low incremental costs, are highly recommended as inclusions in the design of buildings. Ventilation strategies can be effective in the transition season (between summer and winter) to create comfortable conditions inside buildings. The outdoor air quality in Delhi is poor in winter but is moderate for the transition season for natural ventilation. Evaporative coolers can work effectively during the dry period of the year (March to May) but are not effective once the monsoon season sets in (June onwards). Due to the extended operation period of mechanical systems, selecting high-efficiency air-conditioning systems is recommended.

Table A 2.2 shows that passive measures are essential to incorporate in buildings in Ahmedabad. Building orientation, shading, and efficient envelope significantly reduce the cooling needs of buildings in this city. Ventilation, a requirement to achieve desired IAQ, may be suitable for mild months. Whenever active air-conditioning systems are needed, it is recommended that evaporative coolers be used before using high-efficiency air-conditioning systems in the buildings.

Shading and efficient envelope measures significantly reduce the cooling needs of buildings located in Mumbai. Air circulation devices are one of the most effective measures in increasing occupant heat loss through perspiration. Further, the potential for ventilation (for comfort cooling) is significantly lower due to high outdoor humidity. Low-energy air-conditioning systems that primarily reduce moisture loads in the space are effective.

In Bengaluru, where the building loads are low due to the temperate climate, air circulation and ventilation strategies are adequate to cater to the building loads. While the orientation of a building will have a low impact, the position of fenestration is critical to obtain sufficient natural and mechanical ventilation inside the buildings. In a well-designed building in a temperate climate, it is possible to avoid the use of mechanical systems except in extreme climatic conditions or where high internal loads are expected for a specific building typology.

Efficient envelopes, including thermal breaks and thermal mass, are essential measures to implement in the buildings located in Srinagar. Further, the orientation of the building should be designed to maximize solar radiation but minimize heat loss throughout the night and evening periods. Due to extremely cold temperatures, heating systems would be required during winter. Hence, high-efficiency heating systems, such as heat pumps, are recommended for buildings located in Srinagar.

Eco-Niwas Samhita, a voluntary code adopted by the Government of India, provides excellent guidance on designing residential buildings in different climate zones of India. The code specifies envelope efficiency in part 1 of the code and air-conditioning system efficiency in part 2. The code also specifies window opening areas and RETV of less than 15 for residential buildings. While specifying the measures in the code, the residential code ensured that building costs due to the efficient envelope stayed below 3 percent of the incremental cost. It is recommended that this code be used in designing residential buildings in India.

The Energy Conservation Building Code (ECBC), a code adopted by the Government of India and revised in 2017, guides the design of commercial buildings in different climate zones of India. The code specifies envelope and system efficiency in designing ECBC-compliant and ECBC+ (super-efficient) buildings. Various states are gradually adopting the code through urban local bodies to make it mandatory for new buildings to have more than 100 KVA connected load. The use this code in designing commercial buildings in India is recommended.

Currently, many green rating systems are prevalent in India that encourage the use of sustainable design and construction. While thermal comfort, energy efficiency, and IAQ are only some of the requirements of these rating systems, it is recommended that buildings design comply with green building rating systems.

Several bilateral agencies, such as the German and Swiss governments, in partnership with the Government of India, are working towards providing technical guidelines, training materials, and design charrette support for working professionals.

Pakistan

This section provides an additional list of recommendations for buildings in Pakistan. Table A2.3 provides the recommended measures for various cities in Pakistan, along with the expected incremental costs and applicability of the recommended measures.

Table A2.3. Specific interventions for cities in Pakistan

Incremental Cost	Interventions	Karachi, Lahore (Composite)	Islamabad (Cold)
None	Building Orientation	🟩	🟩
	Natural Ventilation	🟥	⬜
Low	Shading	🟩	⬜
	Cool Roof	🟩	⬜
	Air Circulation Devices	🟩	⬜
	Mechanical Ventilation	⬜	⬜
	Evaporative Coolers	⬜	🟥
Moderate	Thermal Mass	⬜	🟩
	Walling Technologies	🟩	🟩
	Roofing Technologies	🟩	🟩
	Fenestration Systems	🟩	🟩
Low	High-efficiency air conditioners	🟩	🟩

🟩 High applicability ⬜ Moderate applicability 🟥 Low applicability

Efficient envelopes, including thermal breaks, are important measures to implement in buildings located in Islamabad. Thermal mass and shading are also practical measures to apply in Islamabad. The city also experiences cold and hot weather, so ventilation strategies are quite effective in transition seasons. The city requires heating and cooling systems for the winter and summer, respectively. Hence, high-efficiency heating and cooling systems, especially heat pumps, are recommended for buildings.

As shown in Table A2.3, building orientation, shading, and efficient envelope significantly reduce the cooling needs of the buildings in Lahore and Karachi. Due to the extended operation period of mechanical systems, high-efficiency heating and cooling systems are recommended for the buildings. Air circulation devices are highly recommended as inclusions in the design of buildings. Ventilation strategies can be effective between the summer and winter to create comfortable conditions inside the buildings.

The National Building Code of Pakistan refers to energy provisions (2011) concerning thermal comfort, IAQ, and building energy efficiency. While the code is prescriptive and focused on one climate zone (Karachi), it is recommended that this code be used in designing commercial buildings in Pakistan.

Only one green rating system currently serves Pakistan and encourages sustainable design and construction use. While thermal comfort, energy efficiency, and IAQ are only some of the requirements of the rating system, it is recommended that building be designed in compliance with the green building rating system.

