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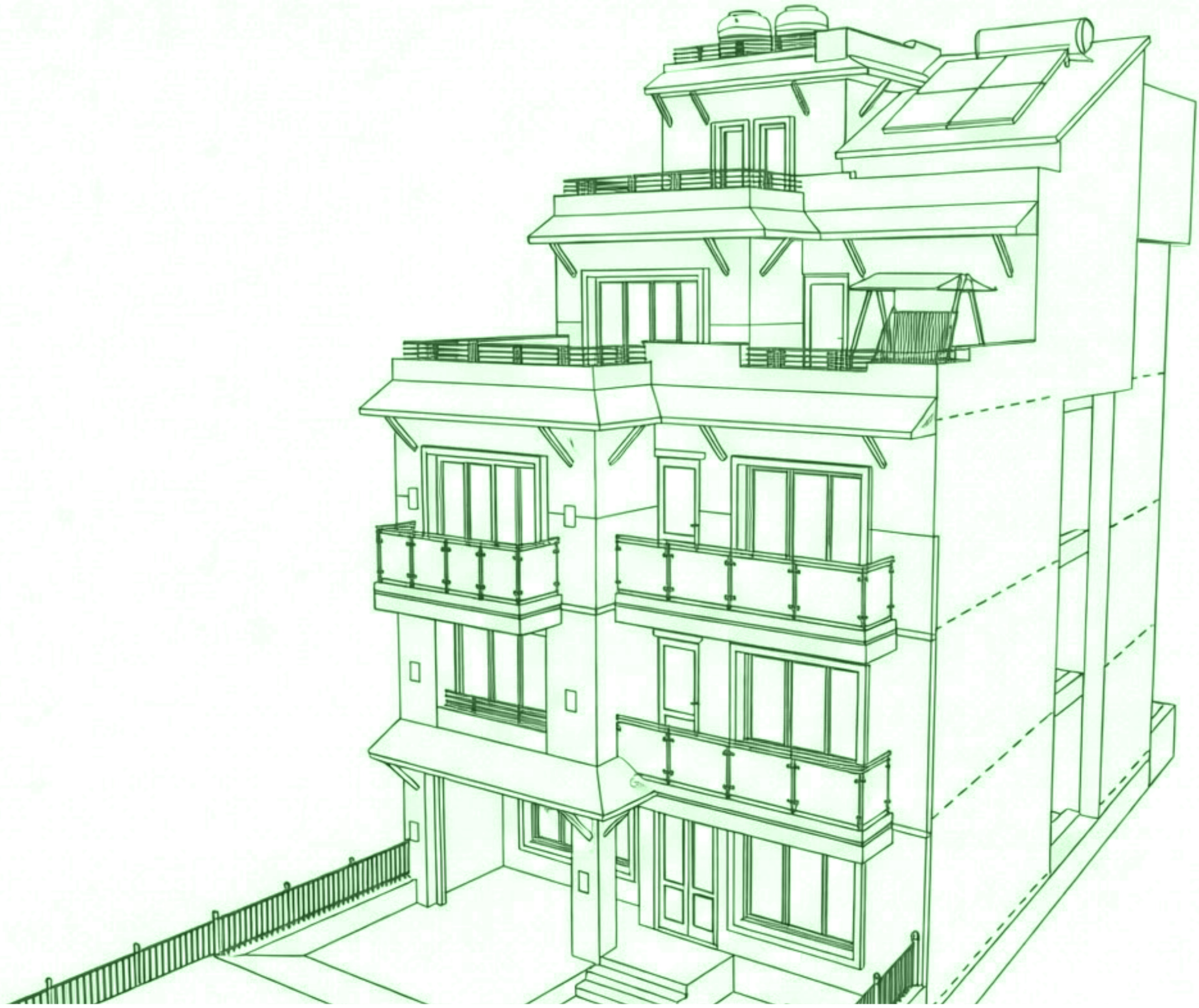

Manual for

ENERGY-EFFICIENT BUILDING DESIGN

SECOND EDITION

universität innsbruck
Unit of
Energy Efficient Buildings

MinErgy

Greentech Knowledge Solutions Pvt. Ltd.

UNE Normalización Española

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Recommended Citation
BUILDING Energy Efficiency in Nepal (BEEN) Project. (2026). MANUAL FOR ENERGY-EFFICIENT BUILDING DESIGN. BUILDING Energy Efficiency in Nepal (BEEN) project funded by the European Union under the SWITCH-ASIA Grants Programme.

https://been.minergynepal.com/resources/#

Edition
Second

Published by
BUILDING
ENERGY
EFFICIENCY IN
NEPAL

MinErgy Pvt. Ltd

Dakshinkali Chowk, Manbhawan, Lalitpur 44700

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Nepal in Data, initiative of Bikas Udhyami

Disclaimer
This publication is funded by the European Union under the SWITCH-ASIA Grants Programme. Its contents are the sole responsibility of the BEEN Project and do not necessarily reflect the views of the European Union.

This Manual is intended as a guide for designers to design energy efficient building in Nepal. The methods described in the manual are based on good practices, research findings, and consultations with professional expertise in energy efficiency and sustainable design. While every effort has been made to ensure the accuracy and reliability of the information presented, it is important to acknowledge that building design and construction practices may vary significantly based on local climate conditions, regulations and project-specific requirements. Thus, the authors, publishers, funders or any legal entity or person associated with this design manual disclaim any responsibility (legal, social or financial) for any adverse conditions/consequences resulting from the suggested procedures, from any undetected errors, or from the readers misunderstanding of the text. Moreover, this Manual is not intended to replace or override any legal or regulatory requirements that may be applicable to the design and construction of buildings in Nepal.

Preface

Energy consumption for space conditioning in buildings is in increasing trend in Nepal. Most of the buildings are continued to be designed without considering local climatic conditions, resulting in poor ventilation, excessive heat gain, or inadequate daylight, which leads to high energy use for heating, cooling, and lighting. Climate-responsive design and energy efficiency are often not prioritized during early stages of planning and design. Much of this can be addressed through simple, well-informed climate-responsive design decisions, such as optimizing the building envelope, ensuring proper orientation, enhancing insulation, designing effective windows and shading, using double-glazed windows, and selecting materials suitable for local climates.

Evidences demonstrated that buildings, designed considering local bio-climatic conditions, can reduce energy demand in its lifetime without compromising on better thermal comfort for users Limited understanding and application of building physics among design professionals has remained a key challenge. This "***Manual for Energy-Efficient Building Design for Architects & Designers***" has been developed to bridge that gap by supporting architects and engineers including building consulting firms in understanding how design decisions affect the energy performance and comfort of buildings. It provides fundamental knowledge and practical strategies to promote thermal comfort, visual comfort, and overall energy efficiency in buildings suited to Nepal's diverse climatic conditions. Concepts are presented in a structured and easy-to-follow manner, from understanding how a building affects the thermal and visual comfort of its occupants to exploring passive design strategies, heat transfer mechanisms, and daylighting techniques.

This revised edition builds on the previous version with updated and expanded technical content, further enhancing its practical guidance for architects, engineers, and building professionals. The revision was prompted by the insights gained from the Training of Trainers, the experience of conducting several trainings as well as improvised based on the simulation results of various building typologies across four bio-climatic zones of Nepal. Based on the feedback and experiences of the trainers, this edition incorporates additional key topics on "Resource-Efficient Materials", Heat Transfer through Fenestration", and "Advanced Construction Technologies". Efforts have been made to ensure better visualization and content clarity throughout the document. Key metrics and terminologies are incorporated aligning to Building By-law and Standard Operating Procedures (SOP) requirements. The content has also been revised with the gender and social inclusion lens to reflect on the thermal safety requirements of the vulnerable populations. It seeks to inspire professionals and provide them the guidance to integrate energy efficiency principles at every stage of the design process.

This Manual was developed as part of the "BUILDING Energy Efficiency in Nepal" (BEEN) project, funded by the European Union under the SWITCH-Asia Grants Programme.

Government of Nepal
Ministry of Federal Affairs & General Administration
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Your Ref No.:

Our Ref. No.:

Message

On behalf of the Ministry of Federal Affairs and General Administration (MoFAGA), I am glad to share this revised version of the **"Manual for Energy-Efficient Building Design".** This manual marks a significant milestone in advancing energy efficiency and promoting climate-responsive building design practices in Nepal ensuring thermally safe, healthy and productive spaces for the occupants. Relevancy of this revised manual has become more prominent with incorporation of the results and practical lessons gained during the implementation of BUILDING Energy Efficiency in Nepal (BEEN) project, funded by the European Union under the SWITCH-Asia Grants Programme. Amidst the incidences of extreme climates and the current practice of building design and construction, energy consumption for space conditioning in buildings has been increasing in recent years.

Mindful design in response to the local climatic conditions not only lowers operational energy costs but also improves thermal comfort to achieve healthy environment for the building users. Acknowledging the crucial role of architects, designers, and engineers in shaping the nation's-built environment, this manual offers practical guidance and methodologies to support design professionals in adopting climate-responsive building design strategies. I am confident that this will also serves as a reference for the technical personnels under the Building Permit Units of the local governments, thereby contributing to the federalization as well as environment-friendly governance practices aligning to the Environment-friendly Local Governance Framework-2013.

I would like to acknowledge the commendable efforts of the **BEEN Project**, implemented in collaboration with **MoFAGA** and supported by national and international partners, in developing this valuable resource. I am confident that this manual will serve as a key reference for local governments, private practitioners, and academic institutions in promoting energy-efficient design practices across Nepal. I encourage all design professionals to utilize this manual effectively and contribute to shaping a more sustainable, energy-secure, and climate-resilient future for our nation.

Nita Pokhrel Aryal
Joint Secretary
Ministry of Federal Affairs and General Administration (MoFAGA)

EUROPEAN UNION
DELEGATION TO NEPAL
Head of Cooperation

Message

This edition of the Manual for Energy Efficient Building Design is a key resource, developed and revised based on the evidence and experiences of the BUILDING Energy efficiency in Nepal (BEEN) project, the stakeholders and value-chain actors, specifically the designers and municipality officials to respond to the specific needs of Nepal's varied bio-climatic conditions. The BEEN project, funded by the European Union's SWITCH-Asia Programme, demonstrated the possibility of decoupling growth from resource use in the building sector, primarily by reducing energy demand for space conditioning in new and existing buildings in Nepal, thereby enabling people to achieve thermal comfort.

The new edition features significant additions, including two new chapters. The first chapter on "Heat Transfer through Fenestration" details how window design impacts indoor comfort and energy consumption. The second chapter on "Resource Efficiency Materials and Construction Technologies" focuses on sustainable construction methods. Images and diagrams have been updated and better tailored to the Nepalese context. Climate graphs from additional locations in Nepal have been integrated to improve relevance. Also, the content addresses thermal safety and comfort in buildings through a crucial gender and social inclusion lens. These additions collectively help designers with technical guidance, tools and best practices to integrate energy efficiency principles into building design. Further, it also serves as a practical instrument for climate-responsive building designs contributing to support Nepal's efforts towards achieving its Sustainable Development Goals and Nationally Determined Contribution targets. This reaffirms our shared commitment to sustainable, inclusive, and resilient development for the people of Nepal.

The European Union (EU) aims to achieve substantial improvements in energy efficiency across all sectors. Energy efficiency is the most immediate and cost-effective approach to reducing energy demand, and crucial for driving sustainable green transitions and enhancing energy security within EU nations. The EU is actively pursuing the decoupling of economic growth from resource use within the EU while simultaneously supporting its partners countries in accelerating their green transitions. Against this backdrop, the EU is committed to supporting Nepal ensuring its infrastructure development with global best practices for energy efficiency, circular economy and climate resilience. This effort aligns with the EU Green Deal and Global Gateway strategies, which serve as the essential delivery mechanism for fulfilling the EU's global climate ambition.

I would like to extend my since appreciation to the government, the private sector, concerned stakeholders, and the BEEN project team for their dedication and collaboration in developing this valuable resource.

Warm regards,

....

Jose Luis VINUESA-SANTAMARIA,
Head of Cooperation
EU Delegation to Nepal
Kathmandu

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Message

Buildings today are not only homes and workplaces; they are also major consumers of energy, with significant implications for the environment, the economy, and people's quality of life. As Nepal continues to experience rapid urbanization, most buildings are designed without adequate consideration of local climatic conditions, leading to an increased demand for energy in buildings for space heating, cooling and lighting purposes.

This challenge also presents a unique opportunity to integrate energy efficiency and climate-responsive design into our building practices. Through the application of passive measures in building design and construction, we can reduce the need for mechanical systems, lower energy demand, and enhance thermal comfort in a cost-effective and environmentally responsible way.

The ***"Manual for Energy Efficient Building Design (Second Edition)",*** developed by the BUILDING Energy Efficiency in Nepal (BEEN) Project, funded by the European Union's under the SWITCH-Asia Grants Programme, aims to support architects, and engineers by providing technical guidance on applying energy-efficient design principles. These include building orientation, envelope design, and other passive strategies. The manual builds upon both global knowledge and local experience, ensuring that solutions are not only technically sound but also appropriate for Nepal's diverse climatic and socio-economic contexts.

I extend my sincere appreciation to all our partners, experts, and stakeholders for their valuable contributions. Together, we are moving closer to our shared goal of promoting sustainable development and improving the quality of life for the people of Nepal through energy-efficient building design and construction.

Warm regards,

DI Dr. techn. Daniel Neyer
Project Leader (BEEN)

Acknowledgement

Development of this revised edition of the "***Manual for Energy-Efficient Building Design for Architects & Designers***" has been made possible through the collaboration and contributions of a wide network of professionals, institutions, and stakeholders. This manual reflects the collective knowledge, experience, and commitment of practitioners, national and international experts, and organizations engaged in promoting low carbon, energy-efficient and climate-responsive building design in Nepal.

We would like to extend our sincere appreciation to all individuals and institutions who have supported in the process of revising and refining this manual. This publication, led by the BUILDING Energy Efficiency in Nepal (BEEN) Project, was financially supported by the European Union under the SWITCH-Asia Grants Programme. We express our deep gratitude to Dr. Ranjan Prakash Shrestha, Senior Programme Manager, Delegation of the European Union to Nepal, for his continued guidance and support.

We also acknowledge the valuable inputs and constructive feedback from the trainers and experts to revise the manual. Their thoughtful suggestions and practical insights have been instrumental in refining and finalizing this updated version of the manual.

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Abbreviations

AAC	Autoclaved Aerated Cement Blocks
ACH	Air Changes Per Hour
ASE	Annual Solar Exposure
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BEE	Bureau of Energy Efficiency
CAD	Computer-Aided Design and drafting
CBE	Centre for the Built Environment
CFL	Compact Fluorescent Lamp
CIBSE	Chartered Institution of Building Services Engineers
CSEB	Compressed Stabilized Earth Block
DA	Daylight Autonomy
DBT	Dry Bulb Temperature
DDH	Discomfort Degree Hours
DEF	Daylight Extension Factor
DF	Daylight Factor
DGU	Double-Glazed Units
DHI	Diffuse Horizontal Irradiance
DNI	Direct Normal Irradiance
ECBC	Energy Conservation Building Code
EIA	Environmental Impact Assessment
EMSyS	External Moveable Shading Systems
EPI	Energy Performance Index
ESF	External Shading Factor
GHI	Global Horizontal Radiation
HVAC	Heating, Ventilation, and Air Conditioning
IEA	International Energy Agency
IES	Illuminating Engineering Society
IESNA	Illuminating Engineering Society of North America
IGBC	Indian Green Building Council
LED	Light Emitting Diode.
LPD	Lighting Power Density

MET	Metabolic Equivalent
MRT	Mean Radiant Temperature
PF	Projection Factor
PMV	Predicted Mean Vote
PPD	Predicted Percentage of Dissatisfied occupants
PVC	Polyvinyl Chloride
RCC	Reinforced Cement Concrete
RH	Relative Humidity
SC	Shading Coefficient
SHGC	Solar Reflective Index
SRI	Solar Reflective Index
SRR	Skylight-to-Roof Ratio
UDI	Useful Daylight Illuminance
VLT	Visible Light Transmission
WBT	Wet-Bulb Temperature
WECS	Water and Energy Commission Secretariat
WWR	Window-to-Wall Ratio
XPS	Extruded Polystyrene

1 INTRODUCTION

What's in this Section?

Introduction

Buildings account for 30% of global final energy consumption and 26% of global energy-related CO2 emissions (IEA, 2023). It is estimated that by 2030, the global building stock will increase by 15% (IEA, 2023). The rise in construction, along with increased urbanization and living standards, especially in developing countries, will continue to drive energy consumption in buildings. The primary sources of energy consumption in buildings encompass the energy used for construction, space heating/cooling, lighting, and the appliances and equipment installed in them.

Nepal is one of the top ten fastest-urbanizing countries (Bakrania, 2015). In 2022, the urban percentage of the country was 22%, and an annual urban population growth of 3.8% (World Bank). Many policies on access to clean, reliable, and appropriate energy in rural areas and the development of the renewable energy sector have been implemented in the country. It has resulted in 94 % of the total population having access to electricity today, whereas only 19% in the year 2000 (IEA, 2023). In Nepal, 70% of the total energy consumption is in the residential and commercial building sectors (WECS W. a., 2022)

Most buildings in Nepal are designed without consideration for local and changing climatic conditions, leading to low thermal comfort and an increased demand for energy to achieve it. The rising heating and cooling needs, driven by an improved living standard and the growing affordability of space conditioning, result in increased energy use when building designs are not appropriate. Passive design strategies during the early phases of the design can enhance thermal comfort and significantly reduce energy consumption.

1.1 Energy Use in Buildings

Globally, around 40% of the energy consumed in buildings is attributed to Heating, Cooling, and Ventilation (HVAC) systems. In developed regions such as the United States and the European Union, the share of HVAC in building energy usage is notably higher, accounting for around 53% (U.S.(EIA), 2019) and approximately 58% (Odyssee, Energy efficiency indicators in seurope, 2021). In India, HVAC systems contribute to 40%-60%[1] of the electricity consumption in commercial buildings, while in urban residential buildings, cooling consumes 30%-40% of the electricity used.

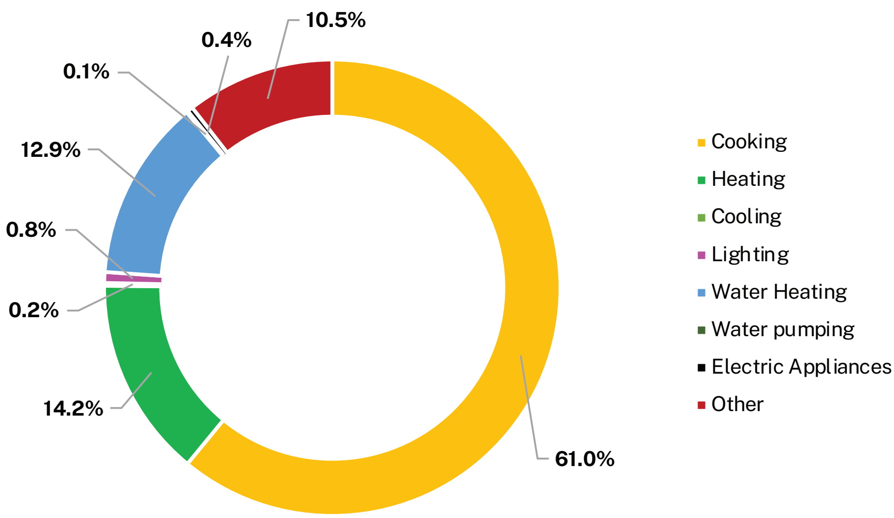
Nepal generates electricity mostly from hydropower, with surpluses exported to India in wet seasons and minor deficits imported from India during the dry seasons. Most of the

1 Building Innovation: A Guide for High-Performance Energy Efficient Buildings in India Reshma Singh, Baptiste Ravache, Dale Sartor Lawrence Berkeley National Laboratory May, 2018

energy supply is from bio-fuels and waste as 21 million people still rely on traditional biomass for cooking (IEA, 2023).

The residential energy consumption in Nepal has been increasing at the rate of 2.23% per annum in the last two years, which is higher than the population growth rate of Nepal (WECS W. a., 2022). Around 14% of the building energy is used for space cooling and space heating in residential sectors (WECS, 2014), and the same amount of energy is consumed for water heating and lighting purposes (WECS, 2014). The energy consumption by end-use for residential buildings in Nepal is shown in Figure 1.

Figure 1: Energy Consumption by End use for Residential Building in Nepal, 2014
Source: (WECS, 2014)



However, the share of space heating and cooling energy is high in new and urban buildings in Nepal. Contemporary buildings in Kathmandu use 60% of their total energy for heating and cooling (Bajracharya, 2014). If buildings are not designed with energy-efficient strategies, this demand will keep increasing at the same pace. In this regard, designers, architects, and civil engineers can play a critical role in designing such buildings in the early phase of the design. This manual targets Nepal's architects and civil engineering community to design energy-efficient and thermally comfortable buildings through passive measures.

1.2 Gender and Social Inclusion (GSI) Lens in Buildings

Applying a Gender and Social Inclusion (GSI) lens to building design is essential, as rising indoor heat disproportionately affects women, marginalized communities, and workers in heat-intensive occupations. Multiple studies have documented that the effects of elevated indoor heat vary across occupational settings and functions. The International Labour Organization (ILO, 2024) reported that workers operating within buildings lacking adequate ventilation or air conditioning -particularly those working near heat-generating machinery, are at increased risk of heat stress (Flouris A. G., 2024). Similarly, (Nepal Vishesh Rana, 2024) concluded that staff working in the waste management section of a healthcare facility equipped with autoclave machines in a warm temperate zone experienced notable thermal discomfort during summer months, in which indoor temperatures were found to be approximately 2°C higher than adjacent office areas.

The impact is also pronounced among women home-based workers. A multinational survey conducted across four countries, including Nepal, revealed that over 40% of these workers reported reduced working hours and income due to increasing temperatures, with some respondents noting up to 30% reduction in output (Coalition, 2022). Given that 75% of Nepal's 1.36 million women home-based workers (Nepal Labour Force Survey, 2017/18) fall into this category, the implications for gendered economic vulnerability are significant. Inadequate thermal comfort, largely resulting from rising heat and compounded by poorly designed buildings, could possibly further deepen the existing socioeconomic disparities.

(Ghimire, 2025) in a research article "Negotiating household heat: thermal labor, energy justice, and women's health in Nepal's Madhesh Province " draws conclusion that indoor heat exposures in kitchen surpasses ILO thresholds (Organization, 2024) during midsummer meal preparation in warm temperate zone, which is more prominent for Dalit women who largely rely on biomass fuels for cooking. Generally, in residential settings, kitchen areas can be presumed to have higher temperature levels than other areas in the buildings due to heat from cooking activities. Social norms predominantly assign women for cooking, and the burden of thermal discomfort disproportionately affects them.

Real-time performance studies of contemporary buildings located in temperate and warm temperate zones of Nepal revealed indoor temperatures exceeding ambient levels by approximately 2.5°C to 4°C (BEEN, 2024).

These evidences strongly advocate for building design practices in Nepal to enhance thermal performance and promote health, well-being, and equity, particularly in the face of rising ambient temperatures due to climate change. This underscores the critical role of inclusive and climate-responsive architectural practices in ensuring thermal comfort across diverse demographic groups and occupational contexts in order to reduce gender and social disparity as well as fulfilling the principles of "Do No Harm" and "Leave No One Behind".

1.3 Objective of the Manual

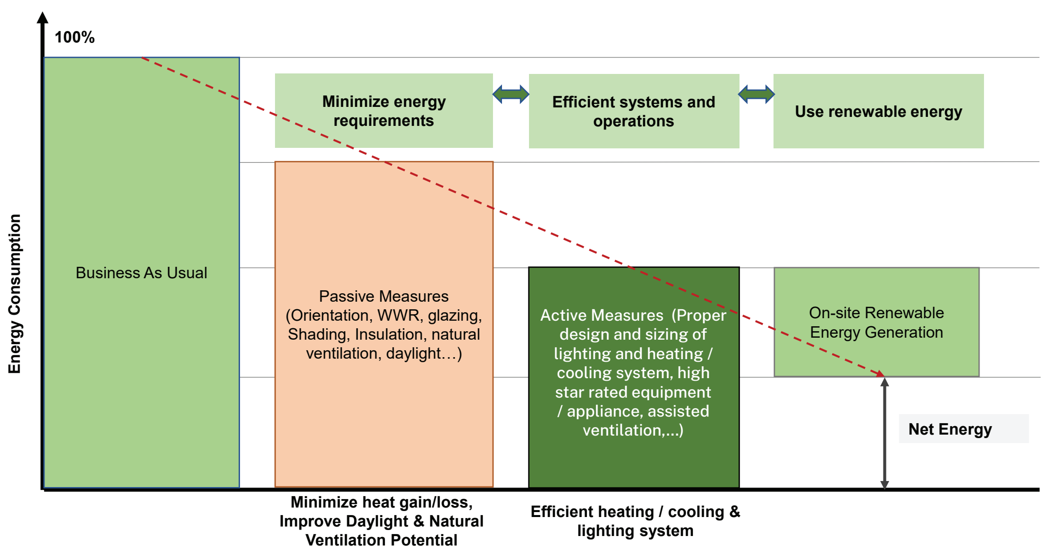
An energy-efficient building is designed based on three guiding principles. An overview of the principles is shown in Figure 2.