Other South Asian Countries

This section provides additional recommendations for buildings in other South Asian countries. **Table A2.4** provides the recommended measures for various cities in Afghanistan, Bhutan, Maldives, Nepal, and Sri Lanka, along with the recommended measures, expected incremental costs and applicability.

Table A2.4. Specific interventions for cities in other South Asian countries

Incremental Cost	Interventions	Hanimaadhoo, Male, Biratnagar, Colombo, Kandy (Warm-humid)	Kandahar (Composite)	Herat, Kabul, Paro, Jumla, Kathmandu, (Cold)
None	Building Orientation	⬜	🟩	🟩
	Natural Ventilation	⬜	⬜	⬜
Low	Shading	🟩	🟩	🟥
	Cool Roof	🟧	🟩	🟥
	Air Circulation Devices	🟩	🟩	🟥
	Mechanical Ventilation	🟥	⬜	⬜
	Evaporative Coolers	🟥	⬜	🟥
Moderate	Thermal Mass	🟥	⬜	🟩
	Walling Technologies	🟩	🟩	🟩
	Roofing Technologies	🟩	🟩	🟩
	Fenestration Systems	🟩	🟩	🟩
High	High-efficiency air conditioners	⬜	🟩	🟩

🟩 High applicability ⬜ Moderate applicability 🟥 Low applicability

Most cities in other countries in South Asia are located in warm and humid or cold climates. The following provides brief guidance on the suggested intervention based on the climate zones. However, it is important to recognize that these cities experience various outdoor conditions and have diverse urbanization patterns, vernacular architecture, and diverse outdoor pollution levels.

Building orientation, shading, and efficient envelope are important measures to reduce the cooling needs of buildings in Kandahar. Many of the vernacular buildings in Afghanistan use shading and orientation as a strategy. If insulation materials are unavailable, traditional cavity walls could be deployed to reduce heat transfer across the envelope. Inclusion of air circulation devices is highly recommended in the design of buildings. Ventilation strategies can be effective during the transition season (between summer and winter) to create comfortable building conditions. Due to the extended operation period of mechanical systems, selecting high-efficiency air-conditioning systems is recommended.

Air circulation devices are one of the most effective strategies to increase occupant heat loss through perspiration in warm and humid climates. Further, shading, and efficient envelope measures significantly reduce the cooling needs of buildings. The potential for ventilation (for comfort cooling) is very moderate due to high outdoor humidity, but it can still be helpful to provide air movement inside buildings.

The building's orientation in a cold climate should be designed to maximize solar radiation but minimize heat loss throughout the night and evening. Volume to surface area is essential when designing a building in a cold climate. Efficient envelopes, especially thermal breaks, are essential measures to implement in buildings located in cold climates. High-efficiency heating systems, such as heat pumps, are recommended for buildings in cold climates. Mechanical ventilation is also recommended to provide better free cooling and maintain IAQ inside the buildings.

Several bilateral agencies, in partnership with Nepal and Bhutan governments, are working towards providing technical guidelines, training materials, and design charrette support for working professionals.

The Sri Lanka Energy-efficiency Building Code specifies the buildings' envelope systems, opening areas, and ventilation rates. However, other governments in South Asia do not have any specific codes focused on thermal comfort, IAQ, and energy efficiency. In the absence of the code, it is recommended that Eco-Niwas Samhita be used for residential buildings and ECBC for commercial buildings in South Asia. These codes are applicable in South Asia due to the diverse climate zones covered in the specifications.

Summary of Active and Passive Measures

This section (Table A2.5) provides a summary of all active and passive measures discussed in the report, including their initial cost, embodied carbon, market availability, recommended climate for use and operational energy savings that can be derived when the measure is implemented in different climate types discussed in section 2.2.1 - 'Outdoor Climate in South Asia'.

Table A2.5. Summary of active and passive measures

Strategy	Initial Cost	Embodied Carbon	Market Availability	Recommended Climates	Operational Energy Savings by Climate				
					Hot and Dry	Warm and Humid	Composite	Temperate	Cold
Building Orientation	Zero	Zero	High	All climates	High	High	High	High	High
Thermal Mass	Moderate to high	High	Moderate	Hot and dry, composite, cold	High	Moderate	High	Moderate	High
External Shading Devices	Zero to Low	Low to Moderate	High	All climates	High	Moderate	High	Low	Moderate
Natural Ventilation	Zero	Zero	High	All climates	High	Moderate	High	High	Low
Envelope Leakage	Low	Low	High	All climates	High	Moderate	High	Low	High
RCC Roof	Moderate to high	High	High	All climates	High	Moderate	High	Moderate	High
Ventilated Cavity Roof	Moderate	Moderate	High	Hot and dry, composite	High	Low	High	Moderate	Low
Green Roofs	Moderate	Low	Low	All climates	High	Moderate	High	High	High
Cool Roofs	Low	Low	High	Hot and dry, composite, warm and humid, temperate	High	Moderate	High	Moderate	High
Films and Coatings (windows)	Low	Moderate	Moderate	Hot and dry, composite, cold	High	High	High	Moderate	Moderate