- First, minimize energy demand through climate-responsive and passive strategies to reduce the cooling and heating demand and lighting loads.
- Second, efficiently meet the reduced energy demand, which relies on the efficiency of the cooling, heating, and lighting systems.
- Third, utilize renewable energy sources to meet the final required energy.

This manual is intended for designers (architects and civil engineers) engaged in building design, specifically considering the first principle of energy-efficient building design. It emphasizes aspects such as building orientation, building envelope, and other design features aimed at minimizing the building's cooling, heating, and lighting loads.

Notably, this manual does not delve into the second and third principles of energy-efficient building design, namely the HVAC systems, artificial lighting systems, and renewable energy systems.

Figure 2: Principles of Energy Efficient Building Design



1.4 Outline of the Manual

The manual has nine chapters as follows:

Chapter 1 introduces the manual with objectives and the outline of the manual.

Chapter 2 covers the understanding of thermal comfort, the factors influencing it, and the thermal comfort standards as an energy-efficient building is primarily focused on thermal comfort and visual comfort with minimal energy.

Chapter 3 explains how climate influences thermal comfort, covering climate variables, sun-path diagrams, and the climate zones in Nepal.

Chapter 4 explains the heat sources in a building and how heat transfer happens through the building envelope and its components.

Chapter 5 covers natural ventilation strategies, including orientation, window operability, cross and single-sided ventilation, shallow floor plans, and fan-assisted ventilation.

Chapter 6 describes other specific design features for passive cooling and heating.

Chapter 7 discusses heat transfer through fenestration, focusing on orientation, window position and its size, shading devices, and tools for shading analysis.

Chapter 8 describes the passive strategies that would be most applicable and impactful in the climate zones in Nepal.

Chapter 9 highlights resource-efficient materials and construction techniques to promote sustainable building material and practices.

2
THERMAL COMFORT

What's in this Section?

Thermal Comfort

2.1 What is Thermal Comfort?

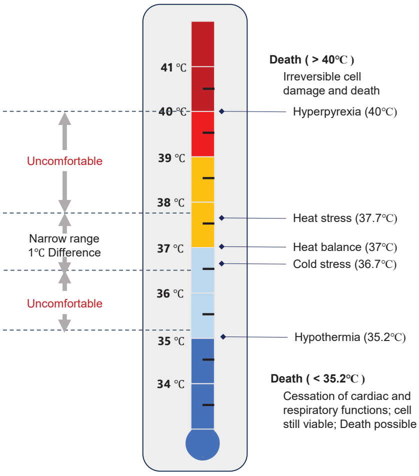
ASHRAE defines thermal comfort as *"that condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation."*

Thermal comfort is a subjective feeling of satisfaction with the thermal environment and is experienced through bodily sensation. It varies from person to person, as what one person finds comfortable might be too warm or cold for another. Therefore, when designing indoor spaces, architects and designers often aim to create an environment that are acceptable to at least 80% of occupants.

2.2 Factors Affecting Thermal Comfort

Thermal comfort is a subjective feeling of satisfaction with the thermal environment and is experienced through body sensation. Our body temperature needs to be controlled within a narrow range of 1°C from 36.7°C to 37.7°C for proper functioning. Figure 3 shows the comfort band of the human body and how the change in temperature of the human body affects health conditions.

Figure 3: Comfort Band of the Human Body



Our body always tries to achieve thermal equilibrium with the surroundings by losing excess heat to the surroundings or generating heat by increasing activity. The prominent modes of heat exchange from the human body are radiation, convection, and evaporation. However, very little quantity is lost by conduction and is dominant in heat exchange with clothing. Thus, the overall heat exchange and thermal comfort are influenced by the following:

- Environmental factors, and
- Personal factors.

2.2.1 Environmental Factors

The environmental factors affecting the thermal comfort of occupants are as follows:

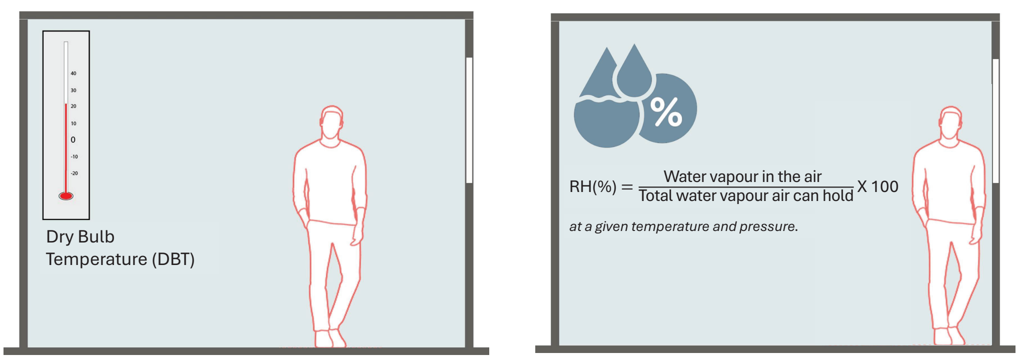
2.2.1.1 Dry Bulb Temperature (DBT) or Air Temperature

The Dry Bulb Temperature (DBT) is the temperature of air measured by a thermometer which is freely exposed to the air but shielded from radiation. DBT is usually thought of as air temperature and does not indicate the amount of moisture in the air. It is usually expressed in °C or °F. It determines whether heat loss can occur through evaporation and convection.

2.2.1.2 Relative Humidity (RH)

Relative Humidity (RH) is the ratio of the amount of water present in the air to the maximum amount that the same volume of air can hold at the same temperature. It signifies the moisture content of the air. The values of both RH and DBT of the surrounding air collectively influence the potential for heat loss through evaporation. In conditions of high RH (indicating high moisture in the air), the likelihood of evaporation to the surrounding air decreases, resulting in less heat released through sweating. Conversely, in low RH conditions (indicating low moisture in the air), the potential for evaporation increases, allowing water vapour to more readily evaporate into the air.

Figure 4: Dry Bulb Temperature (Left) and Relative Humidity (Right)



2.2.1.3 Mean Radiant Temperature (MRT)

The Mean Radiant Temperature (MRT) is a measure of the average temperature of all surfaces surrounding us, with which the human body exchanges thermal radiation. It represents the radiant heat emitted by all the surfaces within the vicinity of a point or a person in space, including walls, floors, and ceilings. Radiation heat loss or gain is driven by the temperature difference ($T_1^4 - T_2^4$, T in Kelvin: °C + 273) of the outer surface of a body (such as exposed skin or the exterior of clothing) and inner surface temperatures of the surrounding surfaces. Since radiation is the dominant form of heat transfer from the human body, MRT becomes a crucial factor in determining thermal comfort.

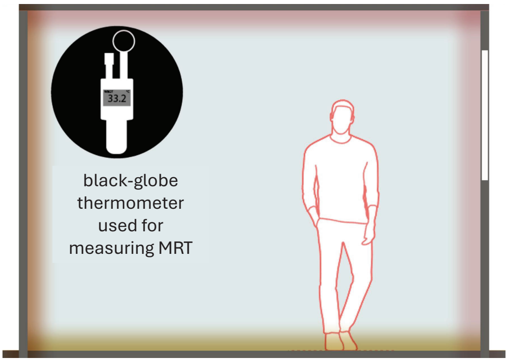
When MRT is too low, individuals may feel cold even in warm temperatures, and conversely, when MRT is too high, they may experience discomfort due to excessive warmth.

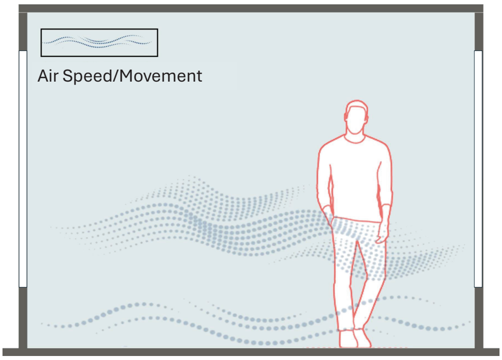
2.2.1.4 Air Speed/Air Movement

Air speed is the average speed of air, indicating its movement within a space. It is usually expressed in terms of m/s. It is averaged over time intervals between one to three minutes due to the continuous variation in air speed.

Elevated air speed influences thermal comfort in several ways. When air moves faster across the skin, it enhances heat transfer from the body to the environment through convection. Additionally, air that has absorbed sweat from the skin in the form of water vapour is carried away, and drier air takes its place, capable of absorbing water vapour through evaporation. This increased heat loss creates a cooling effect, making individuals feel cooler than in still air. However, if the air speed is too high, it can cause discomfort and make individuals feel cold, especially if the air temperature is already low.

Figure 5: Mean Radiant Temperature (left) and Air Speed (right)





Air Movement and Comfort

- Air speed doesn't cool the air itself.
- It creates a "cooling" effect by moving air around the body, increasing heat loss through convection and evaporation.
- Higher air speed increases the rate of heat loss from the skin, making individuals feel cooler.
- In warm temperatures, air movement is comfortable, while low airspeed can lead to a stagnant, stuffy feeling.
- In cold temperatures, airspeed can reduce skin temperature further, potentially causing discomfort by making the body feel colder.

2.2.2 Personal Factors

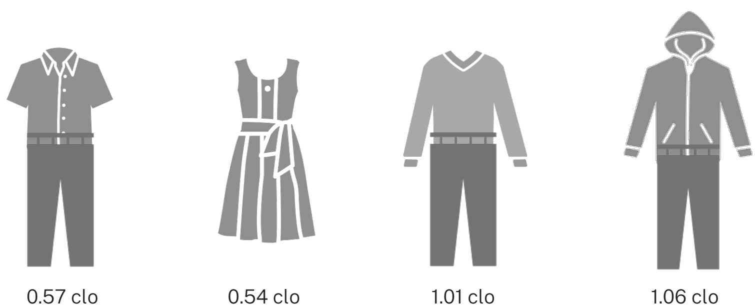
The personal factors affecting the thermal comfort of occupants are the following:

2.2.2.1 Clothing (Clo) Value

Clothing value, or Clo, is a measure of the thermal resistance of clothing and is another crucial factor in determining thermal comfort. Clothing interferes with our ability to lose heat. A resistance of 0.155 m^2K/W is considered a 1 Clo.

The Clo value of clothing is important in determining how much heat is lost from the body to the environment, and it can be used to help determine the appropriate temperature and humidity levels in a space to achieve optimal thermal comfort. In a cold environment, higher Clo values may help retain body heat and increase comfort. However, in a hot environment, a high Clo value can hinder heat dissipation from the body and lead to discomfort. Figure 6 illustrates the change in Clo value based on the clothing type providing thermal resistance.

Figure 6: The Change in Clo Value Based on the Clothing Type Providing Thermal Resistance



Source: ASHRAE-55-2010

2.2.2.2 Metabolic Rate

The metabolic rate is the amount of heat released by the human body, depending on the activities individuals are engaged in. An average person seated at rest typically produces 60 W/m^2 of surface heat and about 100 W/person, which is termed as 1 met. The more strenuous the activity, the more heat is generated.

Higher metabolic rates, such as those experienced during physical activities, can increase heat production, causing individuals to feel warmer and less comfortable. Conversely, lower metabolic rates, such as those during sedentary activities, may require less heat dissipation, allowing individuals to feel cooler and more comfortable. Metabolic rates (met Rate) for different activities are shown in Figure 5.

Figure 7: Metabolic rates (met rate) for different activities.

	Seating	Sleeping	Walking	Running
	58.2 W/m2 1.0 met	40 W/m2 0.7 met	115 W/m2 2.0 met	220 W/m2 3.8 met
About	100 W/Pers.	70 W/Pers.	200 W/Pers.	380 W/Pers.

Source: (ASHRAE, Thermal Environmental Conditions for Human Occupancy, 2010)

2.2.3 Operative Temperature

As mentioned earlier, thermal comfort depends on various personal and environmental factors. Due to the complexity of empirically fitting all these variables, a simple measure can be more practical. Operative temperature, derived from air temperature, mean radiant temperature, and air speed, is the simplified measure of human thermal comfort. When designing a building, achieving a comfortable operative temperature is a key focus.

Operative temperature can be defined as the average of the mean radiant and ambient air temperatures, weighted by their respective heat transfer coefficients. Mathematically, operative temperature can be shown as:

$$t_0 = \frac{(h_r t_{mr} + h_c t_a)}{h_r + h_c}$$ ....Equation 01

Where,

h_c = convective heat transfer coefficient, h_r = linear radiative heat transfer coefficient, t_a = air temperature, t_{mr} = mean radiant temperature, t_o = operative temperature

In simpler terms, it is the mean value of the radiant and the air temperature. (ASHRAE, Handbook on Fundamentals, 2009). This relationship is acceptable when the occupants engaged in near sedentary physical activity (with metabolic rates between 1.0 met and 1.3 met), not in direct sunlight, and not exposed to air velocities greater than 0.10 m/s.

$$t_0 = \frac{(t_a + t_{mr})}{2}$$ ....Equation 02

where t_a and t_{mr} have the same meaning as above.

2.3 Thermal Comfort Models and Indices

The desired range of thermal comfort can be defined for a building based on the comfort expectation of the users of the building and the degree of personal control offered within the indoor environment. The range of desired comfort is based on either of the following two thermal comfort models: the heat balance model and the adaptive comfort model.

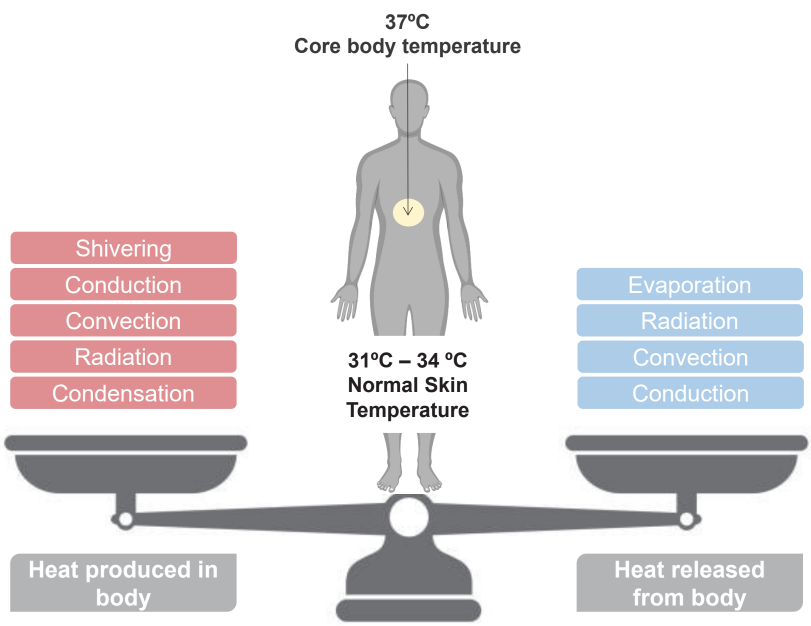
2.3.1 The Heat Balance Model

The heat balance method presents a physics based mathematical model. It establishes thermal comfort when heat loss from the body is exactly equal to the heat produced within the body. The heat balance model is illustrated in Figure 8.

The heat balance method approaches thermal comfort from a biological perspective:

- If heat generation rate > heat loss rate, the individual will feel warm/hot
- If heat generation rate < heat loss rate, the individual will feel cool/cold
- If heat generation rate = heat loss rate, the individual will experience thermal comfort

Figure 8: Heat balance model



The acceptable thermal comfort range in the heat balance method is defined by Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD).

PMV & PPD:

The Predicted Mean Vote (PMV) is an index that predicts the mean value of the votes of a large group of persons on the 7-point thermal sensation scale based on the heat balance of the human body. The sensation scale is expressed from –3 to +3 corresponding to the categories "cold," "cool," "slightly cool," "neutral," "slightly warm," "warm," and "hot." Thermal balance is obtained when the internal heat production in the body is equal to the loss of heat to the environment. PMV can be calculated for different combinations of metabolic rate, clothing insulation, air temperature, mean radiant temperature, air velocity, and air humidity (ISO:7730, 2005).

Once the PMV is calculated, the PPD or Predicted Percentage of Dissatisfied (PPD) can be determined. PPD is an index that establishes a quantitative prediction of the percentage of thermally dissatisfied people who feel too cool or too warm. Thermally dissatisfied people are those who will vote hot, warm, cool, or cold on the 7-point thermal sensation scale. Figure 9 shows the PMV and PPD scale and the comfort criteria.

For example, the desired operative temperature in offices, as per PMV/PPD, is shown in

Table 1. The considered metabolic rate is 1.2 MET, and clothing value is considered 0.5 Clo during summer ('cooling season') and 1.0 Clo during winter ('heating season').

Figure 9: PMV and PPD Scale and the Comfort Criteria

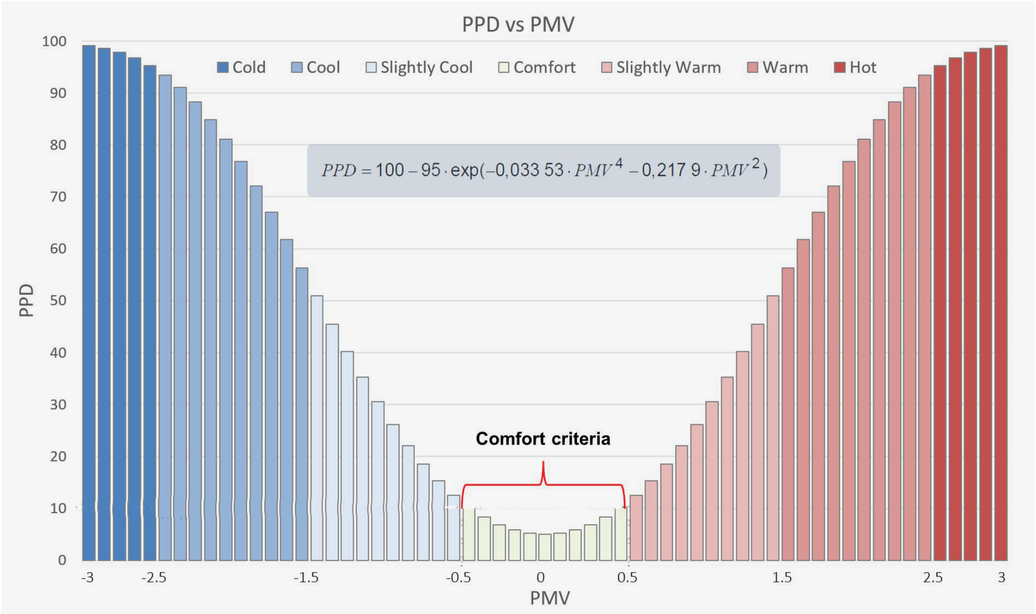


Table 1: Design Criteria for the Operative Temperature in Office Building

Activity	Category	Operative Temperature (°C)	
		Summer (Cooling Season)	Winter (Heating Season)
70 W/m²	**A** − 0.2 < PMV < + 0.2 PPD <6%	24.5 ± 1.0	22.0 ± 1.0
	B − 0.5< PMV < + 0.5 PPD <10%	24.5 ± 1.5	22.0 ± 2.0
	C − 0.7< PMV < + 0.7 PPD <15%	24.5 ± 2.5	22.0 ± 3.0

Source (ISO:17772-1, 2017)

The heat balance method quantifies the heat exchange between the human body and the immediate surrounding environment. It signifies that occupants' perception of thermal comfort relies solely on human psychology and heat transfer mechanisms between the environment and the body. However, research has indicated that thermal comfort perception is also influenced by social factors and the occupants' psychological responses to the environment.

2.3.2 Adaptive Thermal Comfort Model

Human beings naturally adjust and adapt to outside weather conditions, minimizing discomfort through changes in activity, posture, clothing, and the manipulation of windows (opening or closing). Furthermore, individuals tend to find comfort in a broader range of temperatures within a space, influenced by the prevailing outside weather conditions.

The adaptive thermal comfort model was developed to acknowledge the influence of behavioural and psychological adaptations on the human body. The adaptive thermal comfort model takes the physiological, psychological, and behavioural aspects of the occupants and their influence on perception on thermal comfort.

Acceptable thermal conditions in occupant-controlled naturally conditioned spaces: ASHRAE 55

ASHRAE 55 uses an adaptive comfort model to recommend acceptable thermal conditions for naturally ventilated spaces. This method defines acceptable thermal environments only for occupant-controlled naturally conditioned spaces that meet all the following criteria:

- No mechanical cooling system (e.g., refrigerated air conditioning, radiant cooling, or desiccant cooling) was installed. No heating system is in operation.

- Representative occupants have metabolic rates ranging from 1.0 to 1.3 met. They are free to adapt their clothing to the indoor and/or outdoor thermal conditions within a range at least as wide as 0.5 to 1.0 Clo.
- The prevailing mean outdoor temperature is greater than 10°C and less than 33.5°C.

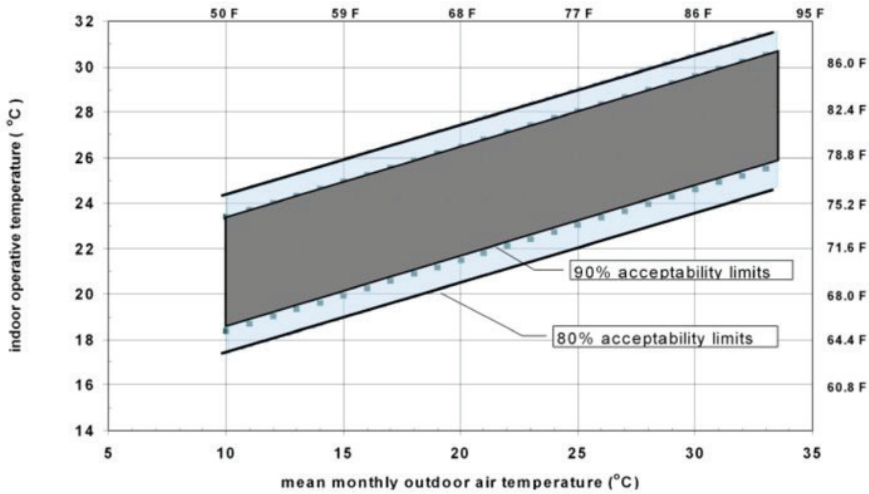
The allowable indoor operative temperatures, t0, shall be determined from the graph in Figure 8 using the 80% acceptability limits. Alternatively, the following Equation 01 and Equation 02 may be used:

Upper 80% acceptability limit (°C) = 0.31 $t_{pma(out)}$ + 21.3 ....Equation 03

Lower 80% acceptability limit (°C) = 0.31 $t_{pma(out)}$ + 14.3 ....Equation 04

Where, $t_{pma(out)}$ is the arithmetic average of the mean daily outdoor temperatures over no fewer than seven and no more than thirty sequential days before the day in question.

Figure 10: Acceptable Operative Temperature to Ranges for Naturally Conditioned Spaces (ASHRAE 55)



The ASHRAE 55 Adaptive Comfort Model has been illustrated four representative cities across varying climate zones in Nepal (Refer Figure 11 & Figure 12):

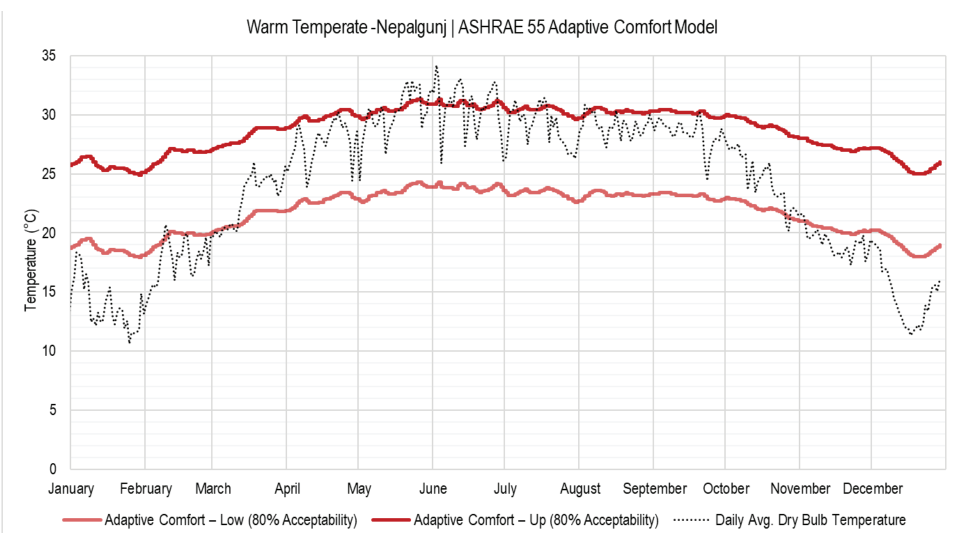
1. Warm Temperate (Nepalgunj)
2. Temperate (Kathmandu)
3. Cool Temperate (Gosainkunda)
4. Cold (Jomsom)

The graphs present the adaptive comfort band based on the 80% acceptability limit, which shifts in response to the prevailing mean outdoor temperature in each climatic zone. The following observations can be made:

- In the warm temperate (Nepalgunj) and temperate (Kathmandu) climate zone (Refer Figure 11), the adaptive comfort band shows a seasonal shift, reflecting occupants' ability to adapt to higher indoor temperatures in summer and lower temperatures in winter. During peak summer month (May), the upper limit of the comfort band reaches to the peak of 31.3°C in the warm temperate zone and 28.8°C in the temperate zone, corresponding to a prevailing mean outdoor temperature. In winter, the lower limit of adaptive band drops to 17.9°C and 17.4°C, respectively.
- In the cool temperate (Gosaikunda) and cold (Jomsom) climate zones (Refer Figure 12), where winters are particularly severe, the lower and upper limits of the adaptive comfort band during winter months remain constant at 17.4°C and 24.4°C, respectively. This indicates that as the prevailing mean outdoor temperature falls below 10°C threshold of ASHRAE 55 , the adaptive comfort band does not extend further downward, indicating a limit beyond which adaptation may be insufficient in an occupant-controlled naturally conditioned spaces, and active heating will be required to maintain thermal comfort.