Strategy	Initial Cost	Embodied Carbon	Market Availability	Recommended Climates	Operational Energy Savings by Climate				
					Hot and Dry	Warm and Humid	Composite	Temperate	Cold
Double Glazed Units	Moderate to high	High	Moderate	Hot and dry, composite, warm and humid, cold	High	High	High	Low	High
Insulation Materials	Moderate to high	Moderate to high	Moderate	All climates	High	Moderate	High	Low	High
Multi-Split Room Air Conditioner - VRF Systems	Moderate to high	High	High	All climates	High	Moderate	High	Moderate	High
Portable Air Filters	Moderate	Moderate	Moderate	All climates	Moderate	Moderate	Moderate	Moderate	Moderate
Centralized Air Conditioners	High	High	High	All climates	Moderate	Moderate	Moderate	Low	Moderate
Air Circulation Devices	Low	Low to moderate	High	All climates	Moderate	High	Moderate	High	High
Mechanical Ventilation Systems	Low	Low to moderate	Moderate	All climates	High	Moderate	High	High	Moderate
Evaporative Coolers	Low	Low to moderate	High	Hot and dry, composite	High	Low	High	Moderate	Low

Annex 3: Additional Resources

This section provides a list of additional tools and references that readers can refer to perform analysis for - climate and comfort, spatial and passive design, thermal properties of construction materials and technologies, and cooling and indoor air quality systems.

Climate and Comfort Analysis Tools

- Climate Consultant by United States Department of Energy (https://climate-consultant.informer.com/6.0/)
- Honeybee by Ladybug (https://www.ladybug.tools/honeybee.html)
- Comfort and Weather Analysis by Centre for Advanced Research in Building Science and Energy (CARBSE) (https://carbse.org/research-tools/)
- Multi-City Comfort and Weather Comparison by Centre for Advanced Research in Building Science and Energy (https://carbse.org/research-tools)
- Cove Tool by Cove Tools (https://www.cove.tools/)
- Center for Built Environment (CBE) thermal comfort tool (https://comfort.cbe.berkeley.edu/)
- The Energy and Resources Institute (TERI) Climate tool (http://tct.teriin.org/ClimatePortal/Default.aspx)
- Climate Studio (https://www.solemma.com/climatestudio)

Spatial and Passive Design Analysis

- Tool – CoolVent by Massachusetts Institute of Technology (http://coolvent.mit.edu/)
- Guidelines and Tool – Low Energy Cooling and Ventilation for Indian Residences (LECaVIR) by Centre for Advanced Research in Building Science and Energy (URL: https://carbse.org/lecavir-3/)
- Book – The Architecture of Natural Cooling by Ford et al., 2019
- Tool – VIZcab (https://vizcab.io)

Thermal Analysis of Construction Materials and Technologies Tools

- THERM by Lawrence Berkeley National Laboratory (https://windows.lbl.gov/software/therm)
- WINDOW by Lawrence Berkeley National Laboratory (https://windows.lbl.gov/software/window)
- Honeybee by Ladybug (https://www.ladybug.tools/honeybee.html)

Cooling and Indoor Air Quality Systems Analysis

- Study – Evaluation of Indoor Air Quality Screening Strategies: A Stepwise Approach for IAQ Screening by Wong et al., 2016

- Tool – Indoor Air Quality Design Tools for Schools by United States Environmental Protection Agency (https://www.epa.gov/IAQ-schools/indoor-air-quality-design-tools-schools)
- Guidelines – Enhance Indoor Environmental Quality (IEQ) by Whole Building Design Guide Sustainable Committee (https://www.wbdg.org/design-objectives/sustainable/enhance-indoor-environmental-quality)