This underscores the relevance of climatic context when applying adaptive thermal comfort models and highlight the need for climate-responsive design strategies tailored to specific regional conditions.

Figure 11: ASHRAE 55 Adaptive Model for the Warm temperate(Nepalgunj) & Temperate (Kathmandu)



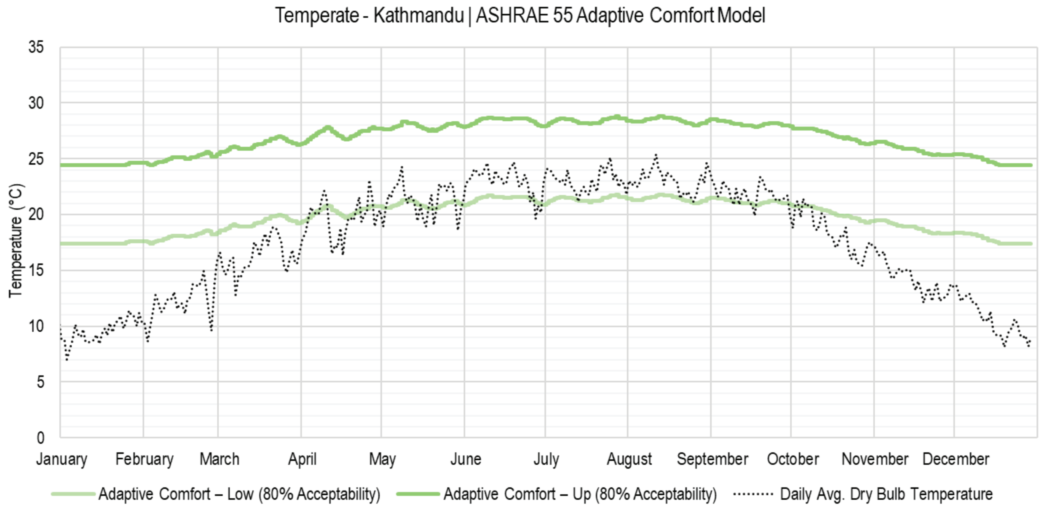
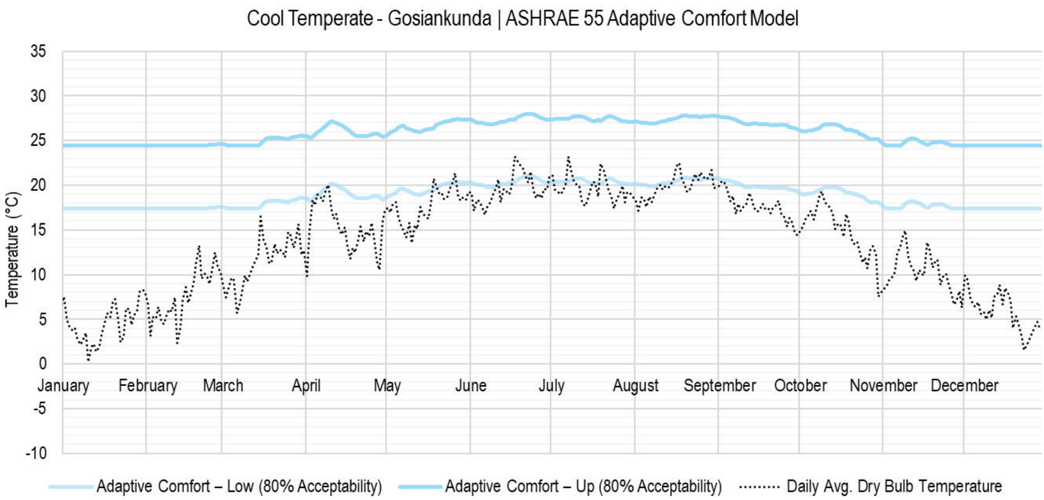
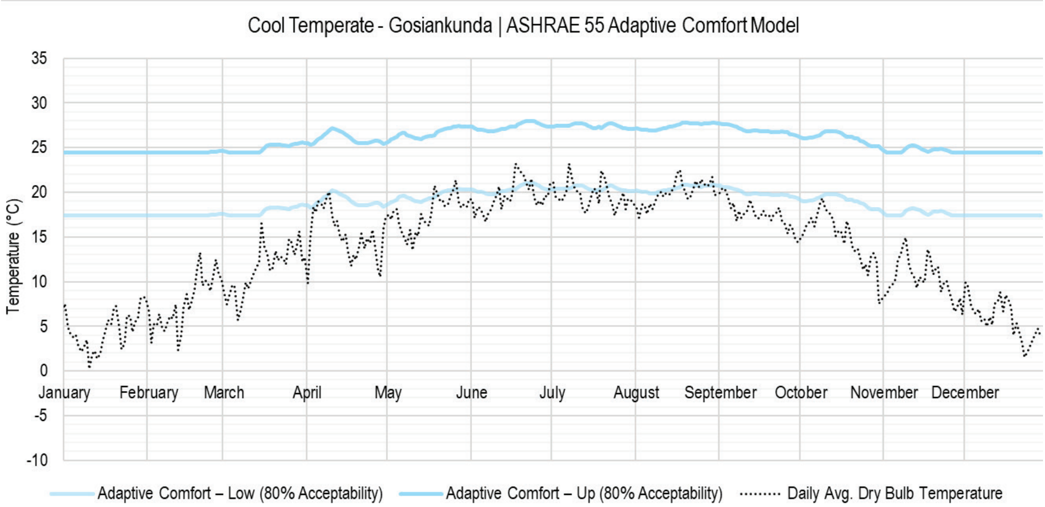


Figure 12: ASHRAE 55 Adaptive Model for the Cool Temperate (Gosiankunda) and Cold Climate (Jomsom) of Nepal





2.3.3 Thermal Safety

As discussed in the previous section, thermal comfort is a subjective feeling of satisfaction with the thermal environment, varying from person to person. However, it is important to recognize that the vulnerable population have varying abilities to adapt to external temperatures and hence have disproportionate impact across demographics as well as to the vulnerabilities. Evidence from various studies showed that the need for thermal comfort and thermal safety is different in terms of sex, age and physical conditions.

(Shreejay Tuladhar, 2019) highlighted the need to consider thermal safety thresholds in the context of Nepal considering the results of thermal analysis of 14 post-disaster temporary shelters that surpass the range of adaptive thermal comfort. The paper proposed and used 35°C [95°F] and 12°C [54°F] for the upper and lower "health risk" temperature threshold to assess thermal safety. Upper limit was determined based on the temperature when ceiling fans become less effective (WHO Europe, 2009) and mortality rate during heat waves (WHO Europe, 2009). The lower limit is based on data susceptibility of cardiovascular problems and strokes among the elderly, sick and small children in sustained exposure below 12°C temperature (Collins, 1986) .

An increase in heat-related deaths in the elderly (65+ yrs) population to about 53 deaths per 100,000 by 2080 is projected compared to 4 deaths per 100,000 (annual average between 1961 and 1990) under high emission scenario-WHO's Climate and Health Country Profile-2015 for Nepal (Honda, 2015) .

Temperature-mortality relationship research in São Paulo found 2.6 percent increase in mortality rates of children under 15 for every degree increase above 20°C and 2.5 percent increment for those over the age of 65-(Gouveia, 2003).

These results signified the need for climate-responsive building design that caters to the varying needs across the demographic population.

- Physiologically men and women are different with women having 0.4 °F higher inner body temperature than men (Kim, 1998). They sweat less and hence release less heat making them more vulnerable, more so during pregnancy. Higher core temperatures during pregnancy increase vulnerability to heat exhaustion during extreme temperatures, with associated risk of harm to the foetus (Jacklitsch, 2016)
- Results of a global analysis across 14 lower-middle income countries indicated an increased risk of still birth or preterm birth among pregnant women who were exposed to extreme heat and smaller diurnal temperature range within the seven days before giving birth (McElroy, 2022).

With these study results, it can fairly conclude that indoor temperature within the buildings has significant impact on women's health, primarily during vulnerable situations like pregnancy and post-maternal stage. This is specifically important for country like Nepal where the healthcare facilities are built without considerations for such thermal needs and where the access to quality and reliable energy is questionable.

2.4 Roles of the Designers

Two decisions need to be taken at the beginning for determination of thermal comfort, which will also impact energy efficiency strategies:

- The comfort expectation of the users of a building depends on the user preference as well as the mode of operation of the building
- The degree of personal control offered over the indoor environment.

Mode of Operation of the Building:

- Naturally Ventilated (NV) buildings rely exclusively on passive design strategies such as operable windows, vents, and airflow driven by wind or buoyancy to maintain indoor thermal comfort, without the use of mechanical cooling systems.
- Air-Conditioned (AC) buildings depend entirely on mechanical systems (HVAC) to control indoor temperature and humidity, with no reliance on natural ventilation.
- Mixed-Mode (MM) buildings integrate both natural ventilation and mechanical systems (cooling, heating, or ventilation) to enhance thermal comfort and improve energy efficiency. In this mode of operation, windows or ventilators are utilized when outdoor conditions are favourable, while mechanical systems are employed when natural ventilation alone is insufficient.

Suppose users expect a narrow range of comfort with a high degree of control. In that case, the expectation is that of an air-conditioned building where the indoor temperature is always controlled within the comfort range. In this case, the comfort range, as per the PMV/PPD model, must be considered. This is usually the case with hospitals, several types of office/commercial buildings, high-end hotels, and even certain high-end residences.

For most residential buildings, schools, institutional buildings, etc., the expectation of comfort and the degree of control is less strict compared to buildings like hotels or office buildings. In these buildings, the adaptive comfort model can be considered. It must be reiterated here that thermal comfort is very subjective, and the comfort ranges given by the models are only guidelines to enable design, where 80% of the users may be thermally comfortable.

The more stringent the user's expectations, the longer the time required for heating or cooling, resulting in increased investment for air conditioning and operational expenses.

Once the desired thermal comfort range is determined, thermal comfort at different design iterations can be predicted through simulations. Simulations can show how many hours in a year the indoor operative temperature of the building will be within the determined thermal comfort range. Alternatively, it can show the difference between the achieved operative temperature and the desired operative temperature, and the duration (measured in hours) for which the difference persists. This is denoted by a term called Discomfort Degree Hours (DDH). It has a unit of °C.h.

It is calculated using Equation 5.

$$\text{DDH (annual)} = (T_{operative} - T_{acceptable}) \times \text{Time} \qquad \text{..............Equation 05}$$

Where,

$T_{operative}$: indicates the measured or achieved operative temperature,

$T_{acceptable}$: indicates the targeted operative temperature based on comfort models,

Time: refers to the duration in hours, for which the difference persists.

The duration usually considered for DDH calculation is one year. DDH may be used to interpret the following:

- Thermal comfort is achieved within a building. Lower DDH indicates a higher amount of thermal comfort provision within the building throughout the year.
- An indicator of the degree of heating or cooling needed. If less DDH is achieved without any mechanical heating or cooling, less energy will be required.

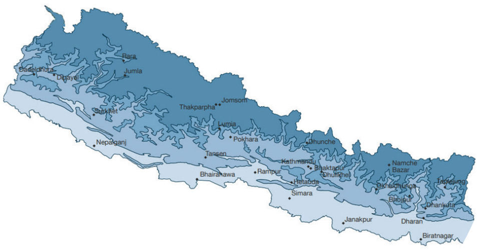
The designer should consider and ask some of the basic questions related to the people or occupants while initiating the design:

- For what demographical population are the buildings being designed? Consider asking about the occupants' age, sex and physical abilities
- Consider asking about the functions of the spaces
- Layout of spaces according to functions has various needs of thermal comfort.
- Consider that the thermal comfort or discomfort have the varying impact on different types of people
- Are the thermal safety needs of vulnerable populations being addressed?

Summary

- ASHRAE defines thermal comfort as "that condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation."
- Thermal comfort is influenced by environmental factors (DBT, RH, MRT and airspeed) and personal factors (Clo value and MET).
- Operative temperature is a simplified measure of human thermal comfort derived from air temperature, mean radiant temperature and air speed.
- Based on the comfort expectation of the users of a building and the degree of personal control offered over the indoor environment, the desired range of thermal comfort may be defined for the building based on the heat balance model or the adaptive comfort model.
- The purpose of these models and indices is to try to provide an acceptable indoor thermal environment for 80% of occupants in each space while mitigating factors that cause overwhelming discomfort.
- Once the desired thermal comfort range is determined, thermal comfort for different design iterations can be predicted through simulations. Simulations can show the Discomfort Degree Hours (DDH) of a design, which shows the difference between the achieved operative temperature and the desired operative temperature, and the duration (measured in hours) for which the difference persists.
- The more stringent the expectation of the user, the longer the time required for heating or cooling, resulting in increased investment and operational expenses.
- Thermal comfort needs vary across sex, age, and health conditions, with vulnerable groups, particularly women, children, the elderly, and pregnant women facing higher health risks from extreme indoor temperatures, underscoring the need for climate-responsive building design in Nepal.

3
CLIMATE



What's in this Section?

Climate

Climate is the long-term pattern of weather in a particular area. Weather can change from hour-to-hour, day-to-day, month-to-month, or even year-to-year. A region's weather pattern, usually tracked for at least 30 years, is considered its climate.

The climate is influenced by various factors some of which are:

- Location of the place on the Earth, i.e., latitude and longitude
- Height of the location from the sea level, i.e., altitude
- Physical features (land mass and water mass) of the area.
- Atmospheric condition.

3.1 Climate Zones in Nepal

Climate zones are regions that share similar climatic conditions. They are typically divided based on several variables that affect the region's climate, including temperature, precipitation, humidity, and other climate variables.

In Nepal, the climate zones are designated by the Central Bureau of Statistics, Government of Nepal. There is a total of five climatic zones in Nepal, classified based on altitude as shown in Table 2.

Table 2: Climate Zones in Nepal (Central Bureau of Statistics, Govt. of Nepal)

	Altitude	Climate Zone
1	Above 5000m	Tundra and arctic climate
2	3000m-5000m	Alpine and Subalpine
3	1000m-3000m	Cool to warm temperature
4	500m-1000m	Sub-tropical
5	below 500m	Tropical

Susanne Bodach (Bodach, 2016) has proposed another climate zone classification based on elevation, as shown in Figure 13. This classification is followed in this manual because it was carried out according to the bio-climatic zoning focusing on the building construction sector. This is relevant to our context and necessary to introduce it in building energy conservation guidelines and standards, as well as in building energy codes. Table 3 shows the climate characteristics of four climate zones with the maximum and minimum DBT & RH for each climatic zone.shows the climate characteristics of four climate zones with the maximum and minimum DBT & RH for each climatic zone.

This classification of climate zone will be helpful for the designer/architect to broadly understand the outdoor condition of their project location. The climate analysis can indicate:

- The comfort and discomfort months of the years.
- At which time of the year, can indoor comfort be achieved for the building occupants with very little or no effort.
- What passive strategies are required, and will they be effective or not?

Figure 13: Climate Zones of Nepal (Bodach, 2016)

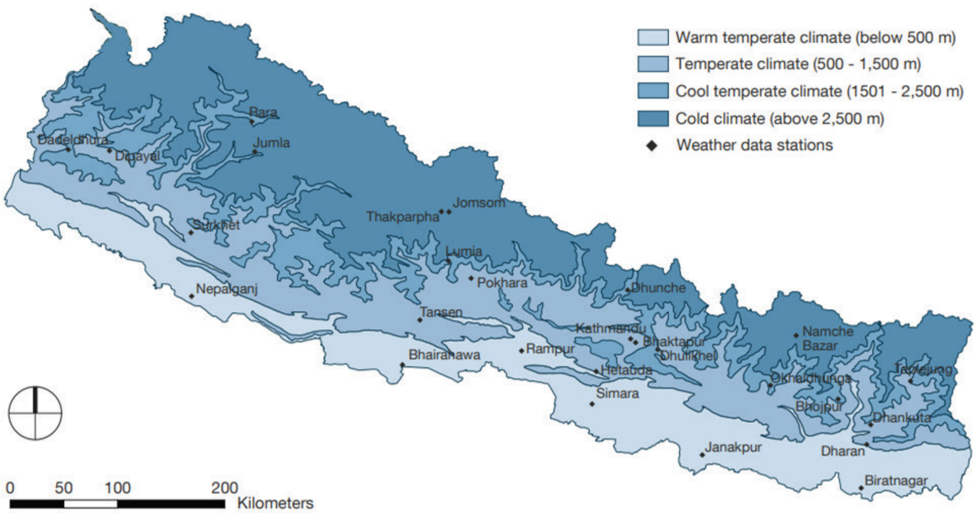


Table 3: Climate zones of Nepal with its Characteristics, Maximum and Minimum DBT & RH

S. N	Climate Zone	Climate Characteristics	Temperature		Avg. Relative Humidity range (%)
			Avg. Max. (°C)	Avg. Min. (°C)	
1	Warm Temperate (Elevation < 500m)	• **Dec-Feb:** Cold & dry season with clear skies • **Mar:** Moderately cold & dry season • **Apr-Jun:** Hot & dry season with clear skies • **Jul-Sep:** Warm & humid season • **Oct-Nov:** Moderately warm & moderately humid season	33-36	8-10	45–85
2	Temperate (Elevation 501m – 1500m)	• **Dec-Feb:** Cold & dry season with clear skies • **Mar:** Moderately cold & dry season • **Apr-May:** Warm & dry season • **Jun-Oct:** Moderately warm & humid season • **Nov:** Cool & moderately humid season	27-30	5-7	60-85
3	Cool Temperate (Elevation 1501m – 2500m)	• **Nov-Mar:** Cold & dry season with clear skies • **Apr:** Cool & dry season • **May-Sep:** Moderately warm & dry season • **Oct:** Cool & dry season	22-24	2-4	60-85
4	Cold Climate (Elevation > 2500m)	• Cold & dry season for most of the year • **Jun-Aug:** Moderately warm day-time temperature	16-18	-11 - -7	40-75

3.2 Climate Analysis

3.2.1 Climate Variables

Climate data is critical for building design and consists of the following climate variables:

1. **Dry Bulb Temperature (°C):** Refer to *Section 2.2.1.1.*
2. **Relative Humidity (%):** Refer to *Section 2.2.1.2.*
3. **Wet Bulb Temperature (°C):** The Wet-Bulb Temperature (WBT) is defined as the temperature of a parcel of air cooled to saturation (100% relative humidity, resulting in the occurrence of water droplets). At 100% relative humidity, the WBT is equal to the DBT at lower humidity levels. The WBT is always lower than the DBT.
4. **Solar Radiation (W/m²):** This is the energy that comes from the sun and is transmitted in the form of electromagnetic waves. The amount and intensity of solar radiation that reaches the Earth's surface can vary depending on factors

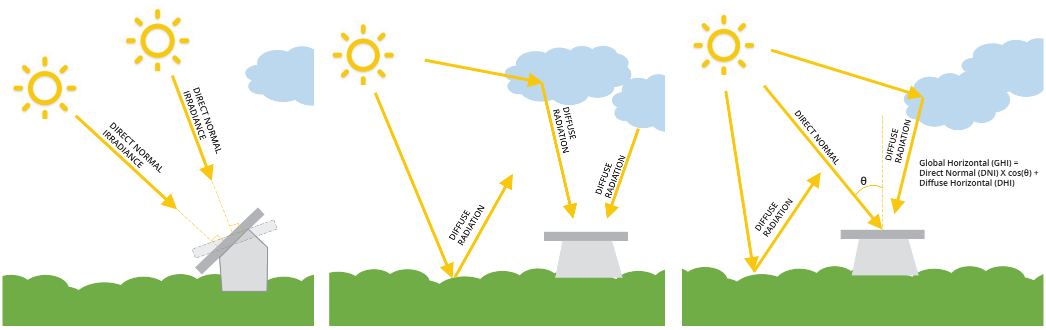
such as time of day, season, latitude, altitude, and atmospheric conditions. The maximum solar radiation with no dust in the air (e.g., after rain) and no clouds is around 1000 W/m^2. This radiation value is taken to define the power of PV modules (including 25°C ambient temperature). Solar radiation has three components as illustrated in Figure 14:

a. Direct Normal Irradiance (DNI): The amount of solar radiation received directly from the sun on a surface perpendicular to the sun's rays.

b. Diffuse Horizontal Irradiance (DHI): The amount of solar radiation that is scattered by the atmosphere and reaches the Earth's surface from all directions, not just from the sun.

c. Global Horizontal Radiation (GHI): The total amount of solar radiation received on a horizontal surface, including both direct and diffuse radiation.

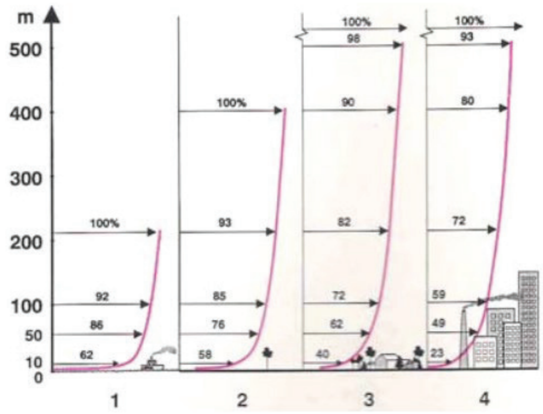
Figure 14: Direct normal irradiance (on left), diffused horizontal irradiation (middle), and global horizontal radiation (on right)



5. **Wind speed and Wind Direction:** Wind speed is how fast the air is moving. It is usually measured in meters per second (m/s) or kilometres per hour (km/h). Wind direction is the direction from which the wind is coming from. It is usually expressed in terms of the eight points of the compass (north, northeast, east, southeast, south, southwest, west, and northwest).

Wind speed varies with the height and this variation depends on the ground roughness (obstructions), differing for each terrain category as illustrated in Figure 15. The wind blows at a given height, with lower speeds in rougher terrains and higher speeds in smoother terrains. Furthermore, in any terrain, wind speed increases along the height up to the gradient height, and the values of the gradient heights are higher for rougher terrains. Wind speeds beyond gradient heights in all terrains are equal (IS:875(Part3), 2015).

Figure 15: Wind profile over height (IS:875(Part3), 2015)



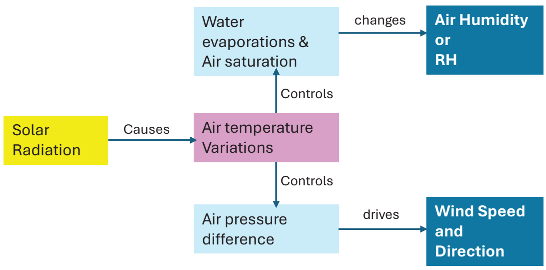
1. Exposed open terrain with a few or no obstructions (structure is less than 1.5 m)
2. Open terrain with well scattered obstructions (surrounding structure 1.5 and 10 m)
3. Terrain with numerous closely spaced obstructions (structures up to 10 m with or without other isolated structure)
4. Terrain with numerous large high closely spaced obstructions.

Climate Variable Relationship

The combined effect of climate variables is crucial to understand for identifying periods of comfort and discomfort. With increasing solar radiation, dry-bulb temperature (DBT) generally rises while relative humidity (RH) tends to drop. However, DBT shows no clear correlation with atmospheric pressure or wind speed (L. Guana, 2007). As illustrated in Figure 16 (a), solar radiation causes air temperature variations, which in turn affect evaporation, humidity levels, air pressure, and wind patterns. These interlinked factors influence thermal comfort and must be evaluated together rather than in isolation.

DBT and RH should be assessed together to understand the thermal condition. Figure 16 (b) presents how different combinations of DBT and RH result in distinct thermal conditions such as hot and humid, comfortable, or cold and dry - highlighting the importance of this integrated approach in climate analysis.

Figure 16: (a) Relationship of the Climate Variables. (b) Thermal Conditions Based on Combined DBT and RH.



(a)

DBT	RH	Thermal Condition
High	High	Hot and Humid
High	Low	Hot and Dry
High	Moderate	Hot
Moderate	Low	Dry
Moderate	Moderate	Comfortable
Moderate	High	Humid
Low	Moderate	Cold
Low	High	Cold and Humid
Low	Low	Cold and Dry

(b)

Source: (L. Guana, 2007)

3.2.2 Weather Files & Climate Analysis Tool

To conduct a climate analysis, representative climate data of the location for the last 10-15 years is needed. Today, several tools can assist in climate analysis. These tools use hourly weather data files[2] as input. These data files give the values for different climate variables (discussed in Section 3.2.1) for each of the 8760 hours of representative year resulting from the previous 10-15 years of climate data. The latest available weather files should be used for climate analysis.

These weather files can be freely downloaded from the following website:

- Energy Plus Weather Data: https://energyplus.net/weather/simulation
- Climate One building: https://climate.onebuilding.org/default.html
- CBE Clima tool: https://clima.cbe.berkeley.edu/
- Ladybug: https://www.ladybug.tools/epwmap/

The downloaded weather file folder will contain all or some of the following file formats shown in Table 4.

Table 4: Types of Weather Datasets Available

	File Type	
1	STAT	Expanded Energy Plus weather statistics
2	EPW	Energy Plus Weather Format
3	DDY	ASHRAE Design Conditions or "file" design conditions in Energy Plus format

2 Hourly weather data files are also used as input for building energy simulation software.

The .epw file is commonly used to perform climate analysis on freely available climate analysis tools. These same files are also used for carrying out the building energy simulation. The list of locations for which .epw files are available as per the climate zone of Nepal is given in Table 5.

Table 5: Places of Nepal with .epw Files

Warm Temperate	Temperate	Cool Temperate	Cold
Nepalgunj	Pokhara	Taplejung	Jumla
Siddharthanagar	Kathmandu	Amargadhi	
Dhangadhi	Dipayal	Okhaldhunga	
Biratnagar	Dhankuta		
Simara	Dang		
	Birendranagar		

If weather data or .epw files are not available for certain locations, the nearest .epw file meeting both requirements should be considered (EnergyPlus, 2023).

- The geographical distance between the two locations should be ≤ 50km.
- The difference in altitude between the two locations should be ≤ 100m.

If both requirements are not met, one may explore the possibility of obtaining data files from various available web sources. These sources often use statistical methods to generate the .epw file for the location. Some of the widely used web sources include:

- Climate.OneBuilding (free access)
- Power Access Data Viewer (https://power.larc.nasa.gov/data-access-viewer/)

Climate Analysis Tools

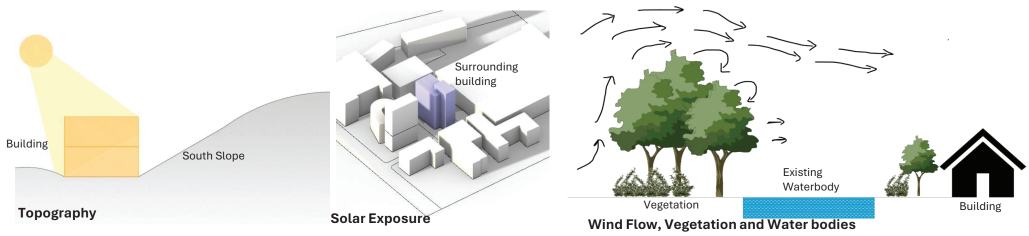
Various climate analysis tools help to visualize the climate data (stored in a .epw file) in a way so that the interpretation can easily be done. Some of the widely used tools are:

- Climate Consultant: A simple-to-use, graphic-based computer program that helps designers understand their local climate.
- CBE Clima: A web-based application built to support climate analysis specifically designed to support the needs of architects and engineers.
- Rhino + Ladybug: Ladybug Tools comprises free computer applications that facilitate environmental design analysis and are freely available. However, Rhino is not open-source.

3.2.3 Microclimate and its Impact on Building

Microclimate refers to the localized atmospheric conditions around a building site, which can differ from the regional climate. Influenced by topography, vegetation, water bodies, surface materials, and nearby structures, microclimate plays a crucial role.

Figure 17: Microclimate Factors



In Nepal's diverse terrain, these site variations can significantly impact a building's thermal performance, energy use, and comfort. Buildings are directly influenced by their immediate microclimate in several ways. The key factors are:

- **Topography:** The shape, elevation and orientation of land influence microclimate.
  - Buildings located on south-facing slopes were found to receive ample winter sunlight, which is beneficial for passive solar heating, while those on north-facing slopes received little to none (Refer Figure 17).
  - Valleys can trap cold air and lower temperatures, while hills or mountains block wind and affect rainfall.
- **Solar Exposure:** The orientation of a building and shading from surrounding trees or structures determine how much sunlight it receives. This solar exposure can be either beneficial or detrimental, depending on the climate zone in which the building is located.
- **Wind Flow:** Nearby terrain, structures, or vegetation can channel, block, or redirect prevailing winds, affecting natural ventilation.
- **Vegetation:** Trees and green cover cool the air, provide shading, and increase humidity, enhancing thermal comfort (Refer Figure 17).
- **Proximity to Water Bodies:** Lakes or rivers (e.g., in Pokhara) can increase local humidity and influence thermal comfort and material selection.
- **Surrounding Surface Materials:** Surrounding surfaces can store and reflect solar radiation based on their angle and material. Additionally, adjacent paved areas(e.g., roads, footpaths) radiate heat and raise surrounding temperatures, while natural ground cover helps keep the temperatures moderate.

In dense urban areas like Kathmandu, the urban heat island effect caused by closely spaced buildings, limited vegetation, and heat-absorbing surfaces leads to increased ambient temperatures. This extra heat makes buildings warmer, reduces comfort inside, and increases the need for mechanical cooling. Therefore, incorporating microclimate analysis into early-stage site planning becomes important, as it enables designers to make site-specific decisions based on the microclimate.

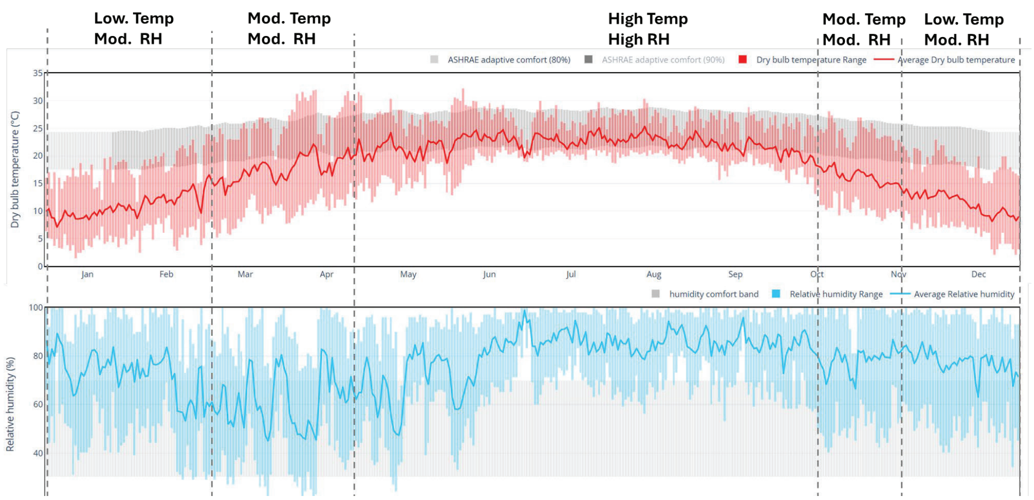
3.2.4 Climate Analysis Example

Climate Analysis Example: Kathmandu (Temperate)

Dry Bulb Temperature and Relative Humidity

Typically, most people find a comfortable Dry Bulb Temperature (DBT) range to be between 20-26°C, and a comfortable Relative Humidity (RH) range between 30-70%. However, if either or both factors are too high or too low, it can lead to thermal discomfort. Hence, it is crucial to consider both factors together. Figure 18 shows the DBT and RH of Kathmandu.

Figure 18: Chart Showing DBT (Top) and RH (Bottom) of Kathmandu (Tool Used: CBE Clima)



By analysing the values of DBT and RH of Kathmandu (Figure 18), we can categorize each month to determine whether it is cold, comfortable, humid, or hot, etc. These categorizations are presented in Table 6.

Table 6: Categorization of Months Based on DBT and RH (Kathmandu)

	DBT	RH	Remark
Nov-Feb	3°C to 20°C.	30%-70% (100% at night)	Low DBT, Mod. RH **Cold**
March-April	15°C to 25°C.	20%-60%	Mod. DBT, Low. RH **Comfortable (Mostly)**
May-Sep	20°C to 33°C.	40%-90% (100% at night)	High DBT, High RH **Hot and Humid**
October	15°C to 26°C.	30%-70% (100% at night)	Mod. DBT, Mod. RH **Comfortable**

Solar Radiation

Figure 19: Annual Graph Showing Global & Diffuse Horizontal Solar Radiation (Top) and Direct Normal Radiation (Bottom) for Kathmandu, Nepal (Tool Used: CBE Clima)

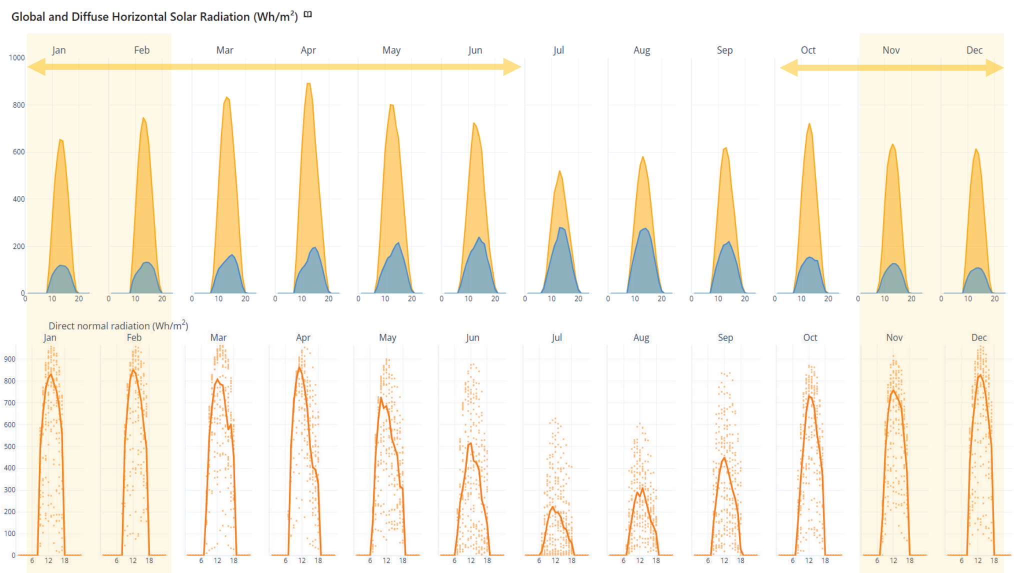
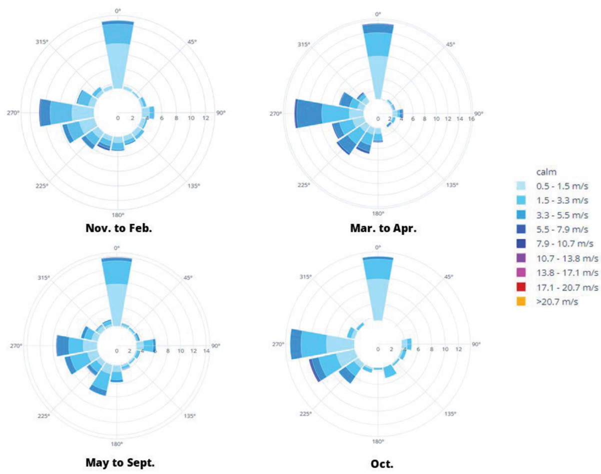


Figure 19 illustrates the global, direct and diffuse solar radiation annually for Kathmandu. It shows that the winter months (Nov. to Feb.) in Kathmandu have clear skies with high solar radiation. This can be used to reduce heating load in the winter. At the same time, solar radiation must be avoided in the hot and humid months.

The solar radiation graph also indicates that there is good potential for solar-based renewable energy throughout the year, except for July to September when the direct normal radiation is quite low due to clouds and precipitation.

Figure 20: Wind Rose Diagram of Months for Which DBT and RH Categorization was Done (Tool Used: CBE Clima Tool)



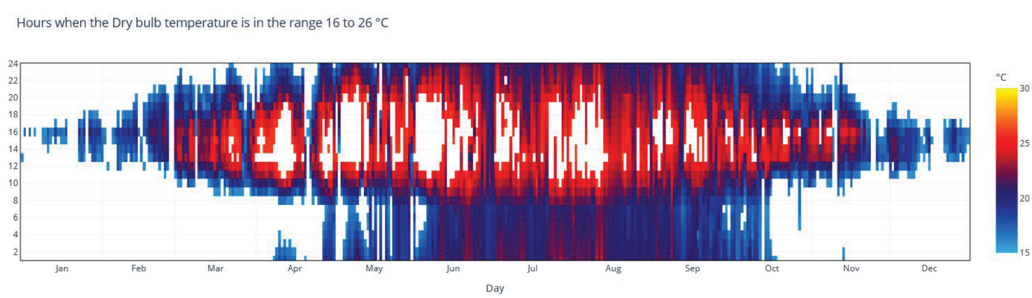
In Figure 20, the prevailing wind direction is mainly from the North and West, consistently exceeding 1.5 m/s for a significant duration. Consequently, during the comfortable months (April, March, and October) and the hot-humid months (May to September), there exists substantial potential for natural ventilation. Thus, strategic decisions regarding building orientation, placement of external and internal windows, and spatial configuration become crucial to harness the maximum benefit from the prevailing wind.

Natural Ventilation Potential

Addressing the following questions during climate analysis can reveal the potential for natural ventilation to contribute to cooling in each climate:

- Which months will require cooling, and what is the relative humidity during those periods? *(Air movement becomes crucial, especially if humidity exceeds 60% alongside high temperatures.)*
- Does the outside temperature in those months drop below 24-26°C, and if so, when does this occur? This is the optimal time for leveraging natural ventilation for effective cooling. *(If outside temperatures remain above this range, outside air may not offer sufficient thermal comfort.)*
- What is the prevalent wind direction and average wind speed during this time? *(For effective wind-driven ventilation, a wind speed of at least 0.5 m/s is typically necessary.)*

Figure 21: Graph Showing Period When DBT is Between 16 and 26°C in Kathmandu



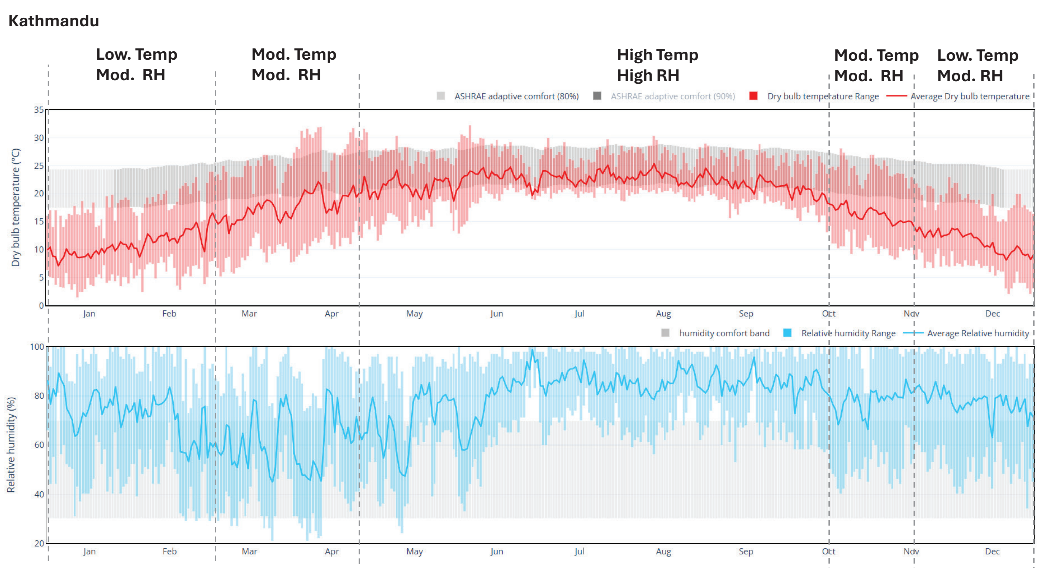
In Kathmandu, the potential cooling months are from March to October. Figure 21 illustrates periods when temperatures in Kathmandu fall between 16 and 26°C. Notably, these temperatures provide favourable conditions for cooling through natural ventilation in March (daytime), June-July (evenings), and August-October (all day). In April-May, natural ventilation remains viable during late evenings and early mornings. During this period, wind speeds consistently exceed 0.5 m/s for most of the time (though this may vary based on the density and features surrounding the building site).

Climate Analysis: Nepalgunj (Warm Temperate)

Dry Bulb Temperature and Relative Humidity

As discussed previously when dry bulb temperature and relative humidity are too high or too low, it can lead to thermal discomfort. Hence, it is crucial to consider both factors together. Figure 22 shows the DBT and RH for the Nepalgunj. The grey bands in DBT graph in Figure 22 represents the ASHRAE 55 adaptive thermal comfort band (80% acceptability) for Nepalgunj.

Figure 22: Annual Graph with Dry-Bulb Temperature (Top) and Relative Humidity (Bottom) of Nepalgunj (Tool Used: CBE Clima)



Categorization of each month to determine whether it is cold, comfortable, humid, or hot, etc. has been shown in Table 7.

Table 7: Categorization of Months Based on DBT and RH (Kathmandu)

	DBT	RH	Remark
Nov-Feb	3°C to 20°C.	45 to 85% (100% at night)	Low DBT, Mod. RH **Cold and Humid**
March	15°C to 25°C.	30 to 70% (100% at night)	Mod. DBT, Low. RH **Comfortable (Mostly)**
April to June	14°C to 40°C	30 to 70%	High DBT, Moderate RH; **Hot**
July to Sep	23.2°C to 35.3°C	50 to 85% (100% at night)	High DBT, Moderate RH **Hot and Humid**
Oct	16.1°C to 34.7°C	50 to 90% (100% at night)	Moderate DBT, High RH; **Humid**

Solar Radiation

Figure 23: Annual Graph Showing Global & Diffuse Horizontal Solar Radiation (Top) and Direct Normal Radiation (Bottom) for Nepalgunj, Nepal (Tool Used: CBE Clima)

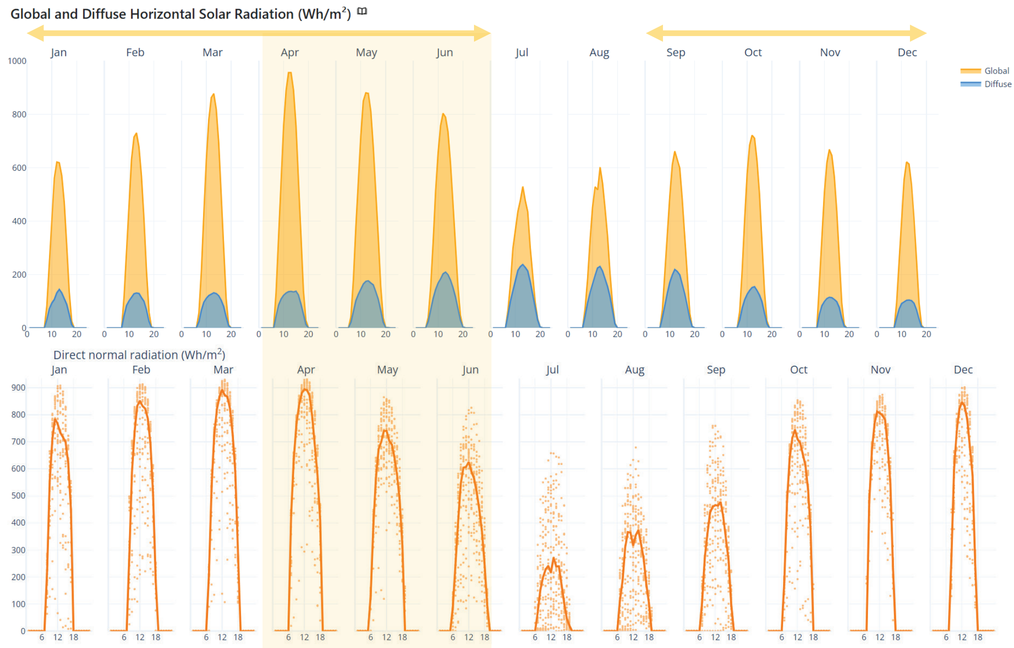


Figure 23 shows that during the summer months (Apr to June.) Nepalgunj have clear skies with high solar radiation, which must be restricted from directly impacting the building. Therefore, decisions regarding building orientation, window shading, and the placement of habitable spaces become crucial. During the winter months, the higher solar radiation can be utilized to reduce heating loads. Additionally, the solar radiation graph indicates a good potential for solar-based renewable energy throughout the year, except from July to September, when direct normal radiation is significantly reduced due to cloud cover and precipitation.

Figure 24: Wind Rose Diagram of Months for Which DBT And RH Categorization was Done (Tool Used: CBE Clima Tool)

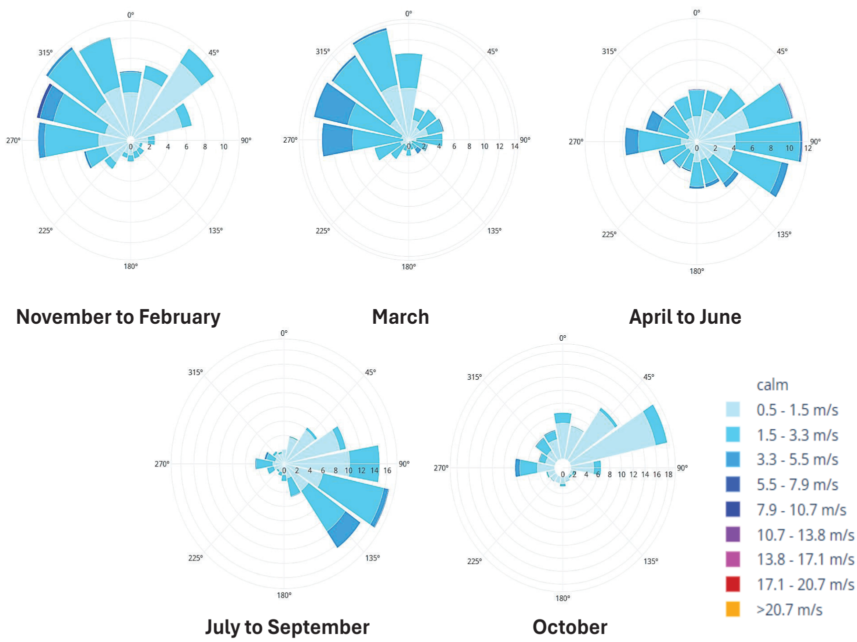
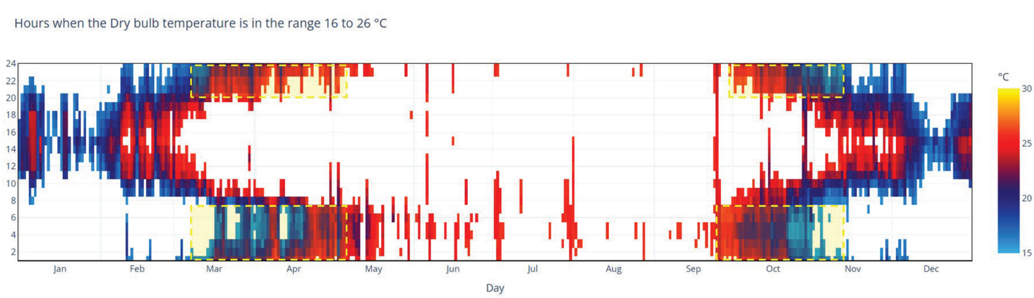


Figure 24 indicates that the prevailing wind direction during the summer months (April to September) is primarily from the east and southeast, while in the winter months (November to February), it predominantly comes from the northwest and west. Wind speeds consistently exceed 1.5 m/s for a significant duration during these periods. Consequently, during the comfortable month of March and the humid month of October, there is substantial potential for natural ventilation. Therefore, strategic decisions regarding building orientation, the placement of external and internal openings, and spatial configuration are crucial to maximize the benefits of prevailing winds.

Natural Ventilation Potential

Figure 25: Graph Showing Period When DBT is Between 16 and 26°C in Nepalgunj (Tool Used: CBE Clima Tool)



As discussed in the previous example of climate analysis, key factors for utilizing natural ventilation include identifying periods when outdoor temperatures are within the comfort range, assessing wind directions, and wind speeds for that time. These parameters help determine the feasibility and effectiveness of natural ventilation as a passive cooling strategy.