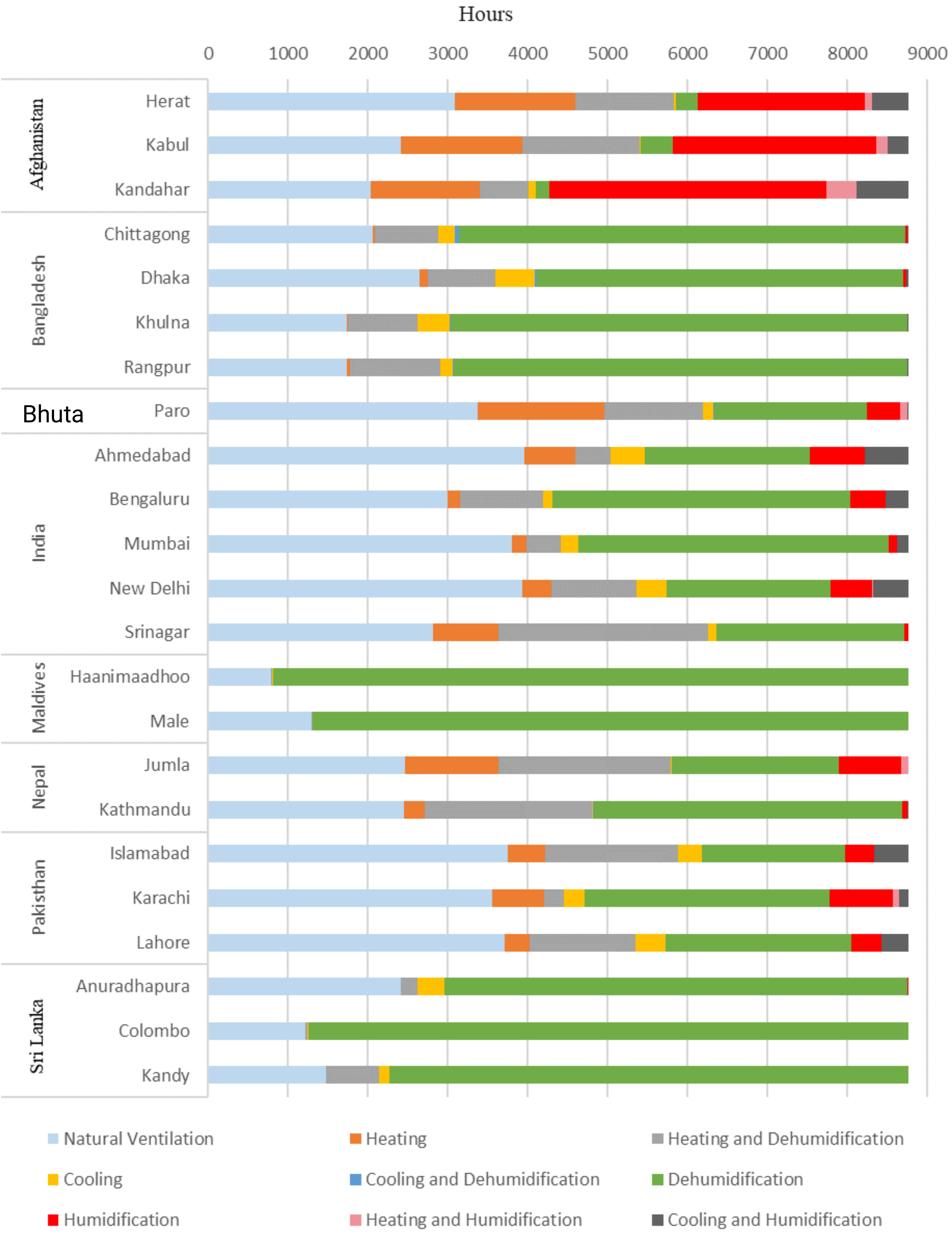
IT-based Analysis of Buildings Tools

- Building Assessment Tool (BAT) by United States Department of Energy (https://www.wbdg.org/additional-resources/tools/building-assessment-tool-bat)
- EnergyPlus by United States Department of Energy (https://www.energy.gov/eere/buildings/downloads/energyplus-0)
- Facility Energy Decision System (FEDS) by Pacific Northwest National Laboratory (PNNL) (https://feds.pnnl.gov/)
- Modelica Buildings Library by Lawrence Berkeley National Laboratory (https://simulationresearch.lbl.gov/modelica/)
- Radiance (https://www.radiance-online.org/)

4.4 Annex 4: India Model for Adaptive Comfort

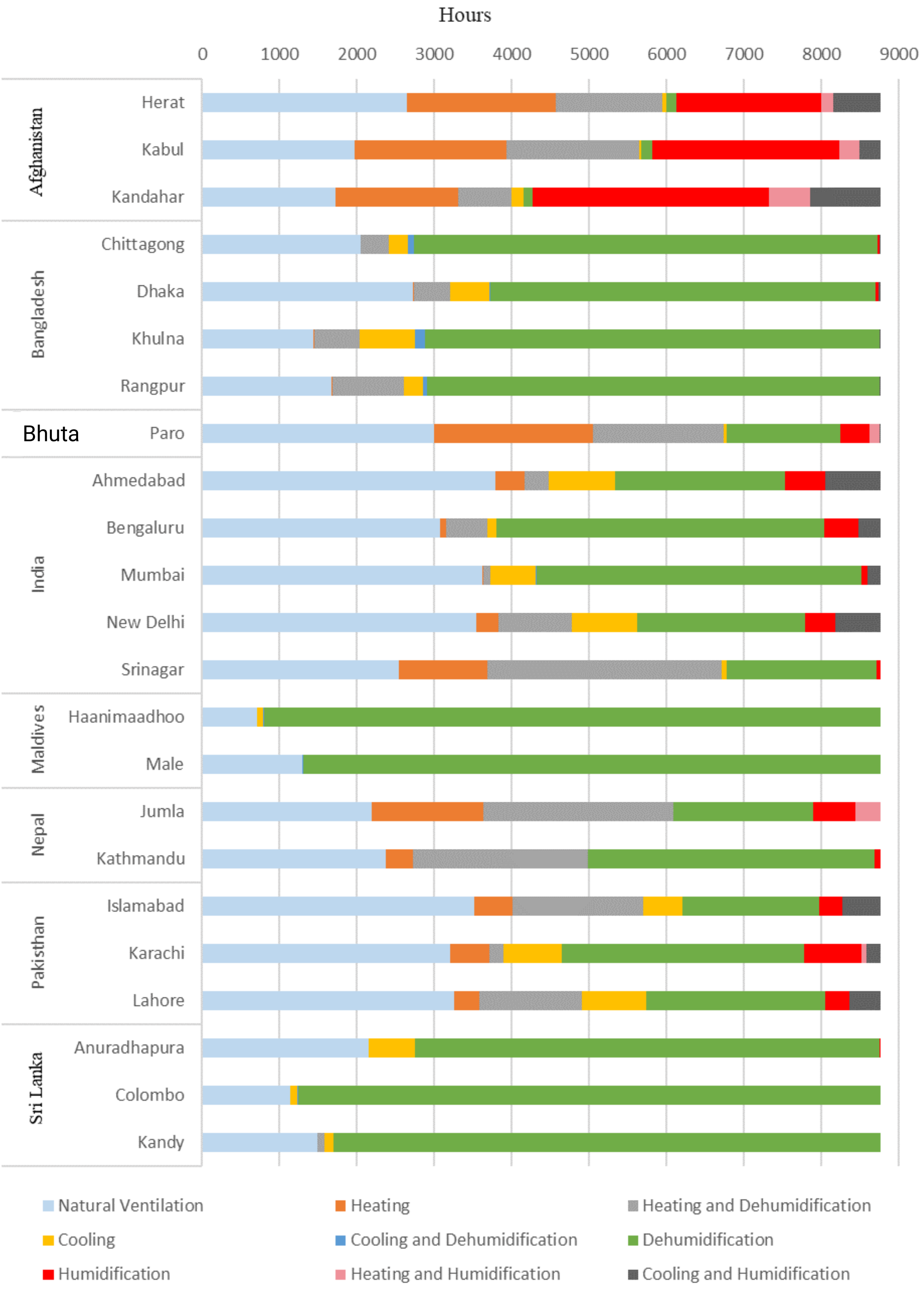
This section provides information on the different strategies buildings need to adopt based on the IMAC. **Figure** A.4.1 shows the operational strategies/modes that can be used in naturally ventilated commercial building, and **Figure A4.2** shows the operational strategies/modes that can be adopted in a commercial office building operating in mixed mode.