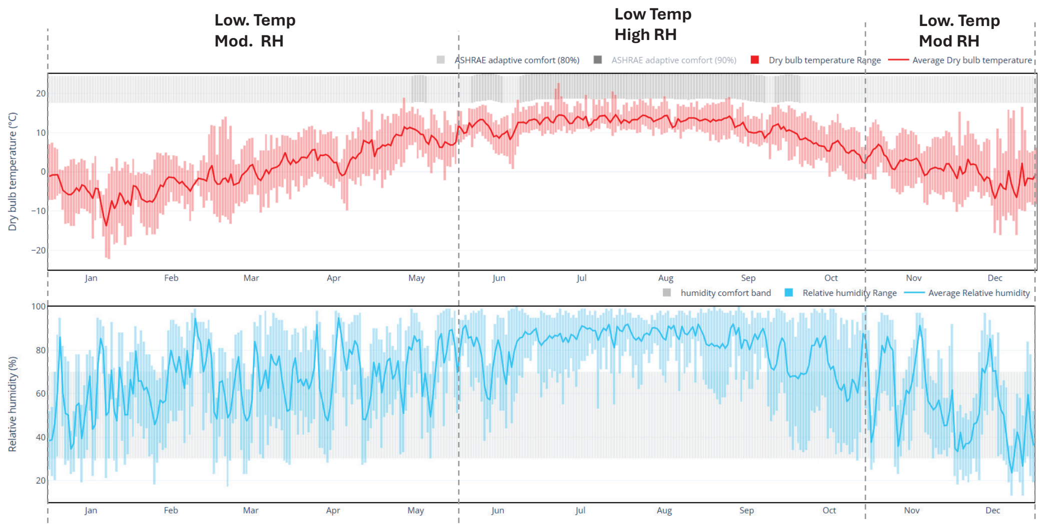
Figure 25 shows the hours when the dry bulb temperature (DBT) falls within the comfort range of 16°C to 26°C. It can be observed that during the months of March, April, and October, there is significant potential for natural ventilation during the night-time hours (8:00 p.m. to 8:00 a.m.). During this period, the prevailing winds are from the northwest and west in March, and from the east and northeast in April and October, with wind speeds consistently exceeding 0.5 m/s for most of the time. Therefore, the placement and design of external and internalopenings, as well as the spatial configuration of the building, must be carefully considered to fully utilize the potential of natural ventilation for cooling.

Climate Analysis: Jumla (Cool Temperate)

Dry Bulb Temperature and Relative Humidity

Figure 26 shows the DBT and RH for the Jumla. The grey band in DBT graph of Figure 26 represents the ASHRAE 55 adaptive thermal comfort band (80% acceptability) for Jumla.

Figure 26: Annual Graph with Dry-Bulb Temperature (Top) and Relative Humidity (Bottom) of Jumla (Tool Used: CBE Clima)



Categorization of each month to determine whether it is cold, comfortable, humid, or hot, etc. has been shown in Table 8. It can be observed that the critical and extended periods of thermal discomfort occur during the cold months from November to May when the temperature is below 0°C for much of the duration.

Table 8: Categorization of Months Based on DBT and RH (Jumla)

	DBT	RH	Remark
Jan. to May.	-22°C to 19°C	35% to 85% (above 90% during night)	Low. Temp, Mod. RH **Cold**
June. to Oct.	1°C to 23°C	63% to 95% (100% during night)	Low Temp, High RH **Cold and Humid**
Nov. to Dec.	-9°C to 17°C	30% to 70% (above 90% during night)	Low. Temp, Mod. RH **Cold**

Solar Radiation

Figure 27: Annual Graph Showing Global & Diffuse Horizontal Solar Radiation (Top) and Direct Normal Radiation (Bottom) for Jumla, Nepal (Tool Used: CBE Clima)

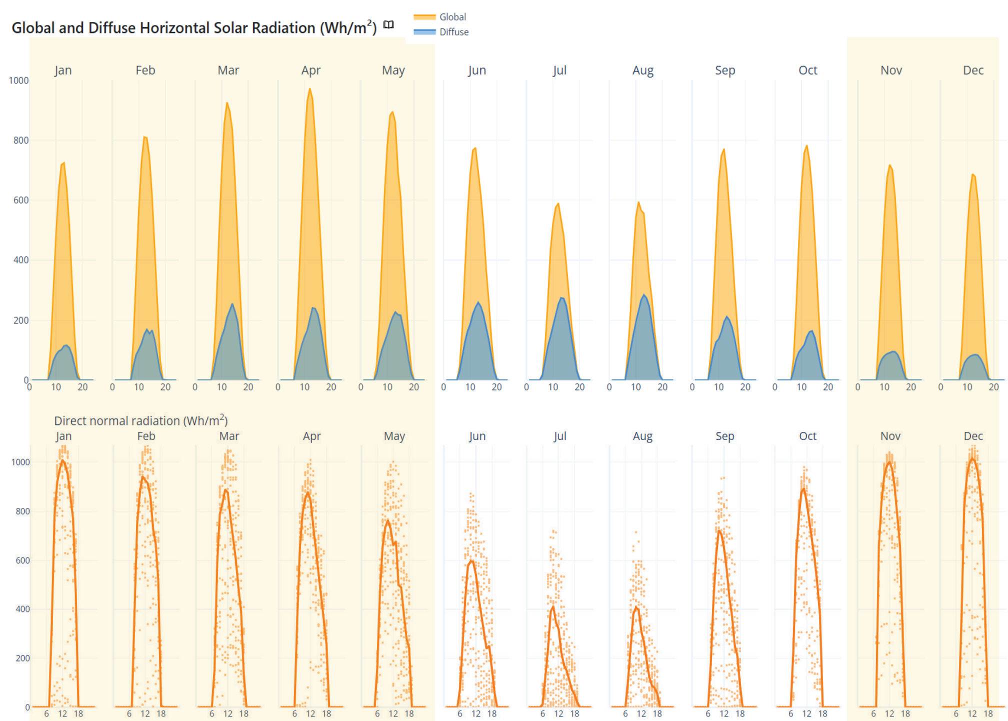
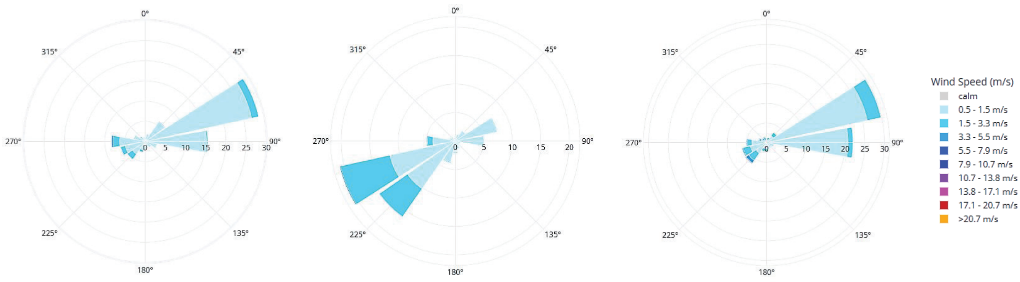


Figure 27 shows that during the cold months from November to May, the skies remain clear with high levels of solar radiation. This solar availability can be utilized to reduce heating loads by incorporating solar passive strategies in the building design. Therefore, decisions related to building orientation, the size and placement of windows and habitable spaces, as well as the selection of building materials, become crucial. Additionally, the solar radiation graph indicates strong potential for solar-based heating system and renewable energy generation throughout the year, except in July and August, as global horizontal radiation is significantly reduced due to cloud cover and precipitation.

Wind

The purpose of analysing wind direction in cold climate zones is to restrict the entry of unintentional cold winds into the building. Figure 28 indicates that during the harsh cold months (Nov. to May) the prevailing wind direction is primarily from the northeast. Therefore, the arrangement of buildings, its spaces and openings should be carefully designed to restrict the entry of these cold winds.

Figure 28: Wind Rose Diagram of Months for Which DBT and RH Categorization was Done (Tool Used: CBE Clima Tool)



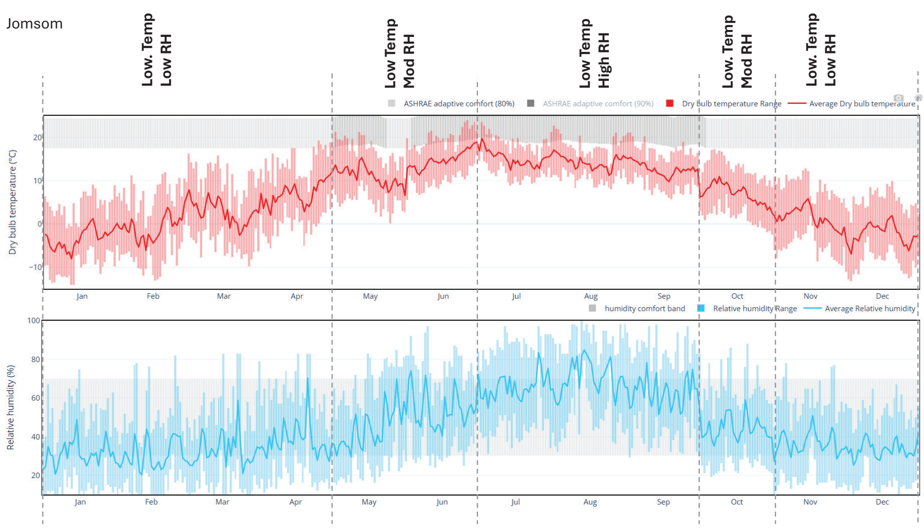
Jan to May **Jun. to Oct.** **Nov. to Dec.**

Climate Analysis: Jomsom (Cold)

Dry Bulb Temperature and Relative Humidity

Figure 29 shows the DBT and RH for the Jomsom. The grey band in DBT graph of Figure 29 represents the ASHRAE 55 adaptive thermal comfort band (80% acceptability) for Jomsom.

Figure 29: Annual Graph with Dry-Bulb Temperature (Top) and Relative Humidity (Bottom) of Jomsom (Tool Used: CBE Clima)



Categorization of each month to determine whether it is cold, comfortable, humid, or hot, etc. has been shown in Table 9. It can be observed that the critical and extended periods of thermal discomfort occur during the cold and dry months from November to April.

Table 9: Categorization of Months Based on DBT and RH (Jomsom)

	DBT	RH	Remark
Jan. to Apr.	-14°C to 19°C	10% to 55%	Low DBT, Low RH **Cold and Dry**
May. to Jun.	0°C to 24°C	25% to 70%	Low DBT, Moderate RH **Cold**
Jul. to Sept.	6°C to 24°C	40% to 80% (100% at night)	Low DBT, High RH **Cold and Humid**
Oct.	-3°C to 17°C	25% to 60%	Low DBT, Moderate RH **Cold**
Nov. to Dec.	-13°C to 13°C	15% to 60%	Low DBT, Low RH **Cool and Dry**

Solar Radiation

Figure 30: Annual graph showing global & diffuse horizontal solar radiation (top) and direct normal radiation (bottom) for Jomsom, Nepal (Tool used: CBE Clima)

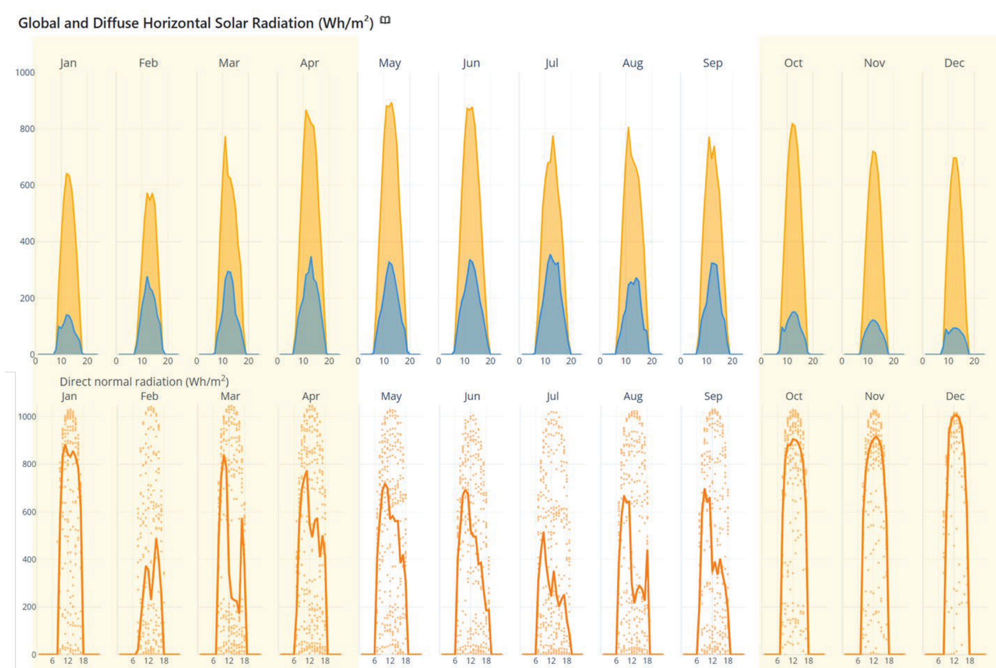


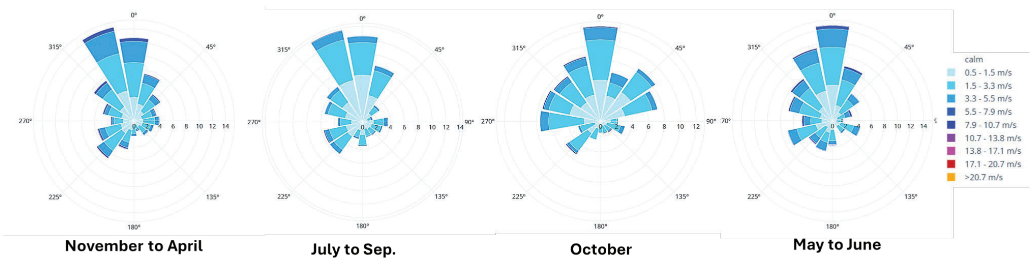
Figure 30 shows that during the cold and dry months from November to April, the skies remain clear with high levels of solar radiation. This solar availability can be utilized to reduce heating loads by incorporating solar passive strategies in the building design. Therefore, decisions related to building orientation, the size and placement of windows and habitable spaces, as well as the selection of building materials, become crucial. Additionally, the solar radiation graph indicates strong potential for solar-based heating system and renewable energy generation throughout the year, except in February and July, when direct normal radiation is significantly reduced due to cloud cover or precipitation.

Wind

The purpose of analysing wind direction in cold climate zones is to minimize unintentional infiltration of high-speed cold winds into the building.

indicates that during the cold and dry months (November to April), the prevailing wind direction is primarily from the north and northeast. Therefore, the arrangement of buildings, as well as the size and openability of windows, should be carefully designed to restrict the entry of these cold winds.

Figure 31: Wind Rose Diagram of Months for Which DBT And RH Categorization was Done (Tool Used: CBE Clima Tool)



3.3 Sun Path Analysis

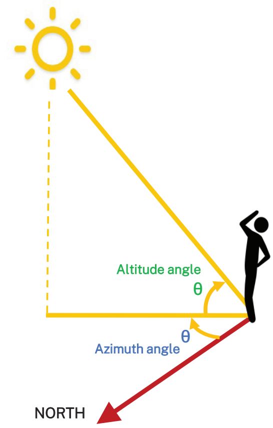
The sun's movement is dynamic and influenced by variations in altitudes, angles, and solar radiation. This movement becomes both critical and complex as it interacts with buildings. To simplify the understanding of the sun's trajectory, a 2D graphical representation known as 'Horizontal Sun Path Diagrams' or 'Sun Path Diagrams' is generated.

3.3.1 Sun Path Diagrams

Two essential terms for interpreting sun path diagrams are the altitude angle and the azimuth angle of the sun as shown in Figure 32.

- **Altitude angle:** This angle is the measurement between the horizon and the sun's position in the sky, ranging from 0° (when the sun is on the horizon) to 90° (when the sun is directly overhead). It is measured in degrees.
- **Azimuth angle:** This angle is the measurement between the direction of true north and the direction of the sun. It is measured in degrees clockwise from a reference direction, typically the true north, and spans from 0° to 360°. Some simulation tools may use south as the reference direction (0°), which should be double-checked when utilizing these tools.

Figure 32: Solar Position Angles

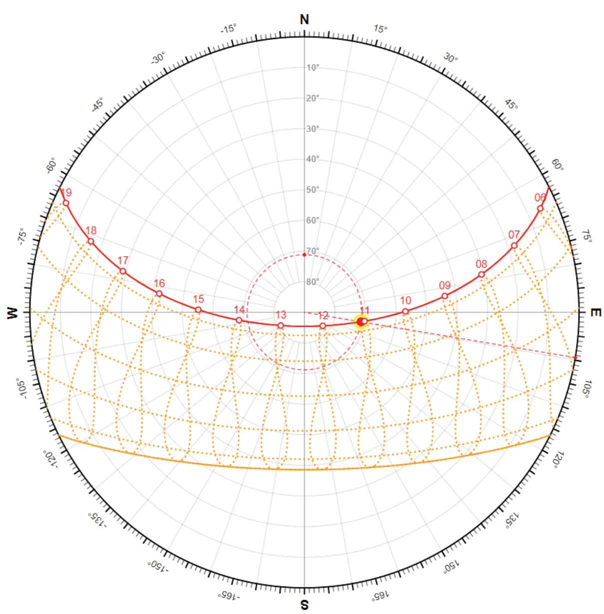


3.3.2 Sun-path Diagram Tools

Several online tools offer sun-path diagrams for specific locations based on their latitude and longitude. For example, the Sun Path Diagram of Kathmandu is shown in Figure 33. Two notable free tools include:

- **Andrewmarsh.com:** This online tool provides both 2D and 3D sun path diagrams.
- **CBE Clima:** (https://clima.cbe.berkeley.edu/)

Figure 33: Sun path diagram of Kathmandu, Nepal (Tool Used: AndrewMarsh.com)



By understanding the altitude angle and the azimuth angle of the sun at different times of the day and year, architects and building designers can optimize:

- The placement (direction) of windows and skylights.
- Shading devices to control the amount of solar heat gain.
- Designers can take advantage of the sun's angle in the winter to maximize passive solar heating in buildings, while also minimizing heat gain in the summer by incorporating shading devices (southern walls).

3.3.3 Important Dates for Sun-path Analysis

The sun's position, indicated by altitude and azimuth angles, can be extracted from the sun path diagram for any specific date and hour of the year. For designers, understanding the sun's position on the dates mentioned in Table 10 is crucial.

Table 10: Important Dates for Sun-path Analysis

	Date (Northern Hemisphere)	Description
Summer Solstice	20 or 21 June	The Extreme of the sun’s position i.e., at the highest altitude. Sunrise and sunset slightly north. Longest day.
Autumn Equinox	21 September	Average of the sun position i.e., sun rises due east and sets due west. Equal day length day/night.
Winter Solstice	21 or 22 December	The extreme of the sun’s position i.e., at the lowest altitude. Shortest day. Sunrise and sunset slightly south.
Spring Equinox	21 March	Average of the sun position i.e., sun rises due east and sets due west. Equal day length day/night.

Summary

- This manual adopts the following climate zone classification for Nepal:

    1. Warm temperate climate (below 500m)
    2. Temperate climate (501-1500m)
    3. Cool temperate (1501-2500m)
    4. Cold climate (above 2500m)

- Conducting climate analysis, involving the examination of various climate variables like DBT, RH, solar radiation, wind speed, and direction for a specific location, helps in identifying:

    1. The comfortable and uncomfortable months of the year.
    2. The periods when achieving indoor comfort for building occupants requires minimal or no effort.
    3. The necessary passive strategies and their anticipated effectiveness.

- Weather files encapsulate climate variable data for a representative year (8760 hrs.), derived from the recorded climate data of the location over the past 10-15 years. The .epw (Energy Plus Weather) format is widely employed for climate analysis, as well as building energy and comfort simulation.
- Analyzing a location's sun path, which depicts the sun's position at various times throughout the day and year, empowers architects and building designers to make informed decisions regarding:

    1. Building orientation
    2. Window and skylight placement
    3. Implementation of shading devices to regulate solar heat gain in summer
    4. Maximizing passive solar heating in winter

4

HEAT TRANSFER IN BUILDINGS

What's in this Section?

Heat Transfer in Buildings

Thermal comfort inside a building depends on the heat transfer that happens through the building envelope. It is important to understand the principles of these heat exchanges to implement appropriate passive strategies.

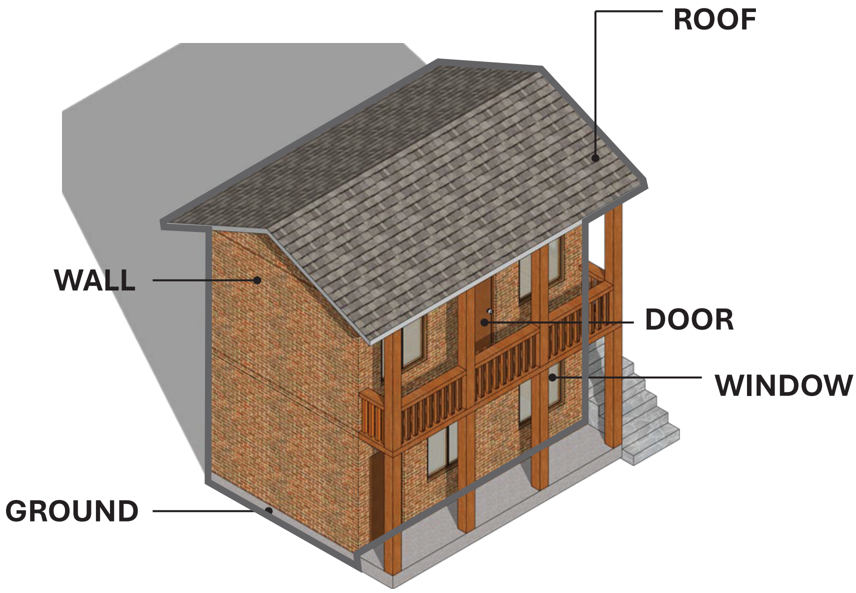
Forms of Heat: Sensible & Latent

1. **Sensible heat:** Sensible heat refers to the heat transfer that causes a change in the temperature of a substance without changing its state (phase). For e.g., when you warm up a cup of tea, the heat you're adding is sensible heat. It's the heat that makes the tea hotter.
2. **Latent heat:** Latent heat is involved when a substance changes its form, like from ice to water or water to steam, without changing its temperature. It's the heat that's hidden or "latent" during these phase changes.

4.1 Building Envelope

The building envelope, often referred to as the "skin" of the building, serves as the physical barrier between the interior and exterior environments. It plays a critical role in regulating the transfer of heat, air, moisture, and light, thereby contributing to indoor thermal comfort, energy efficiency, and protection against external climatic conditions. Figure 34, shows the key building envelope components, which include the ground floor, walls, roof, and all types of fenestrations such as doors, windows, skylights, and other openings.

Figure 34: Building Envelope and its Components.



4.2 Heat Sources For Buildings: Internal & External

4.2.1 Internal Heat Gains

Building occupants generate heat based on their metabolic rate. In addition to this, heat is produced within the space by electrical lighting and equipment. This heat generation within the building, collectively referred to as internal heat gains (refer to Figure 35), its closely associated with the building type (e.g., office, education, or residential) and its occupancy.

Figure 35: Internal Heat Gains Through Occupants, Equipment and Artificial Lighting

Occupancy Heat Gains

To determine the occupancy heat gains in a space, one must know the activity-related heat gain from a person and the number of occupants in the space. Occupancy also varies throughout the day. Thus, occupancy schedules should be ascertained. These schedules are important especially when using energy simulation software to predict energy use in buildings.

The activity related to heat gain/person or rates of heat (sensible and latent) given off by humans at different states of activity are given in ASHRAE 55: Thermal Environmental Conditions for Human Occupancy.

Lighting Heat Gains

The heat gained from artificial lighting in a building is found by multiplying the number of lights of each type and its respective wattage. Multiplying this with the number of hours of use of the lights gives the total heat gains from artificial lighting.

Alternatively, recommended Lighting Power Density (LPDs) may be used to ascertain the lighting heat gains. LPD represents the power consumed by lighting per unit of floor area and is typically measured in watts per square meter (W/m^2). Recommended LPD for different types of spaces are given in various standards, including ASHRAE 90.1.

Equipment Heat Gains

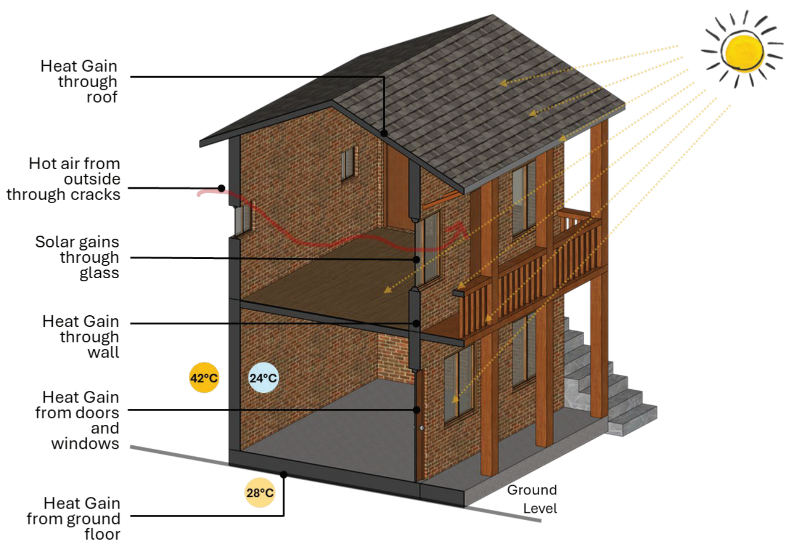
The heat gained during the use of equipment (such as microwave oven, toasters, ovens, computers, etc.) in a building can be determined by multiplying the rated input of the equipment (in watts) by the usage factor of the equipment and the fraction of heat radiated to the space.