Figure A4.1. Operation modes for naturally ventilated commercial buildings



Source: Author's analysis.

Figure A4.2. Operation modes for commercial buildings operating in mixed mode



Source: Author's analysis.

Annex 5: Climate Analysis for South Asian Cities

Table A5.1 shows the UTCI, WBGT, and HI values for all the identified cities in South Asia in the report.

Table A5.1 Number of days in a year binned into thermal index categories for each city

Country	City	UTCI >46	UTCI between 38 and 46	HI >54	HI between 41 and 54	WBGT >30	WBGT between 28 and 30
		Extreme heat stress	Strong heat stress	Sweltering (extreme danger)	Very hot (dangerous)	Sweltering (extreme danger)	Very hot (danger)
Afghanistan	Herat	138	106	0	4	15	36
	Kabul	22	110	0	1	3	6
	Kandahar	124	120	0	33	51	35
Bangladesh	Dhaka	130	109	0	195	240	29
	Khulna	204	100	1	221	256	19
	Chittagong	92	151	0	208	244	32
	Rangpur	107	130	0	152	218	29
Bhutan	Paro	6	117	0	1	1	7
India	Ahmedabad	311	16	0	191	226	46
	Bengaluru	153	119	0	0	44	120
	Delhi	229	78	2	152	182	28
	Mumbai	242	36	0	220	276	58
	Srinagar	89	162	0	0	10	27
Maldives	Hanimaadhoo	183	102	0	308	365	0
	Malé	139	38	0	332	365	0
Nepal	Biratnagar	126	154	1	183	228	38
	Jumla	4	200	0	0	1	2
	Kathmandu	22	127	0	1	22	74
Pakistan	Islamabad	164	115	0	4	15	36
	Karachi	242	71	0	169	209	31
	Lahore	220	98	0	150	183	20
Sri Lanka	Anuradhapura District	202	91	0	201	352	13
	Colombo	196	142	0	230	363	2
	Kandy	160	113	0	33	51	35

Annex 6: Climate Classification of Additional South Asian Cities

The report primarily focuses on the building-level ventilation and cooling of a few South Asian cities. However, the benefits of these strategies can be estimated using the climate classification of additional South Asian cities provided in **Table A6.1.**

Table A6.1. Climate classification of additional South Asian cities

India		
S.no	**Cities**	**Climate Zones**
1	Ahmedabad	Hot & Dry
2	Allahabad	Composite
3	Amritsar	Composite
4	Aurangabad	Hot & Dry
5	Bangalore	Temperate
6	Barmer	Hot & Dry
7	Belgaum	Warm & Humid
8	Bhagalpur	Warm & Humid
9	Bhopal	Composite
10	Bhubaneswar	Warm & Humid
11	Bikaner	Hot & Dry
12	Chandigarh	Composite
13	Chennai	Warm & Humid
14	Chitradurga	Warm & Humid
15	Dehradun	Composite
16	Dibrugarh	Warm & Humid
17	Gorakhpur	Composite
18	Guwahati	Warm & Humid
19	Gwalior	Composite
20	Hissar	Composite
21	Hyderabad	Composite
22	Imphal	Warm & Humid
23	Indore	Composite
24	Jabalpur	Composite
25	Jagdalpur	Hot & Dry
26	Jaipur	Composite
27	Jaisalmer	Hot & Dry
28	Jalandhar	Composite
29	Jamnagar	Warm & Humid
30	Jodhpur	Hot & Dry
31	Jorhat	Warm & Humid
32	Kochi	Warm & Humid
33	Kolkata	Warm & Humid
34	Kota	Hot & Dry
35	Kullu	Cold