ASHRAE Fundamentals 2017 provides heat gain values for appliances. Equipment Power Density (EPD) is another term used, representing the power consumed by equipment per unit of floor area and is typically measured in watts per square meter (W/m^2).

4.2.2 External Heat Gains

The heat from the sun, earth, and the external environment, which is transferred through the building envelope, constitutes external heat gains (refer Figure 36). Further examination on modes of heat transfer through the building envelope is provided in Section 4.4.

Figure 36: External Heat Gains Through Building Envelope



4.2.3 Internal Vs. External Heat Gains

Densely populated buildings with high activity and/or energy-intensive equipment, such as office buildings, malls, and cinema halls, are typically characterized by dominant internal loads. On the other hand, less populated buildings with minimal activity or equipment, such as residences and warehouses, are generally dominated by external loads. The significance of internal heat loads in comparison to external loads from the sun, wind, and ambient temperatures is determined by the building envelope and massing.

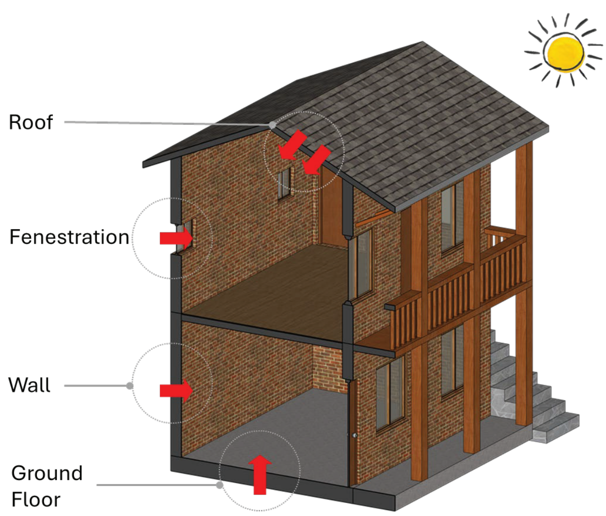
4.3 Modes of Heat Transfer Through the Building Envelope

Heat is a form of energy, and it always flows from warm to cold. This can be explained at the molecular level. Temperature at the molecular level signifies the movement of molecules, which is a form of kinetic energy. The higher the temperature, the faster the molecules move. If one side of a solid is hotter than the other side, the fast-moving molecules will likely collide with the slower ones, transferring energy and accelerating them. Eventually, all molecules reach a uniform speed due to the uniform temperature, and the overall movement slows down. There is a less possibility for slower molecules to collide with faster ones and become even slower, while the faster molecules become even faster. This phenomenon is similar to pouring hot tea into lukewarm water, which does not make the water colder and the tea hotter. This is explained by the second law of thermodynamics, which states that heat flows from hotter regions to colder regions. The first law of thermodynamics asserts that heat cannot be lost but only transferred to another form.

4.3.1 Conduction

Conduction is the process of heat transfer that occurs through heat flux in non-moving material. In buildings, conduction occurs when heat moves through walls, floors, roofs, and other solid components. The amount of heat exchange through these envelope components depends on the properties of these envelopes and the temperature difference between the two sides. In a building, conduction happens through the roof, walls, fenestration and ground (refer to Figure 37). The conduction of the different wall layers is part of the U-value of a wall.

Figure 37: Transfer of Heat by Conduction Through Roof, Wall and Fenestration

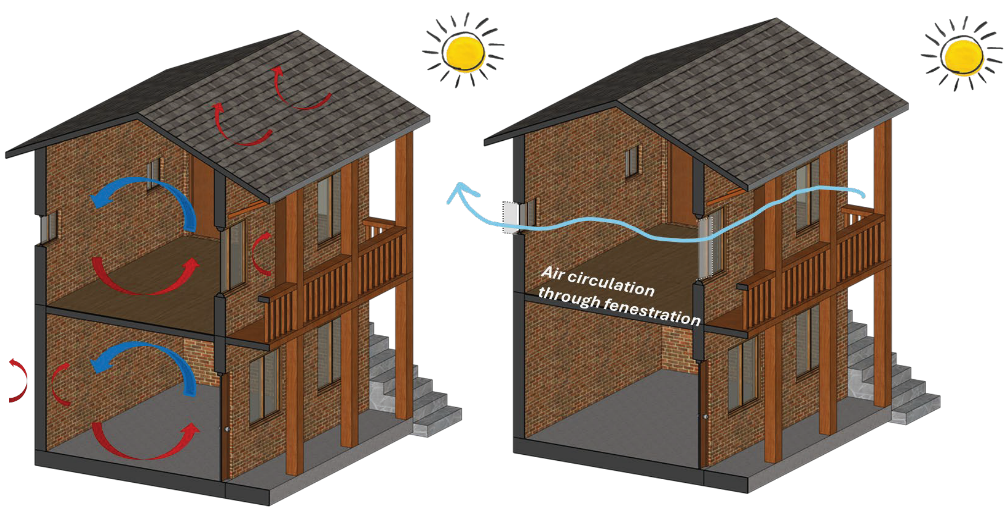


4.3.2 Convection

Convection is the transfer of heat through the movement of fluids (liquids or gases). In the building, the spaces and the outside environment consist of air. There are two different ways in which convection heat transfer occurs in buildings:

- Heat is transferred from the surface of a wall to the surrounding air. If the wall surface temperature is higher than the air, the air molecules near the wall surface are heated up by the wall. Their speed increases, and they need more space. This results in the decrease of the density of air (number of molecules in a volume). This air layer near the wall now has less weight than the air away from the wall and starts moving upwards. Colder air from the bottom comes to the wall surface, and as the temperature difference between the wall surface and surrounding air molecules remains high, heat is transferred continuously. This process is natural convection, and it is a part of the whole U-value of a wall.
- Air exchange happens through openings in the building (e.g. fenestration, cracks, and crevices). This happens in both directions (infiltration and exfiltration). E.g. in cold climates, the air coming in from outside will mix with the inside air and must be heated to reach the required room temperature. On the other hand, the heat of the warm air leaving the room is lost to the cold outside air. The amount of heat exchange happening through air exchange depends on the size of the openings, outside wind speed, the orientation of the openings with wind direction, and the temperature difference between the outside and inside air. Figure 38 demonstrates the exchange of heat by Convection.

Figure 38: Exchange of Heat by Convection (Natural Convection (On Left) and Air Exchange (On Right))

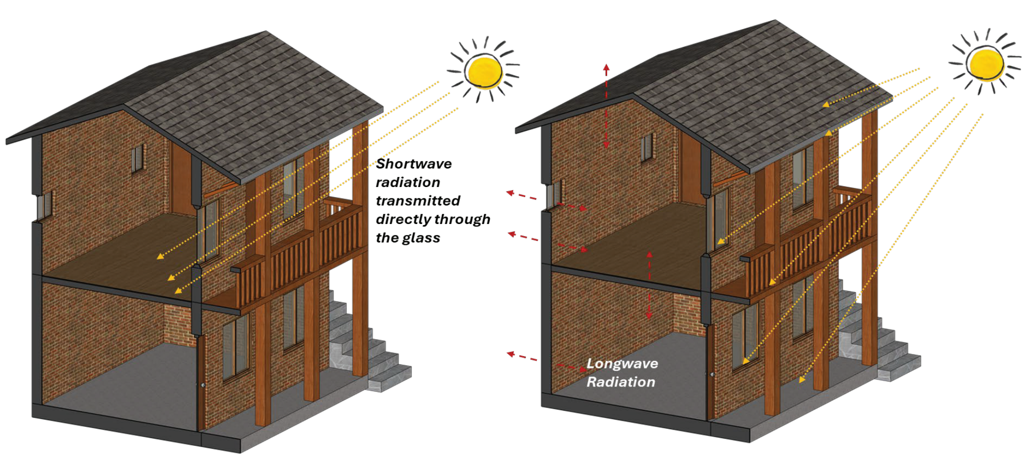


4.3.3 Radiation

Radiation is the transfer of heat in the form of electromagnetic waves without the need for a medium. All matter (especially, solids and liquids, but also some gases) with a temperature above 0 K (-273°C) emits radiation. The higher the temperature, the higher will be the radiation power and the shorter the wavelength of the emitted radiation. There are many wavelengths of radiation emitted by a body distributed around a maximum like a normal distribution. Wavelengths between 380 and 780 nm (Nanometer) are visible from blue to red. UV - radiation has a shorter wavelength. Thermal radiation of materials of buildings has wavelengths higher than 3000 nm. Two types of radiative heat transfer happen in buildings.

- Short-wave radiation, released by the sun between 250 and 2500 nm with a peak at 500 nm, passes through transparent building elements, such as the glass in windows and doors. Due to its transparency, glass allows short-wave solar radiation to enter the building directly. Additionally, some of the short-wave radiation is absorbed (partly) by the roof and walls, leading to an increase in the outside surface temperatures. This, in turn, induces additional conductive heat flux into the interior and convection heat flux to the surrounding environment.
- Long-wave radiation is emitted by all elements of the building and the surface of the human body based on their respective temperatures. Whether there is a net heat flux from one surface to another depends on the emissivity of the surfaces, how the radiation from one surface interacts with the other (view factor), and the temperature difference between both surfaces (expressed not linearly, but as T14 – T24, T in Kelvin).

Figure 39: Demonstrates the Heat Transfer Through Radiation.



4.4 Heat Transfer Through the Building Envelope

Heat exchange through the building envelope primarily occurs through its three main components: the roof, walls, and windows.

4.4.1 Through Walls and Roof (Opaque Components)

The transfer of heat through walls and roofs is primarily determined by their materials. Different materials possess varying properties that impact their ability to conduct, absorb, and reflect heat.

The key metrics for assessing these wall and roof assemblies are as follows:

- Reflectance of shortwave & Emissivity of long wave radiation, collectively referred to as the Solar Reflective Index (SRI)
- Thermal conductivity & transmittance (ability to conduct heat)
- Thermal mass (ability to absorb and store heat)

The roof and external wall surfaces are predominantly exposed to outside/ambient conditions and possess a substantial surface area. During the daytime, when solar radiation falls on these surfaces, a portion of the radiation is reflected, while some is absorbed and subsequently re-emitted. The extent to which heat is reflected and emitted is influenced by the SRI of the surface.

Throughout the day, solar radiation falling on the outer surface leads to an increase in the outside surface temperature through the absorption of the radiation. Moreover, the ambient air contributes to heating or cooling the surface through convection. Depending on both the outside and inside surface temperatures, heat will either flow from the outside to the inside or vice versa through conduction. The extent of heat flow depends on thermal transmittance and mass of the wall and roof assembly.

The Key Thermal Properties of Materials:

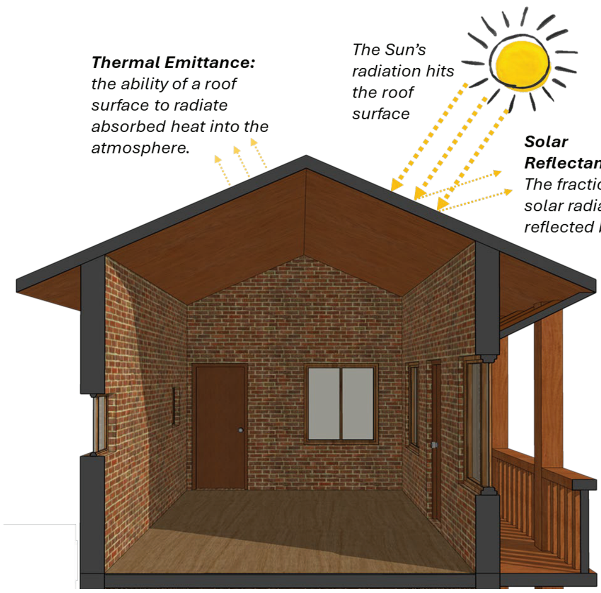
- **Density (kg/m^3):** This refers to the mass of the material per unit volume.
- **Thermal Conductivity (W/m·K):** This measures how easily heat passes through a material. Materials with low conductivity, like insulation, resist heat flow and help maintain comfortable indoor conditions.
- **Specific Heat Capacity (J/kg·K):** This is the amount of heat required to raise the temperature of one kilogram of the material by one degree Celsius. Materials with high specific heat can absorb and store more thermal energy, which is useful for delaying temperature changes.

4.4.1.1 Solar Reflective Index (SRI)

The SRI is a calculated value that combines solar reflectance and thermal emittance into a single number. Both solar reflectance and thermal emittance are expressed on a scale of 0.0 to 1.0, where 1.0 represents 100% reflectance.

SRI serves as an indicator of heat a surface is likely to absorb when exposed to solar radiation. SRI values typically range from 0 to 100, although values outside this range are possible. High SRI roof and wall finishes are particularly beneficial in warm and hot climates. Figure 40 shows the Solar Reflectance and Emissivity.

Figure 40: Solar Reflectance and Emissivity



4.4.1.2 Thermal Conductivity

Thermal conductivity is a property that defines a material's ability to conduct heat. It serves as a measure of how easily heat can traverse through a substance. Specifically, it quantifies the rate at which heat is transferred through a unit area (1 m^2) and unit thickness (1 m) of material when there is a temperature difference of one degree (1 K or 1° C) across it. Figure 41 shows the thermal conductivity of a material.

Thermal conductivity is typically represented by the symbol "k" and is measured in units of watts per meter-Kelvin (W/(m.K)). This property is denoted by the Equation 6:

$$k = \frac{Qd}{A\Delta T} \quad \text{................Equation 06}$$

Where,

k = thermal conductivity (W/(m.K))

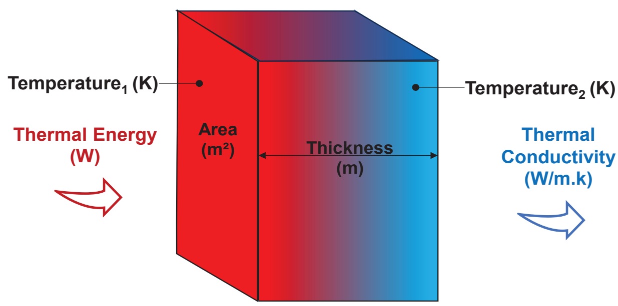
Q = amount of heat transferred (W)

d = distance between the two isothermal planes (m)

A = area of the surface (m^2)

ΔT = difference in temperature (K)

Figure 41: Thermal Conductivity of a Material



Materials with high thermal conductivity effectively conduct more heat, while those with low thermal conductivity serve as better insulators by impeding the transfer of heat.

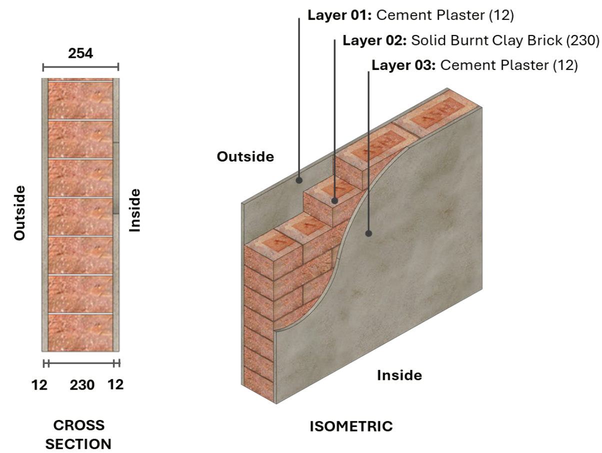
The majority of common walling masonry and roofing materials used today, including RCC roofs and solid burnt clay brick walls, typically exhibit thermal conductivities between 0.6 and 1.0 W/m·K. However, AAC blocks stand out as an exception with lower thermal conductivity. Thermal insulation products, on the other hand, boast thermal conductivities of less than 0.1 W/m·K. For a detailed list of thermal conductivities for common building materials and insulating materials, please refer to Annex 01 .

Typically, materials with high thermal conductivities also possess high densities and high specific heat capacities. In the case of high-insulating materials, where thermal conductivity (k) is low, the volume of the material is often air, and in some instances, other gases or even a vacuum. Compared to solids and liquids, gases exhibit much lower molecular density for heat transfer and considerably lower k values. Consequently, all materials employed for thermal insulation are lightweight.

4.4.1.3 Thermal Transmittance

Thermal conductivity is an intrinsic property that solely depends on the material. However, conductive heat transfer is influenced by both the material and the thickness used. Moreover, roof and wall assemblies are typically constructed with layers of different materials, each having varying thickness. For example, consider the conventional brick wall, as shown in Figure 42. The overall heat transfer through these wall assemblies is described by thermal transmittance, often represented as the U-value.

Figure 42: Wall section of conventional brick wall



Thermal transmittance, or U-value (also known as Overall Heat Transfer Coefficient), is defined as the heat transmission per unit time through the unit area of a material or construction induced by a unit temperature difference between the environments on either side. This encompasses convection and radiation heat transfer at the surfaces, as well as conduction within the solid layers. The unit of the U-value is $W/m^2.K$, as denoted by Equation 7.

$$U = \frac{Q}{A\Delta T} \qquad \text{................ Equation 07}$$

Where,

U = thermal transmittance ($W/m^2.K$)

Q = amount of heat transferred (W)

A = area of the surface (m^2)

ΔT = difference in temperature (K)

Condensation Analysis Through Glaser Diagram

The Glaser diagram is a graphical method used to assess the risk of interstitial condensation within building assemblies such as walls, roofs, or floors. It helps designers understand how temperature and water vapor pressure change across each layer of a building wall/roof assemblies, allowing them to determine whether condensation is likely to occur inside the assembly.

Condensation analysis plays a vital role in designing durable and energy-efficient wall assemblies, in nearly all climates from cold, cool and warm temperate climate zones, because the risk of interstitial condensation is high most often for some periods in the year due to large temperature and humidity differentials across the building envelope. In cold climates, the winter and in warm temperate climates, the summer are the critical periods.

In such climates, proper selection and placement of the materials of the wall/roof assemblies becomes crucial as improper selection or placement of materials can lead to moisture accumulation within wall/roof, resulting in reduced insulation performance, mould growth, corrosion, and long-term damage to the structure.

It is recommended to use insulation materials which have a high diffusion resistance factor. The diffusion resistance factor, often denoted by μ (mu), quantifies a material's resistance to water vapor diffusion in comparison to air.

It is generally recommended to place insulation on the exterior side of the wall. External insulation minimizes heat gain or loss and enables effective utilization of the thermal mass of the masonry wall, which helps stabilize indoor temperatures and enhances overall comfort and energy performance. In hot and humid climates, when dehumidification is not provided, placing insulation on the interior side can be safer.

However, if insulation to be placed inside due to design or site constraints, a vapor barrier or retarder must be installed to control moisture ingress. Additionally, it is advisable to maintain an air gap between the insulation and the interior finish. This space facilitates the integration of electrical services or the use of fasteners (e.g., for hanging fixtures) without compromising the vapor barrier or retarder.

For more information readers can refer to: “Manual on Application of Building Insulation Material” & for the condensation analysis user can refer to excel based tool “U Value and Glaser” available at https://been.minergynepal.com/.

4.4.1.4 Thermal Mass

Thermal mass is a property of a building's mass that allows it to store heat, offering "inertia" against temperature fluctuations. Scientifically, thermal mass is synonymous with heat capacity, representing the amount of heat required to produce a unit change in temperature for a given mass of material. This property is measured in Joules per Kelvin per kilogram. Heat stored in the building's mass is given by Equation 8.

$$Q = m \times c \times \Delta T \qquad \text{...............Equation 08}$$

Where,

Q = Heat Stored (J)

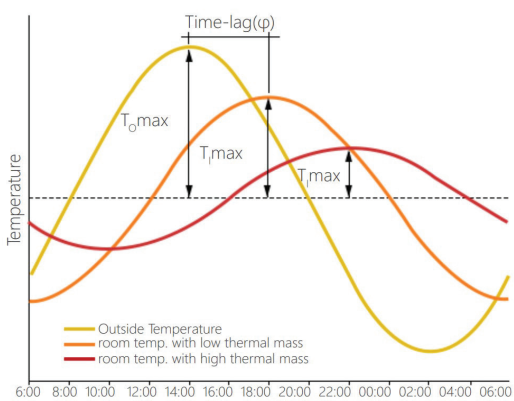
m = Mass (kg)

c = specific heat of capacity (J.kg/K)

ΔT = temperature difference (K)

Thermal mass depends on both the mass and specific heat capacity of a material. Furthermore, for effective heat transfer, the material's conductivity is crucial, allowing heat to move from the surface into the material and back out. This is particularly important for heating or cooling places deeper within the material. The thermal variations in buildings follow a day-night rhythm (sun–heating, no sun–cooling). During the day, high thermal mass walls absorb and store heat, reducing indoor heat gain. At night, as outdoor temperatures drop, the stored heat is released outward (Refer Figure 43). Appropriate design strategies should be selected based on climate and thermal comfort needs — whether to reduce heat gain or retain indoor coolness.

Figure 43: Effect of Thermal Mass in Delaying Heat Transfer from Outside to Inside.

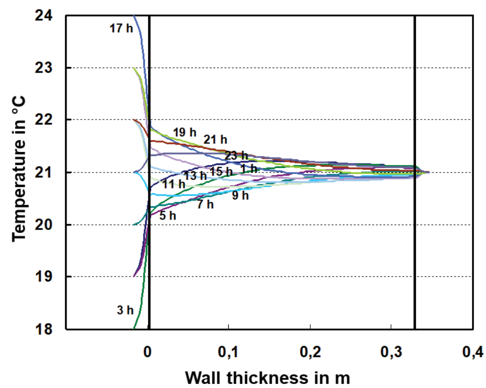


(Source: European High Quality Low Energy Buildings (https://www.new-learn.info/packages/euleb/en/glossary/index6.html)

The advantage of high thermal mass within a building's interior envelope is that the heat absorbed by the wall throughout the day doesn't directly impact the air within the space. This reduces the load on cooling and heating systems. To absorb heat effectively the next day, the room temperature must be lower than the wall temperature throughout the night. If the wall remains warm, the room must be even warmer the following day for the wall to retain its heat.

In Figure 44, the temperature profile of a 0.33 m thick concrete wall is illustrated, featuring a 24-hour temperature fluctuation between 18°C – 24°C on one side and a constant temperature of 21°C on the other side. Despite the concrete wall's excellent conductivity, it is notable that the temperature variation and, consequently, the stored heat become significantly smaller with a wall thickness exceeding 0.10 m.

Figure 44: Temperature Course in a 0.33 m Concrete Wall with 24 H Temperature Variation (Streicher, 2025)



The utilization of materials with high thermal mass proves most advantageous when there is a substantial daily temperature difference, characterized by significant variations between day and night temperatures. In summer, where outdoor temperatures vary greatly from day to night, thermal mass can absorb the sun's heat during the day. The room can then be cooled at night, for example, through night ventilation by keeping windows open. Conversely, in winter, the room can harness more solar heat through the windows during the day without overheating. The retained heat in the thermal mass then warms the room at night.

How to Calculate the U-Value of a Wall/Roof Assembly

Step 1: Calculate the thermal resistance of each uniform material layer that constitutes the building component using Equation 9:

$$R_i = \frac{t_i}{k_i} \qquad \text{......... Equation 09}$$

Where,

R_i is the thermal resistance of the material, $m^2.K/W$

t_i is the thickness of material, m

k_i is the thermal conductivity of the material, W/(m.K)

Step 2: Find the total thermal resistance, R_T, using Equation 10:

$$R_T = R_{si} + R_{se} + R_1 + R_2 + R_3 + \text{.......} R_n \qquad \text{......... Equation 10}$$

Where,

R_T is the total thermal resistance, m²·K/W

R_{si} is the interior surface film (convection and radiation) thermal resistance, $m^2.K/W$

R_{se} is the exterior surface film (convection and radiation) thermal resistance, $m^2.K/W$

R_1 is the thermal resistance of material 1, $m^2.K/W$

R_2 is the thermal resistance of material 2, $m^2.K/W$

R_3 is the thermal resistance of material 3, $m^2.K/W$

Values of Interior and Exterior Surface Film Thermal Resistance as per Climate Zone are given in Table 11.

Table 10: Categorization of Months Based on DBT and RH (Jomsom)

	Wall	Roof	
	All Climatic Zones	Warm-Temperate and Temperate Climate	Cool Temperate and Cold Climate
R_{si}	0.13	0.17	0.10
R_{se}	0.04	0.04	0.04

The thermal conductivity of commonly used building materials is provided in Annex 1, which can be utilized to calculate the thermal resistance (R-value).

Step 3: Calculate the thermal transmittance (or overall heat transfer coefficient, U-value) of a wall or roof assembly as given by Equation 11:

$$U = \frac{1}{R_T} \qquad \text{......... Equation 11}$$

Where,

U is the overall heat transfer coefficient, $W/(m^2.K)$

R_T is the total thermal resistance, $m^2.K/W$

Thermal Bridging

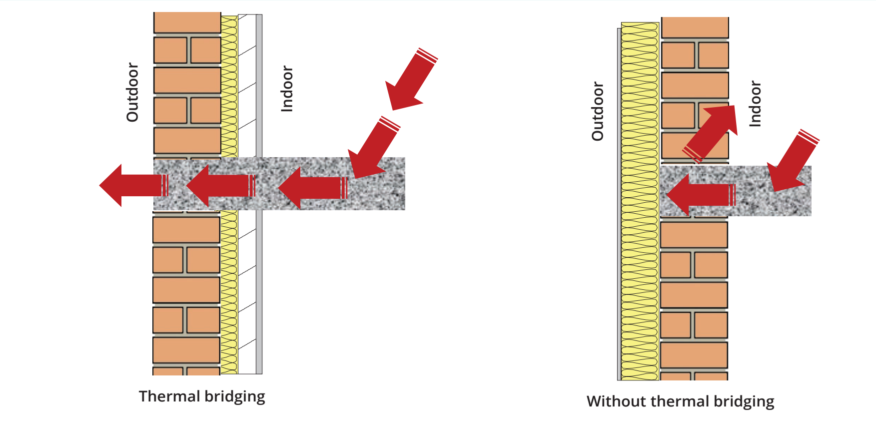
A thermal bridge refers to an area in a building construction with significantly higher heat transfer compared to the surrounding materials. When thermal bridging occurs in an insulated or low U-value building envelope, it results in undesirable heat gains or losses.