36	Kurnool	Warm & Humid
37	Leh	Cold
38	Lucknow	Composite
39	Ludhiana	Composite
40	Manali	Cold
41	Mangalore	Warm & Humid
42	Mumbai	Warm & Humid
43	Nagpur	Composite
44	Nellore	Warm & Humid
45	New Delhi	Composite
46	Panjim	Warm & Humid
47	Patna	Composite
48	Pune	Warm & Humid
49	Raipur	Composite
50	Rajkot	Composite
51	Ramgundam	Warm & Humid
52	Ranchi	Composite
53	Ratnagiri	Warm & Humid
54	Raxaul	Warm & Humid
55	Saharanpur	Composite
56	Shillong	Cold
57	Sholapur	Hot & Dry
58	Srinagar	Cold
59	Sundernagar	Cold
60	Surat	Hot & Dry
61	Tezpur	Warm & Humid
62	Tiruchirappalli	Warm & Humid
63	Tuticorin	Warm & Humid
64	Udhagamandalam	Cold
65	Vadodara	Hot & Dry
66	Veraval	Warm & Humid
67	Vishakhapatnam	Warm & Humid
Pakistan		
1	Faisalabad	Warm & Humid
2	Islamabad	Cold
3	Karachi	Hot & Dry
4	Lahore	Warm & Humid
5	Multan	Warm & Humid
6	Rawalpindi	Cold
Bangladesh		
1	Dhaka	Warm & Humid
2	Chittagong	Warm & Humid
3	Khulna	Warm & Humid
4	Rangpur	Warm & Humid

Sri Lanka		
1	Ampara	Warm Dry
2	Anuradhapura	Warm & Humid
3	Anuradhapura	Warm Dry
4	Badulla	Uplands, Warm Dry, Warm & Humid
5	Batticaloa	Warm Dry
6	Colombo	Warm & Humid
7	Galle	Warm & Humid
8	Gampaha	Warm & Humid
9	Hambantota	Warm Dry
10	Jaffna	Warm Dry
11	Kalutara	Warm & Humid
12	Kandy	Warm & Humid, Warm Dry
13	Kegalle	Warm Dry
14	Kilinochchi	Warm Dry
15	Kurunegala	Warm & Humid, Warm Dry
16	Mannar	Warm Dry
17	Matale	Warm & Humid, Warm Dry
18	Matara	Warm & Humid
19	Monaragala	Warm Dry
20	Mullaitivu	Warm Dry
21	Nuwara Eliya	Uplands, Warm Dry, Warm & Humid
22	Polonnaruwa	Warm Dry
23	Puttalam	Warm Dry
24	Ratnapura	Warm & Humid, Warm Dry
25	Trincomalee	Warm Dry
26	Vavuniya	Warm Dry

Annex 7: Simulation Details

Geometry and simulation inputs (including operation schedules, setpoints, internal loads, and ventilation strategies) of BAU residential apartment are detailed here. The simulation was conducted in the EnergyPlus engine. Further, the simulation was run for a middle-floor apartment to determine the energy saving of the proposed measures (except for roof insulation). The top-floor apartment was used in the simulation for roof insulation measures to estimate the energy benefit. For commercial buildings, the geometry and simulation inputs are extracted from baseline units specified in Energy Conservation Building Code 2017 (ECBC 2017).