Thermal bridges can manifest at various locations within a building envelope, frequently occurring at junctions between two or more building elements, including:

- Floor-to-wall or balcony-to-wall junctions
- Roof/ceiling-to-wall junctions
- Window-to-wall junctions
- Wall-to-wall junctions
- Concrete or steel members, such as columns and beams in an external masonry wall
- Windows and doors, particularly frame components

External insulation offers more advantages than internal insulation in reducing thermal bridges. Additionally, strategic placement of insulation in and around junction details proves effective in minimizing thermal bridging. Example of thermal bridging is shown in Figure 45.

Figure 45: Example of Thermal Bridging



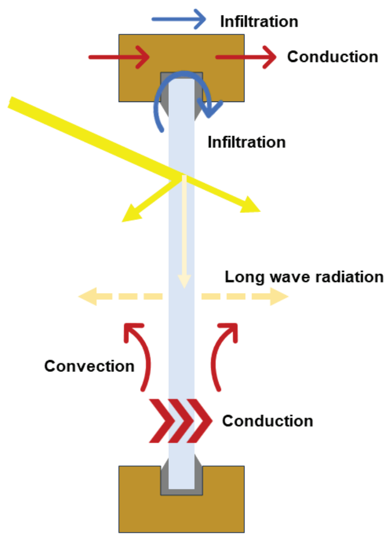
4.4.2 Through Fenestration (Non-Opaque Components)

In a building, fenestration comprises both opaque and solid elements (such as wood, aluminium, etc.) and non-opaque or transparent elements (i.e., glass). Between the two, a significant amount of heat transfer occurs through the glass. The crucial thermal properties of fenestration include:

- Solar Heat Gain Coefficient or SHGC (fraction of solar radiation radiated inside through the glass).
- Thermal conductivity and transmittance of frames and glass (ability to conduct heat).

In addition to conduction, heat transfer also occurs through infiltration, i.e., unintentional air entering a space through the cracks and gaps in the fenestration elements. This is part of the air exchange process. Figure 46 shows the modes of heat transfer through the Fenestration.

Figure 46: Modes of Heat Transfer Through the Fenestration



4.4.2.1 Solar Heat Gain Coefficient (SHGC)

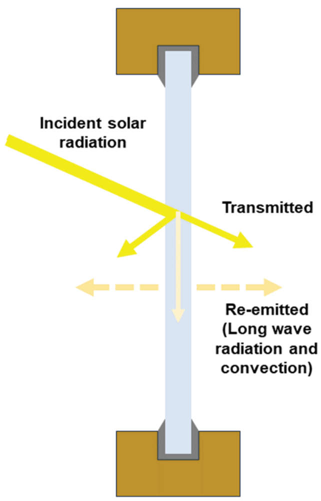
When solar radiation strikes the glass component of fenestration, some of the radiation is directly transmitted inside, while another portion is absorbed and re-emitted as long-wave radiation and convection. Additionally, some of the radiation is reflected (refer to Figure 47). The re-emitted radiation into the indoor space is referred to as secondary heat gain. The SHGC represents the fraction of solar radiation admitted through a glass — either transmitted directly and/or absorbed — and subsequently released as heat inside a home. It is calculated using the following Equation 12:

$$SHGC_{unshaded} = \frac{Transmission + Secondary\ Heat\ Gain}{Incident\ Solar\ Radiation} \quad \text{......Equation 12}$$

The SHGC is measured on a scale from 0 to 1, with a lower value indicating less solar heat gain. Conversely, a higher SHGC implies that a window or glazing system allows more solar radiation to pass through, resulting in increased heat gain inside the building.

Typically, 5mm – 6mm clear glass has an SHGC of 0.8 – 0.85. Glass with even lower SHGC values is also available. Another effective method to reduce SHGC is by implementing external shading for windows.

Figure 47: Solar heat gain Coefficient (SHGC)



$$SHGC_{unshaded} = \frac{Transmission + Secondary\ Heat\ Gain}{Incident\ Solar\ Radiation}$$

External shading devices influence the SHGC of fenestration by affecting the incident solar radiation. The impact of the shading device on the un-shaded SHGC leads to the concept of SHGC equivalent. The calculation of the SHGC equivalent is detailed in Annex 2.

Shading Coefficient (SC)

The Shading Coefficient is a measure of how much heat is transferred through a glazing system. It typically falls within the range of 0 to 1 and has no units. As the shading coefficient decreases, less heat is transferred through the system.

SC is the ratio of solar radiation at a given wavelength and angle of incidence passing through a glass unit to the radiation that would pass through a reference window of frameless 3 millimetres (0.12 in) Clear Float Glass.

The following Equation 13 is used to convert between SC and SHGC:

SC= SHGC/0.86 ....Equation 13

SC = Shading Coefficient

SHGC = Solar heat gain coefficient

For example, if SHGC of a glass is given as 0.5, then SC is 0.5/0.86 = 0.58

SHGC is more commonly used as the standard property for assessing window solar gains in the US and Asia.

4.4.2.2 U-Value

In addition to heat transfer through direct solar radiation, fenestration elements also contribute to heat transfer through radiation, conduction, and convection.

Heat is also transferred through conduction in both the glass and the frame. The U-value of the glass and frame represents this conductivity, with lower U-values indicating lower heat transfer. Table 12 illustrates the U-values of various glass types. Among common frame materials, timber and UPVC generally have lower U-values compared to aluminium frames.

Table 12: U_g (U Value of Glass) for Different Glass Types

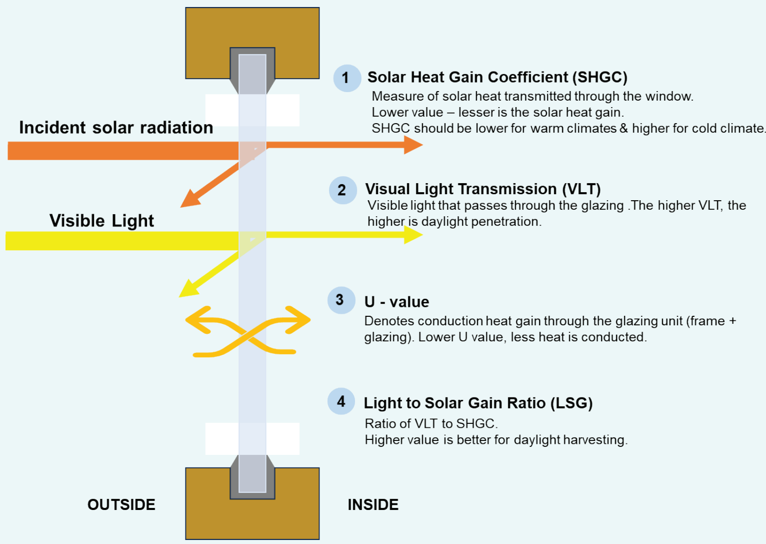
Glass Type	Thickness of Glass (mm)	U_g (W/m².K)
Single clear	6	5.8
Single Clear (with coating) Saint Gobain India	6	3.6 – 5.6
DGU (air gap) Saint Gobain India	6 (Glass)-12 (Air gap)-6 (Glass)	1.5 – 2.8
DGU (air gap) (assembled in Nepal)	6 (Glass)-12 (Air gap)-6 (Glass)	2.4 – 2.8
DGU (Argon gap, low e coating) (assembled in Europe)	4 Glass – 14 (Argon gap) – 4 Glass	1.3

Visible Light Transmittance (VLT) of Glass

One of the primary functions of a window is to facilitate daylight inside a space. The property of glass that indicates the amount of visible light entering through the glass into the space is known as Visible Light Transmission (VLT). VLT is expressed as a number ranging from 0 to 1. The higher the VLT, the greater is the amount of light passing through the glass, and vice versa.

Figure 48 shows Image Explaining Solar Heat Gain Coefficient (SHGC), Visual Light Transmission (VLT), Thermal Transmittance (U-Value), and Light to Solar Gain Ratio for a Window (LSG).

Figure 48: Image Explaining Solar Heat Gain Coefficient (SHGC), Visual Light Transmission (VLT), Thermal Transmittance (U-Value), and Light to Solar Gain Ratio for a Window (LSG)



4.5 Metrics That Matter

Table 13 outlines the key parameters of building components that influence heat transfer through the envelope.

For walls, the U-value determines conductive heat transfer, while in climate where outside temperature having good diurnal variation, the thermal mass expressed through the specific heat capacity of materials also plays a crucial role.

In non-opaque fenestration including windows, doors and skylights, conductive heat gain is governed by U-values. Additionally, solar heat gain is influenced by the Solar Heat Gain Coefficient (SHGC), or with Shading Coefficient (SC) of glazing, and daylight entry is affected by Visible Light Transmittance (VLT) of glazing. High VLT is desirable for natural lighting, while low-e coatings can be applied to reduce solar heat gains without significantly impacting daylight. Typically, opaque fenestrations like doors are majorly governed by U-values, if there is no glazed element.

Roofs is analysed similar to walls in terms of U Value. However, to reduce radiative heat gains, reflective surface treatments or cool roof coatings can be applied to the exterior roof surface. The reflectivity of roof surfaces is typically measured using the Solar Reflectance Index (SRI), which serves as a key metric for evaluating their effectiveness.

Table 13: Metric that Affects the Heat Transfer from Building Envelope

Building Envelope Components	Parameter	Metric
External Wall	*Thermal Conductivity*	**U Value**
	Thermal Mass	**Specific Heat Capacity**
Fenestrations (non-opaque) • Windows • Skylights • Doors	*Thermal Conductivity*	**U Value**
	Solar Gains	**Solar Heat Gain Coefficient(SHGC)/ Shading Coefficient (SC)**
	Daylight	**Visible Light Transmittance (VLT)**
Roof	*Thermal Conductivity*	**U Value**
	Solar Reflectance	**SRI**
Ground	*Thermal Conductivity*	**U Value**

Heat Gains and Losses

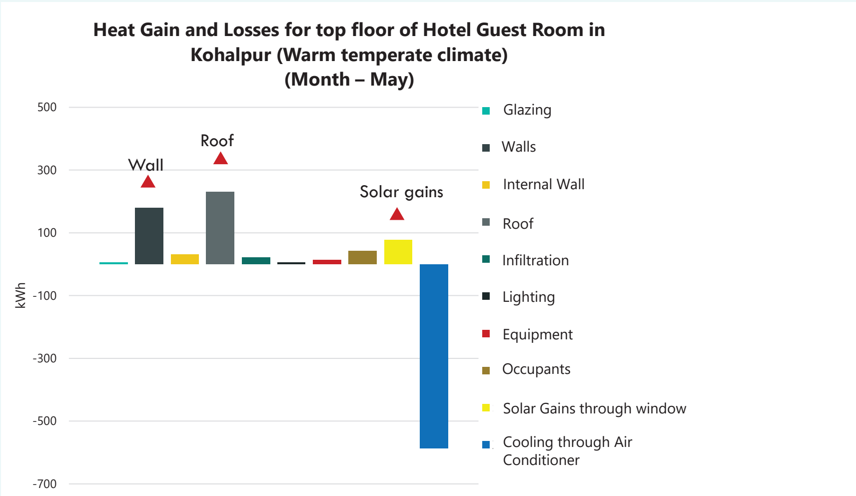
Analysing heat gains and losses is essential to understand how heat enters, is stored in, and exits the building envelope, directly affecting thermal comfort and energy use. As discussed earlier, these are influenced by external and internal loads, along with the properties of building envelope assemblies.

Key metrics such as U-value and Solar Heat Gain Coefficient (SHGC) are critical for design decisions. In warm climates, walls and roofs with higher U-values permit greater heat gain through conduction, while glazing with a high SHGC and poor shading increases indoor temperatures through direct solar gains. In cold climates, higher U-values cause significant heat losses through walls, roofs, ground, and windows. However, south-facing windows with glazing that combines a higher SHGC, and lower U-value can be advantageous, allowing useful solar gains during the day while reducing night-time heat loss.

By understanding these dynamics, designers can identify weak points in the envelope and apply passive strategies such as improved ventilation, optimized insulation, high-performance glazing, and effective shading.

Example: Figure 49 illustrates the heat gains and loss of a hotel guest room located on the top floor in Kohalpur, which lies in the warm temperate climate zone characterized by long, harsh summers. The analysis for May shows that most heat gains occur through the roof, followed by the walls and solar gains through exterior windows. This accumulated heat is offset by the air conditioning system, which increases energy consumption as heat gains rise. To improve energy performance, reducing heat transfer through the building envelope is essential. This can be achieved by using roof and wall assemblies with lower U-values to minimize conductive heat gain. Using proper external shading for windows and glazing with lower SHGC to reduce the direct solar gain.

Figure 49: Heat Gain and Losses for Guest Room of Hotel in Kohalpur (Warm Temperate), for the Month of May



Summary

- Heat gains or "heat sources" for a building
  - External heat: Outdoor heat that is transferred through the building envelope.
  - Internal heat: Generated by occupants' activity as metabolic heat, electrical devices, or thermal emission from artificial lighting.
- Heat transfer in a building occurs through conduction, convection, and radiation.
- The following properties impact heat transfer for opaque building envelope components, i.e., walls and roof:
  - Solar Reflective Index (SRI)
  - Thermal conductivity and thermal transmittance (U-value)
  - Thermal mass
- The following properties impact heat transfer for non-opaque building envelope components, i.e., glazed windows, doors etc.
  - Solar heat gain coefficient (SHGC)
  - Thermal transmittance (U-value)
- By understanding heat gain and loss, designers can identify weak points in the building envelope and apply energy conservation measures.

5

NATURAL VENTILATION

What's in this Section?

Natural Ventilation

Natural ventilation holds significant potential in reducing cooling loads in the warm temperate and temperate climates in Nepal. This chapter covers the principles of improving ventilation. It's crucial to note that minimizing heat gains through other passive strategies is imperative for natural ventilation to provide the best possible impact.

5.1 Ventilation and Natural Ventilation

Ventilation is the intentional introduction of outdoor air into a space, primarily employed in buildings to maintain indoor air quality. In hot climates, it can additionally enhance thermal comfort by extracting heat from the interior. Typically, around 10 ACH (Air Changes per Hour) is required for this purpose.

Ventilation contributes to improved thermal comfort through:

- Cooling indoor air by either replacing it with outdoor air or diluting it if outdoor temperatures are lower than indoor temperatures.
- Cooling the building structure, such as the thermal mass of the building.
- Providing a direct cooling effect on the human body through convection and evaporation.

Air Changes Per Hour (ACH)

Air Changes per Hour (ACH) is a metric representing the number of times that the total air volume in a room or space is completely replaced within an hour. The higher the ACH, the greater is the ventilation as given by the Equation 14.

$$ACH = \frac{3.6\,Q}{Vol}$$ ....Equation 13

Where,

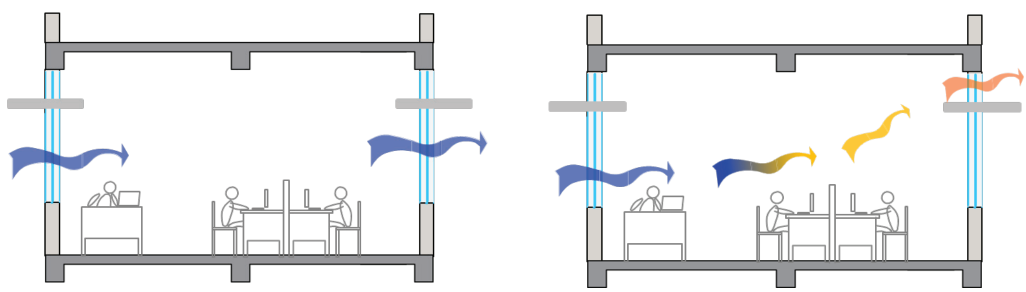
Q = Volumetric flow rate of air in litres per second (L/s)

Vol = Space volume = L × W × H, in cubic metre

Natural ventilation, devoid of mechanical systems, can be categorized into wind-driven or buoyancy-driven modes.

- Wind-driven ventilation relies on wind pressure to propel air movement. Wind striking the windward facade generates positive pressure, creating a pressure difference that induces air movement. Similarly, as wind flows away from the leeward facade, a region of lower pressure is formed, further driving air movement.
- Stack or buoyancy-driven ventilation involves the natural movement of air through a building due to differences in vertical pressure caused by temperature variations in the air. Warm air escapes from openings at a considerable height on the building envelope, drawing in colder, denser outside air through lower openings in the building.

Figure 50: Wind-driven (Left) and Buoyancy-driven (Right) Natural Ventilation



For most buildings, enhancing wind-driven natural ventilation or employing a fan to accelerate air movement is often more feasible. The stack effect becomes significant only when there is a considerable vertical distance between higher outlet openings and lower inlet openings, coupled with a substantial temperature difference.

5.2 Guidelines to Utilise Maximum Natural Ventilation Potential Through Windows

5.2.1 Orientation

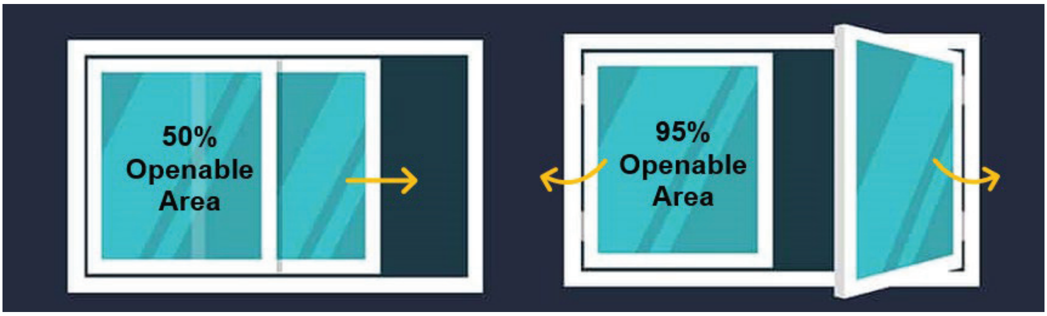
Orienting a building for a favourable wind direction is not as straightforward as aligning it according to the constant sun path of the location. Wind direction is unpredictable, and even for a given site, it keeps changing in terms of both direction and speed. Nevertheless, the average hourly wind speeds and wind direction for selected cities can be found in their climate files as explained in Chapter 3. Climate analysis, using available tools, can show the times of the year when the outside air is cool enough to provide cooling inside homes, i.e., the period with greatest cooling potential through natural ventilation. The wind rose diagram of that period can be consulted to know the most likely wind direction during that period. This can inform the position of openings in the building.

The requirements to manage solar gains and utilize wind flows may sometimes lead to conflicting results. Analysing such conflicts is crucial for each case to find the optimum solution. Regardless of the orientation of the building and windows, it's essential to ensure that critical facades and windows are well-shaded to prevent solar radiation from directly impacting them.

5.2.2 Design for Openability and Better Air Distribution Inside

- The more openable the windows, the better the natural ventilation potential. Casement windows provide more openable area than a sliding window of the same size as shown in Figure 51.

Figure 51: Sliding Window (Left) and Casement Window (Right)



- Openable window-to-floor area ratio (WFRop) indicates the potential of using external air for ventilation. It is defined as the ratio of openable area of doors and windows in the habitable spaces to the floor area of the habitable spaces.

Openable area to floor area ratio (WFR$_{op}$) (%)

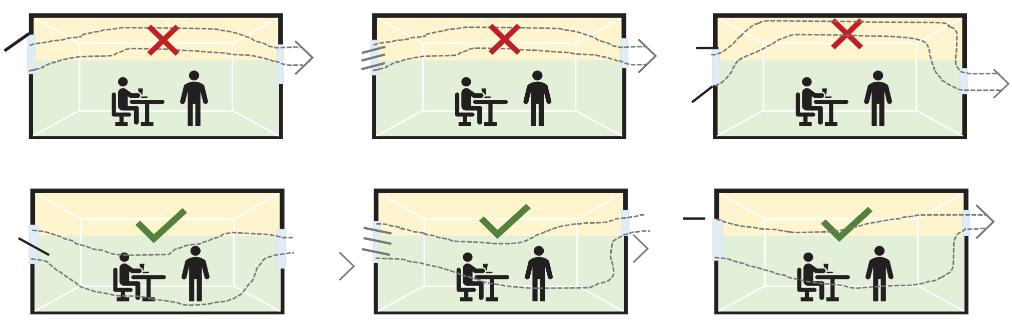
$$= \frac{Openable\ area\ (doors, windows)\ in\ the\ habitable\ spaces\ (m^2)}{Area\ of\ habitable\ spaces\ (m^2)} x100$$

.............Equation 13

The openable area of all the doors and windows in the habitable spaces, which is directly connected to the ambient or outside environment , is to be considered for the calculation.

- The Nepal Building Code:206, 2024 gives the minimum requirement for openable area to floor area ratio (WFR$_{op}$) for different climate zones of Nepal. The minimum openable area to floor area ratio (WFR$_{op}$) ensures there is sufficient provision for natural ventilation in the building. Please see Annexure 03 for these thresholds.
- The position of overhangs, louvers, etc. can be used to direct the air inside at the required level and area as shown in Figure 52.

Figure 52: Use of Louvers, Overhangs etc. to Direct Air Inside



5.2.3 Improving Cross Ventilation

The following is the preferred method for ensuring effective natural ventilation:

- Windows should be positioned on two walls in a manner that allows incoming air to travel through a larger area of the room and at the level of the occupants (refer to Figure 53 and Figure 54).
- The inlet and outlet openings should be either of the same size, or the outlet opening should be larger than the inlet opening.

Figure 53: Arrangements for Cross-Ventilation (Plan)

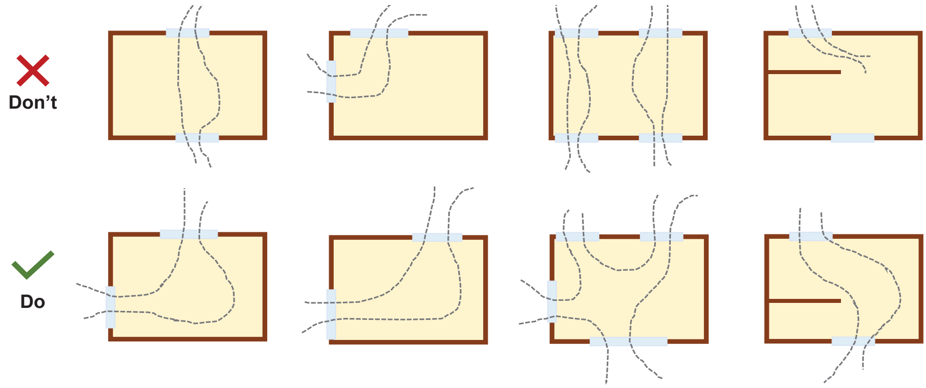
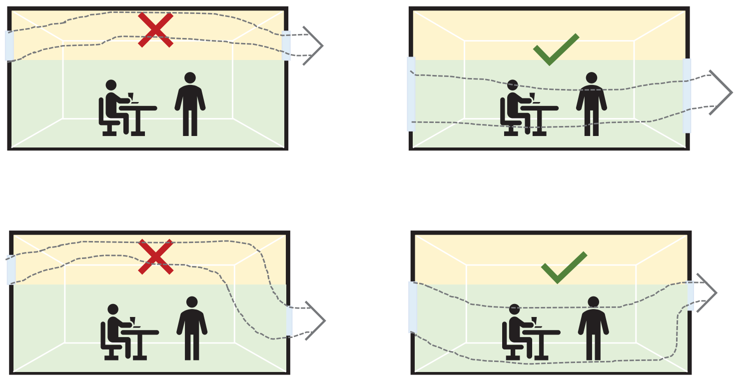


Figure 54: Arrangements for Cross-Ventilation (Section)



5.2.4 Improving Single-sided Ventilation

Single-sided ventilation occurs when only a single façade of the building is exposed to wind, and openable windows are located solely on that particular wall. In such cases, it is recommended to provide at least two windows on the façade. Two examples of how this can be achieved are illustrated in Figure 55 and Figure 56.