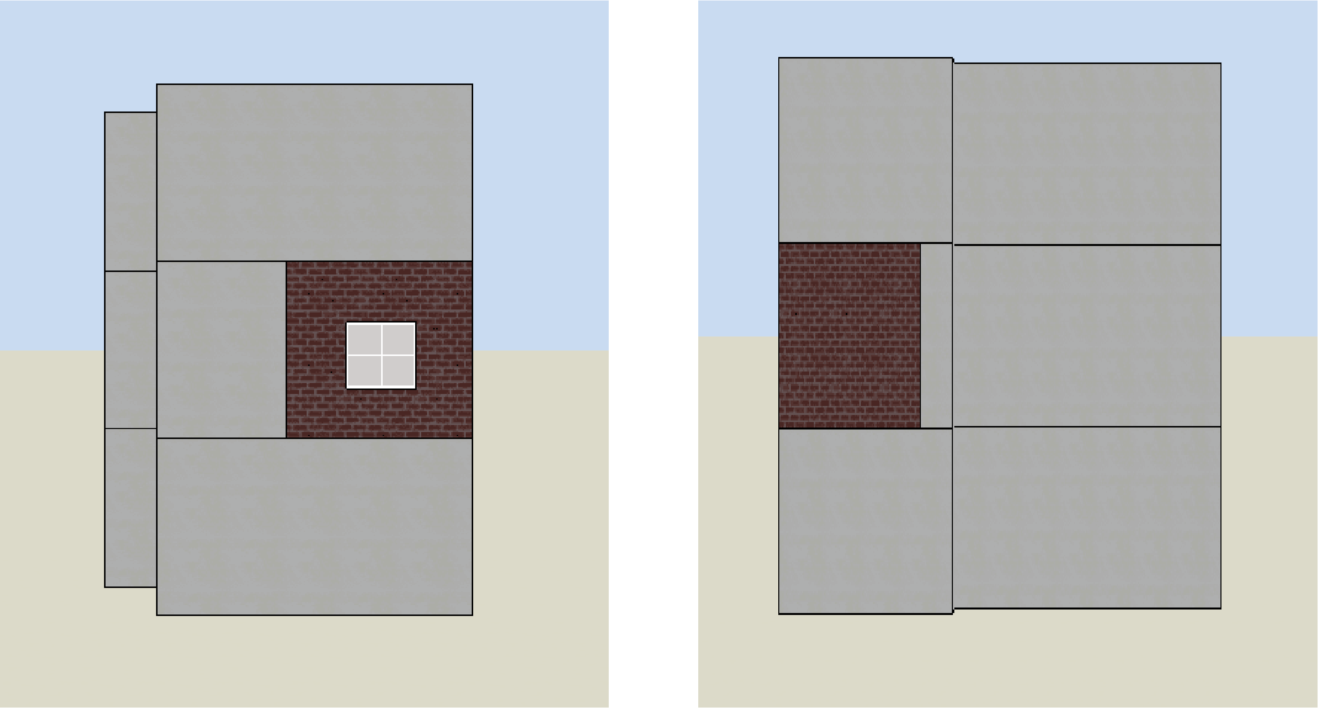
7.1. Simulation Inputs

Table A7.1. Simulation inputs for measures assessed in the report

Indicators	BAU inputs	Parametric inputs
Geometry	25 m * 40 m, with a room height of 3 m single zone for commercial buildings 3.3 m * 2.9 m, room height of 3 m, with a window of size 1.1 m * 1.1 m for residential buildings	-
Orientation	E-W elongated (0°)	90°, 180°, 270°
Wall construction	230 mm brick wall	510 mm brick, 680 mm brick, AAC block, SIP
Wall U-value	1.722 W/m²K	1.2, 0.9, 0.8, 0.52
Roof construction	100 mm RCC	Vegetated roof, Cool roof
Roof U-value	2.94 W/m²K	1.5, 0.4
Window construction	Single clear 3 mm	3 mm single Low-E, DGU with Argon
Window U-value	5.894	3, 2.2
Window SHGC	0.861	0.27, 0.25
Window VLT	0.898	0.8, 0.8
Shading depth	No shading	0.7m
Window operation	24/7 Off	Open based on outdoor conditions
WWR	30%	30%
HVAC system CoP	3	4.5
LPD	15 W/m²	15 W/m²
EPD	24 W/m²	24 W/m²
Lighting schedule	As per ECBC	As per ECBC
Equipment schedule	As per ECBC	As per ECBC
HVAC schedule	As per ECBC	As per ECBC

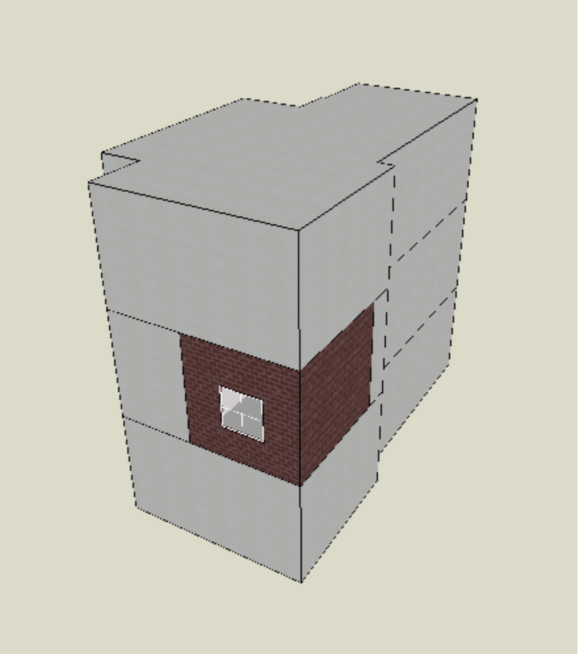
7.2. Residential Building Model

Figure A7.1. Residential building: Views 1 & 2



Source: Author

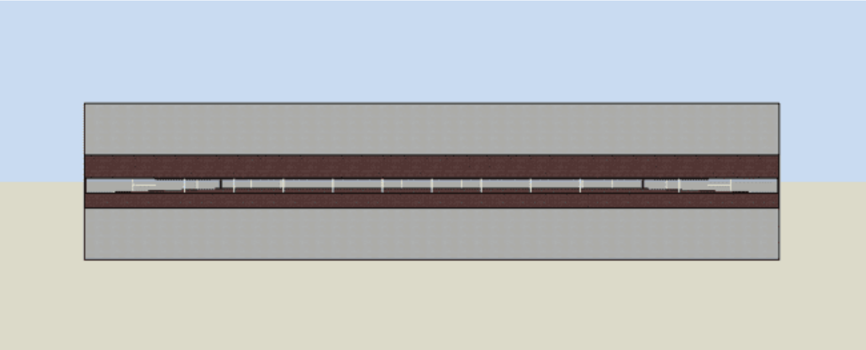
Figure A7.2. Residential building: View 3



Source: Author

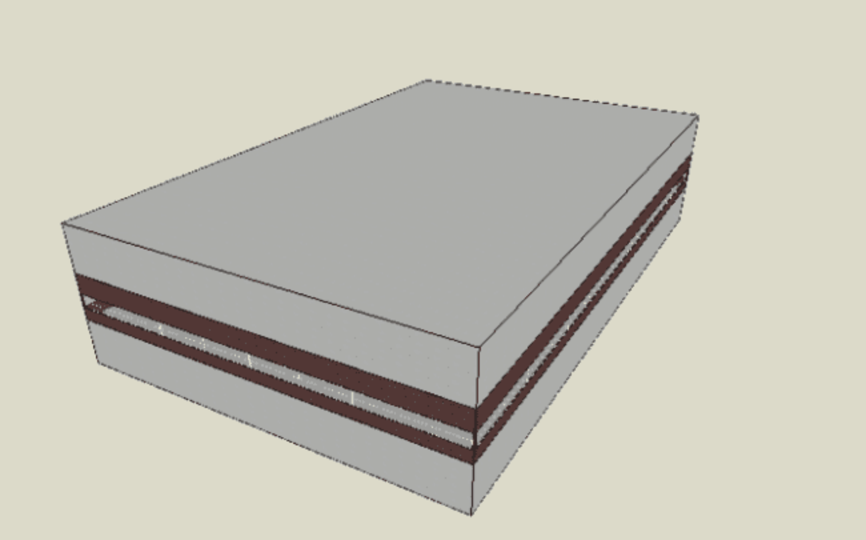
7.3. Commercial Building Model

Figure A7.3. Commercial building model: View 1



Source: Author

Figure A7.4. Commercial building model: View 2



Source: Author

Annex 8: Survey with Stakeholders

We conducted a survey of stakeholders including industry professionals and domain experts from India (10), Pakistan (eight), Sri Lanka (seven), and Bangladesh (seven). The following survey form was shared with all the stakeholders to gather inputs on the regional market availability of passive and active design measures and their incremental costs. However, as the stakeholders had questions on the survey form that required clarification, a structured discussion over 40-50 minutes using the survey form as a questionnaire was held with the stakeholders, and all their inputs were recorded and presented in the report.

The survey form is a part of the study conducted by the Center for Advanced Research in Building Science and Energy (CARBSE) to assess multiple market-ready building-level cooling and ventilation interventions qualitatively.

Market Availability

Low availability—Significant efforts are required to procure and implement the solution.

Moderate availability—Strategy is accessible but difficult to procure and implement.

High availability—The strategy is feasible to implement with minimal effort.

Incremental Costs

Low cost—The strategy has a low incremental cost.

Moderate cost—The strategy has a moderate incremental cost.

High cost—The strategy has a high incremental cost.

Please select only one box (high, moderate, or low) for each strategy regarding market availability and climate dependency on cost-effectiveness.

Qualitative Assessment of Strategies	Market Availability			Incremental Costs		
	High	Moderate	Low	High	Moderate	Low
Building Orientation						
Natural Ventilation						
Shading						
Cool Roof						
Air-Circulation Devices						
Mechanical Ventilation						
Evaporative Coolers						
Thermal Mass						
Walling Technologies						
Roofing Technologies						
Fenestration Systems						
High-efficiency AC						

Definition of strategies

Building Orientation – Considering the layout and solar orientation of the building in response to the site location, topography, vegetation, wind flow, and natural shading.

Natural Ventilation - Natural ventilation uses the natural forces of wind and buoyancy to deliver fresh air into buildings.

Shading - Fixed and moveable building shading devices have great potential to reduce heat ingress through the windows by blocking direct solar gains with minimum energy consumption, improving thermal and visual comfort.

Cool Roof - Cool Roof coatings applied on rooftops have high solar reflectivity leading to decreased roof surface temperatures.

Air-circulation Devices - Air circulation devices, such as ceiling fans, are a reliable solution to reducing the reliance on air-conditioning in climates where passive solutions are insufficient. Air-circulation devices do not actively contribute to improving ventilation in the space.

Mechanical Ventilation - Ventilation or introducing outdoor/fresh air into the building by mechanical means such as fans or Air-Handling Units (AHU).

Evaporative Coolers – In evaporative coolers, the cooling process involves water passing over a wet pad, and the air is made to flow through it, where the heat is transferred from air to water.

Thermal Mass - The thermal mass of the building describes the ability of the building to provide inertia against indoor temperature fluctuations compared to outdoor temperatures.

Walling Technologies – Walling technologies improve the thermal performance of the walls by using different materials such as fly ash bricks, Autoclaved Aerated Concrete (AAC) blocks, or technology such as Structurally Insulated Panels (SIP).

Roofing Technologies - Roofing technologies improve the thermal performance of roofs by using different materials such as cool roof paints or technology such as vegetated roofs and ventilated cavity roofs.

Fenestration Systems – Highly efficient single-glazed low e-coating films and double-glazed units with inert gases like argon.

High-efficiency air conditioners – Super efficient air-conditioners with high co-efficient of performance. Including air-conditioning systems for residential as well as commercial purposes.

Annex 9: Air Quality in South Asian Countries

This section provides details of the average annual concentration of PM 2.5 levels in all cities. The data were sourced from the WHO air quality database for the year 2021.

Table A4.1. PM 2.5 average annual concentration of all cities

	PM 10 (µg/m³)		PM 2.5 (µg/m³)	
	Annual mean concentration	24 h concentration	Annual mean concentration	24 h concentration
Interim target – 1	70	150	35	75
Interim target – 2	50	100	25	50
Interim target – 3	30	75	15	37.5
Air quality guideline	20	50	10	25
Afghanistan	-	-	62	-
Bangladesh	-	-	46	-
Bhutan	-	-	26	-
India	-	-	50	-
Maldives	-	-	13	-
Nepal	-	-	36	-
Pakistan	-	-	50	-
Sri Lanka	-	-	23	-

[1] PM 10: Airborne particulate matter smaller than 10 µm (includes both coarse and fine particles that enter the respiratory tract).

[2] PM 2.5: Airborne particulate matter smaller than 2.5 µm.

[3] Interim targets represent incremental steps in a progressive reduction of air pollution. Annual mean concentrations provide an estimate of long-term exposure for comparison.

[4] *Lowest levels at which total, cardiopulmonary, and lung cancer mortality have been shown to increase in response to long-term exposure to PM 2.5.