Figure 55: Single-sided Ventilation (Plan, Section and Elevation) - 1

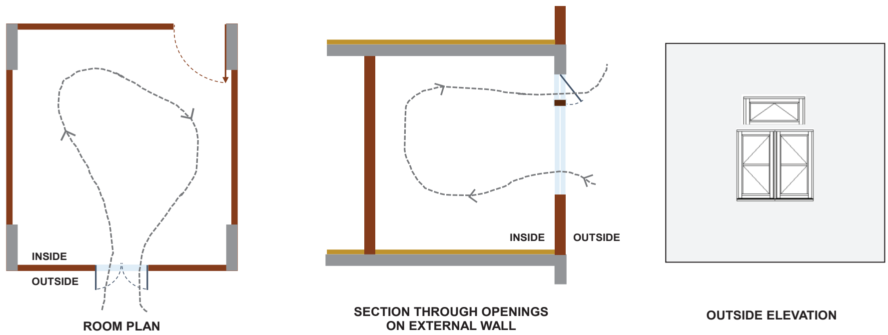
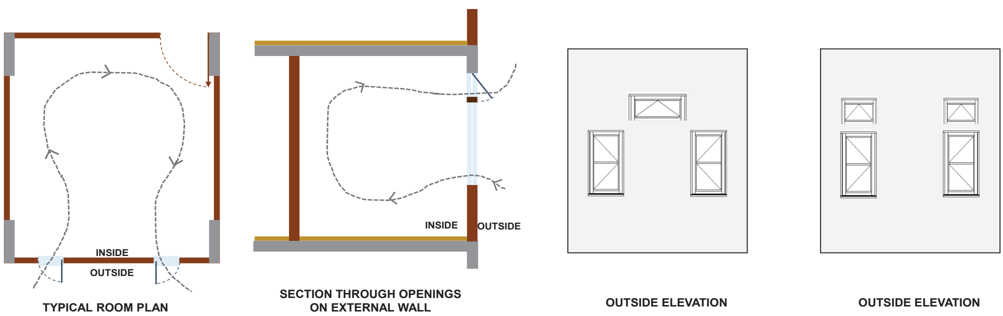


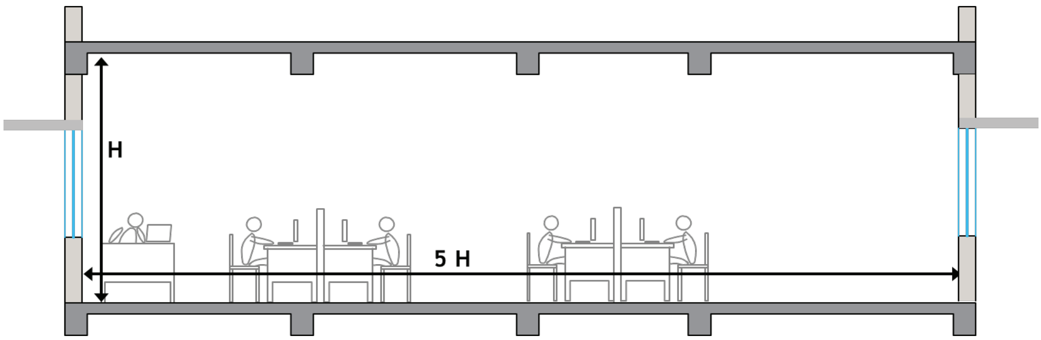
Figure 56: Single-sided Ventilation (Plan, Section and Elevation) - 2



5.2.5 Shallow Depth of Floor Plan

A shallow floor plan facilitates better cooling through natural ventilation. In a cross-ventilated space with appropriately sized and located windows (openable windows on opposite walls or adjacent walls), a depth of up to 5 times the room height can be effectively considered for cooling. For a single-side ventilated space, a depth of up to 2.5 times the room height can be considered. Figure 57 shows the depth of the floor plan for good cross ventilation.

Figure 57: Depth of Floor Plan for Good Cross Ventilation



5.3 Fan-assisted Ventilation

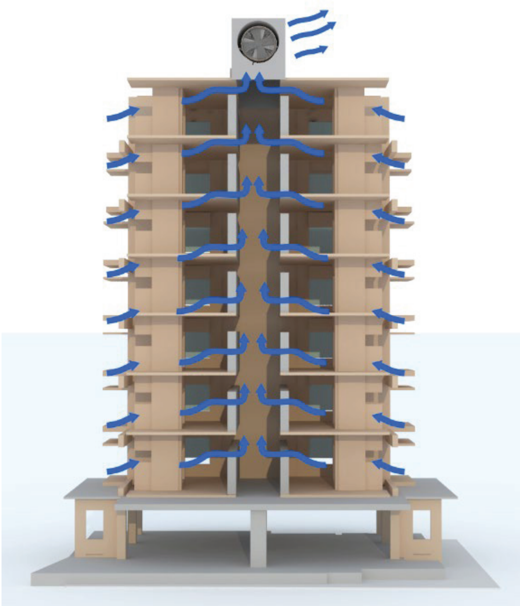
In situations where ambient wind velocity or wind direction is insufficient for cooling, fan-assisted ventilation becomes a viable option. Fans can be employed to generate a pressure difference, enabling controlled air movement. This ensures the desired air circulation, as fan requirements can be calculated and controlled.

In Figure 58, an example in the context of an apartment building is illustrated. The system operates as follows:

- A roof-top fan, situated above the common utility shaft between flats, creates a negative pressure.
- Flats open into the shaft through openings in the bathrooms. All other openings into the shaft are closed to establish a closed system, allowing air flow only as required.
- The negative pressure generated by the fan draws ambient air through the flats.

This strategy involves exchanging all the air in the building many times every hour, particularly when sufficiently cool outside air is available for cooling. It becomes particularly useful when external temperatures are lower than internal temperatures and the ambient wind speed is not sufficient for natural ventilation.

Figure 58: Fan-assisted Ventilation



It is important to note that, as fans use electricity, they come with operational expenses. To achieve an effective ventilation cooling effect, the Air Changes per Hour (ACH) should be 10 or higher, indicating a high level of ventilation. Whenever possible, pure natural ventilation should be prioritized.

Opening windows at night for natural ventilation when the building is unoccupied may not always be possible due to security concerns. In such cases, louvred shutters, security grills, fly-mesh screens, and blinds inclined towards the outside and overlapped to prevent water infiltration, even during heavy rains, can be valuable. When manufactured with sufficient strength, these elements also provide adequate security.

Use of Personal Fans (Ceiling Fans, Table Fans, etc.):

The use of personal fans does not contribute to increased ventilation rates through a space. Nevertheless, they prove to be an effective means of enhancing convective heat transfer around the human body, creating a sensation of cooler temperatures. Fans can provide a perceived temperature that is 2°C–4°C lower, offering a low-energy cooling option before resorting to air-conditioning.

The CBE Thermal Comfort Tool (https://comfort.cbe.berkeley.edu/) can indicate the improvement in comfort due to increased air movement.

Summary

- Natural ventilation holds significant potential in reducing cooling loads, particularly in warm temperate, temperate, and cool temperate climates in Nepal.
- Ventilation involves intentionally introducing outdoor air into a space. Natural ventilation, which doesn't rely on mechanical systems, can be wind-driven or buoyancy-driven.
- To improve natural ventilation through windows, consider the following guidelines:
  - Orient windows for favourable wind direction and ensure shading for all windows.
  - Casement windows generally allow better ventilation compared to sliding windows.
  - Strategically locate windows to enhance cross-ventilation and single-sided ventilation.
  - Consider a shallow depth for the building floor plate.
- In cases where ambient wind velocity or direction is insufficient for cooling, fan-assisted ventilation can be employed.
- Louvered shutters, security grills, and fly-mesh screens are options that enable night ventilation while ensuring security.

6

VISUAL COMFORT & DAYLIGHTING

What's in this Section?

Visual Comfort & Daylighting

Lighting stands as the next largest consumer of energy in buildings. Passive design for lighting revolves around maximizing the use of daylight when available. Beyond contributing to energy efficiency, daylight plays a crucial role in human health and performance. This chapter explores both the qualitative and quantitative assessment of daylighting, presenting various strategies and rules that can be implemented to enhance daylight in a building.

6.1 Lighting Terminology

6.1.1 Quantitative Terminology

6.1.1.1 Luminous Flux

Luminous flux is defined as the amount of light flowing through space, measured in lumens (lm). The quantity of lumens is contingent on the specifics of the lighting fixture, where a higher lumen value corresponds to more light. However, lumens are also associated with energy consumption, indicated by a term known as efficacy as given by Equation 16.

$$Efficacy = \frac{\text{light output (lumens)}}{\text{energy input (watt)}}$$ ....Equation 16

Table 14 displays the luminous efficacy of typical lighting fixtures, presenting the lumen output considering typical efficiency. Notably, daylight exhibits the highest luminous efficacy.

Table 14: Light fixtures and their luminous efficacy

Light Fixture/Light Source	Luminous Efficacy with Typical Efficiency
Incandescent Bulb	10 - 15 lm / W
Halogen Light	15 - 20 lm / W
CFL	50 - 70 lm / W
LED	80 - 150 lm / W
Daylight through Window Glass	75 - 130 lm / W

Source 1: https://lamphq.com/led-energy-efficiency/
Source 2: https://spectrum.ieee.org/our-best-lamps-still-cant-equal-the-luminosity-of-the-sun

6.1.1.2 Irradiance or Illuminance

Light falling on a surface is termed illuminance, measured in lumens per square meter (lux) in the SI system, and lumens per square foot (foot-candles) in IP units. Illuminance is not solely a property of the light source; it depends on factors such as lumens emitted, distance from the surface, and often the lightness or darkness of surrounding surfaces. A lux meter is commonly used to measure illuminance.

Recommended illuminance levels for various spaces are specified by different standards. Some of these standards include:

a. Illuminating Engineering Society (IES Standard)

b. European standards - EN 17037, EN 12464-1, and EN 15193

c. Chartered Institution of Building Services Engineers (CIBSE)

6.1.1.3 Luminance/Radiance

Light reflected from a surface is termed luminance, with its SI unit expressed as candela per square meter and in IP units as foot-lambert per square foot. It's important to note that luminance and brightness, while closely related, are distinct concepts. Luminance is a quantitative measurement of light reflected from a surface, whereas brightness is a qualitative aspect representing human perception.

6.1.1.4 Reflectance

This metric, known as reflectance and measured in percentage (%), expresses a surface's ability to reflect light. The higher the reflectance value, the lighter the surface will reflect, and vice versa. Lighter surfaces generally have higher reflectance than darker ones.

In interior spaces, using materials with high reflectance values on the interior surfaces is advisable. This practice enhances daylight within the space through internal reflection.

6.1.2 Qualitative Terminology

6.1.2.1 Brightness

Brightness is the subjective visual sensation linked to the intensity of light produced or reflected from a surface or a point source. Humans perceive the brightness of a subject relative to its surroundings. For instance, a car with its headlamp on during the day doesn't significantly affect driving. However, during the night when the surroundings are dark, the car's headlamp becomes a source of brightness, making it challenging to drive.

6.1.2.2 Contrast

Contrast is the distinction between the brightness of an object and its immediate background. Objects with higher contrast are easier to see than those with lower contrast.

6.1.2.3 Glare

Glare is commonly defined as discomfort to the eye caused by bright light or extreme contrasts. Glare may be direct, i.e., caused by the light source, or indirect, i.e. caused by light reflected through surfaces.

6.2 Daylighting Strategies

When designing for daylight, achieving the right balance between heat ingress and daylight is crucial, particularly in climates requiring cooling during the summer. Designers can make critical decisions in the early stages of building design to strike a balance between effective daylighting and controlling heat ingress. Further sections will discuss important aspects and thumb rules for early-stage design.

6.2.1 Orientation And Planning The Spaces For Optimum Daylight And Heat Ingress

In the warm temperate and temperate climates of Nepal, the optimal placement for glazed openings for daylight is on the north and south facades. The north facade, receiving the least direct radiation, requires minimal shading and glazed openings provide glare-free daylight without excessive heat. On the other hand, the south facade, while receiving significant solar radiation, can be shaded in the summer easily.

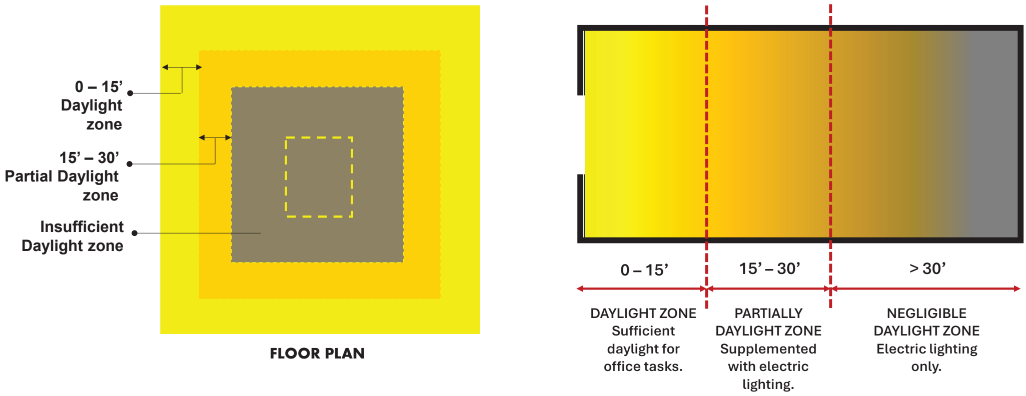
In the and cool-temperate and cold climate of Nepal, placing glazed windows on the south facade is ideal for maximizing daylight and allowing in the sun's heat for thermal comfort. Some shading should be implemented to prevent overheating in the summer months. Conversely, the north facade, although providing daylight, is less suitable for large glass areas due to minimal heat ingress and maximum heat loss on this side.

6.2.2 Planform Depth: The 15/30 Rule

Typically, in buildings, a 15 ft (4.5 m) perimeter zone can be fully daylit, with an additional 15 ft (4.5 m) beyond that partially daylit by windows. Beyond 30 ft (9 m), insufficient or no daylight is expected, necessitating the use of electric lighting. This rule serves as a practical guideline for determining the form and zoning of internal spaces in cases where window height is unknown.

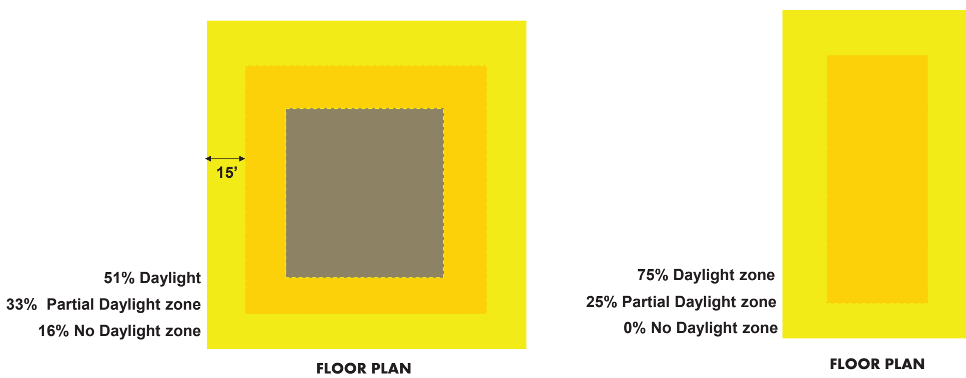
Figure 59 shows the daylight availability about the distance from the envelope or fenestration.

Figure 59: Daylight Availability in Relation to Distance from Envelope or Fenestration (Plan and Section)



The square plan in Figure 60 illustrates that 16 percent of the area receives no daylight, and an additional 33 percent can only be partially daylit. If this square plan is replaced with a rectangular plan of the same area, it can eliminate the core area without daylight entirely. However, there will still be a substantial area that receives only partial daylight.

Figure 60: Daylight Availability in a Square vs. a Rectangle

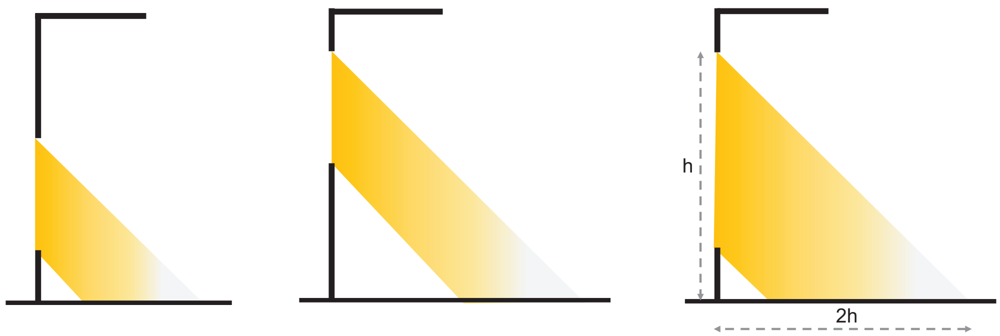


A narrow building design enables daylight to reach the maximum depth of the structure. If windows are placed on only one side, the optimal building width falls within the range of 7.5m to 10.5m. Alternatively, when windows are provided on both sides, the recommended building width extends to the range of 15m to 21m.

6.2.3 Vertical Position Of Glazed Openings On The Wall: The 2h Rule

The 2H rule estimates the depth of daylight penetration when the window head height or lintel height is known. According to this rule, the daylight penetration is approximately 2 to 2.5 times the height of the head (H). Refer to Figure 61 for a visual representation. Therefore, the higher the head height, the greater will be the amount of light that can reach deeper areas within the spaces.

Figure 61: 2H Rule – The Higher the Head Height, the Deeper the Light Penetrates into Space



6.2.4 Area Of Glazed Openings On Walls

The glazed area-to-floor area ratio (GFR) indicates the provision of daylight in a space. It is defined as the ratio of the glazed area of doors and windows in the habitable spaces to the total area of the habitable spaces.

Openable area to floor area ratio (WFRop) (%)

$$= \frac{Total\ glass\ area\ (doors, windows) of\ habitable\ spaces\ (m^2)}{Area\ of\ habitable\ spaces\ (m^2)} x100$$

.............Equation 17

The glazed area of all the doors and windows in the habitable spaces, which is directly connected to the ambient, is to be considered for the calculation.

The Nepal Building Code:206, 2024 gives the minimum requirement for glazed area to floor area ratio (GFR) for all zones of Nepal. The minimum glazed area to floor area ratio (GFR) ensures there is sufficient provision for daylight in the building. Please see Annexure 03 for these thresholds.

6.2.5 Area of Skylights: Skylight-To-Roof Ratio (SRR)

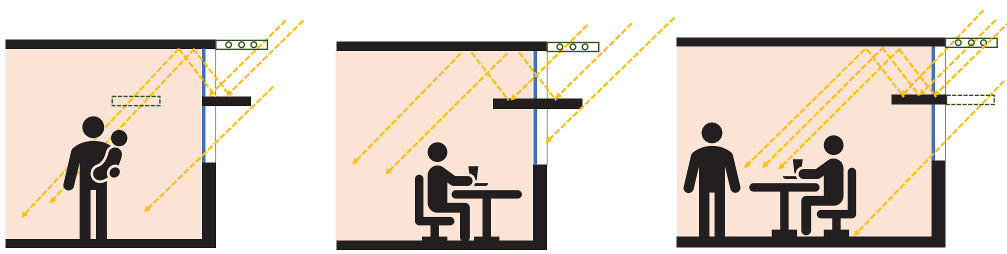
The recommended ratio of the total skylight area to the roof area falls within the range of 3% to 5%. As an example, if the roof area is 100 m^2, the maximum skylight area should be 5 m^2.

6.2.6 Reflecting Light Further Inside: Light Coloured Interiors And Light Shelves

The use of light-coloured interior surfaces, especially on the ceiling, enhances daylight coverage in space and reduces luminance contrast.

The term "light shelves" typically refers to horizontal surfaces installed partway up a glazed opening. These shelves can be mounted inside a building, outside, or both. Light shelves serve to divide windows, separating the viewable portion from the section that allows additional natural light. They bounce this light upward, reflecting it off the ceiling to enable deeper penetration of daylight into the floor plate. The working principle of light shelves Figure 62.

Figure 62: Working Principle of Light Shelves



6.3 Daylight Performance Metrics

These metrics are employed to assess the daylight potential within a designed space, necessitating the utilization of daylight simulation tools.

6.3.1 Daylight Factor (DF)

The Daylight Factor (DF) is defined as the ratio of interior illuminance to outdoor illuminance, at the same time, under overcast skies. This metric is calculated and expressed as a percentage as given by Equation 18.

$$Daylight\ factor = \frac{\text{Interior Illuminance}}{\text{Outer Illuminance}} \times 100\% \qquad \text{.............Equation 13}$$

Various standards, including those set by the Illuminating Engineering Society (IES), EN 17037, EN 12464-1, EN 15193, and the Chartered Institution of Building Services Engineers (CIBSE), provide daylight factor values for different types of buildings and spaces. However, it is important to note that the daylight factor doesn't account for the impact of factors such as orientation, building location, time of day, and local sky conditions. It is calculated under overcast sky conditions, which represent the worst-case scenario and may lead to oversized window designs. Due to these limitations, other daylight performance metrics have been developed.

6.3.2 Daylight Autonomy (DA) and Continuous Daylight Autonomy (CDA)

Daylight Autonomy is expressed as a percentage of annual daytime hours during which a specific point in space is illuminated above a designated illumination level as given by Equation 19.

$$DA_{(illumination\ level)} = \frac{\text{Daytime hours above the specified illumination level}}{Total\ Annual\ Daytime\ Hours} \times 100$$ ....Equation 19

Specified illumination levels, or lux levels, for different spaces, are defined by various standards such as IESNA and CIBSE.

The daylight autonomy metric, however, doesn't account for lux values just below the specified lux level. To address this limitation, "continuous daylight autonomy (CDA)" was introduced. Continuous daylight autonomy is a modification of daylight autonomy that linearly assigns partial credits to values below the user-defined threshold as given by Equation 20.

$$DA_{(illumination\ level)} = \frac{\text{Daytime hours above the specified illumination level}}{Total\ Annual\ Daytime\ Hours} \times 100$$ ....Equation 20

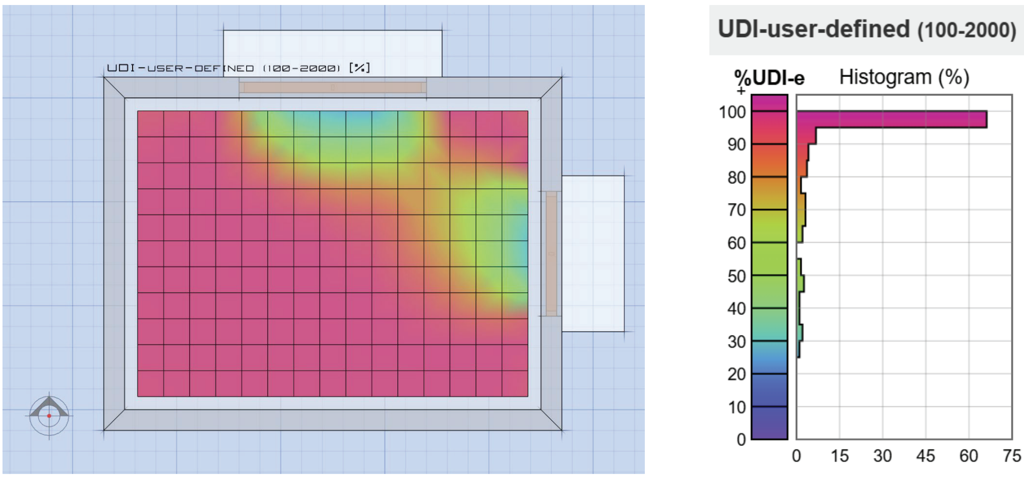
However, continuous daylight autonomy doesn't account for the upper threshold of lux levels, which is crucial as higher lux levels can lead to discomfort due to glare. To address this, "Useful Daylight Illuminance" was introduced. This metric considers both the lower and upper thresholds of the useful lux levels.

6.3.3 Useful Daylight Illuminance (UDI)

Useful Daylight Illuminance (UDI) is the percentage of annual daytime hours during which a specific point on a work plane height of 0.8 m receives daylight between the lower threshold of lux level (usually 100 lux) and the upper threshold of lux level (usually 2000 lux). Currently, UDI is the most widely accepted daylight performance metric.

In various standards, the minimum percentage of annual daylit hours for a point with UDI is specified. For instance, if UDI should account for 90% of annual daylight hours, then Useful Daylight Illuminance (i.e., ≥ 100 lux and ≤ 2000 lux) for a point receiving daylight for ≥90% of the annual daylight hours will be considered and represented as UDI(100-2000,90%). Figure 63 shows the UDI visualisation (lower threshold 100 lux, upper threshold 2000 lux).

Figure 63: UDI Visualisation (Lower Threshold 100 lux, Upper Threshold 2000 lux) (Image Generated Using https://drajmarsh.bitbucket.io/daylight-box.html)



6.3.4 Useful Daylight Spatial Daylight Autonomy and Annual Sun Exposure

Spatial Daylight Autonomy is defined as the percentage of floor area that receives at least 300 lux for at least 50% of the annual occupied hours. Achieving Spatial Daylight Autonomy with at least 50% of the floor area is considered acceptable, and if ≥ 75% of the floor area achieves this, it is preferred.

Annual Solar Exposure (ASE) measures the percentage of floor area that receives at least 1000 lux for at least 250 occupied hours per year. A minimum of 10% of the floor area should meet the requisite ASE.

6.4 Evaluating Daylight Design: Simplified Manual Method

The simplified method provides a straightforward approach to assessing the floor area likely to be daylit, as outlined in the Energy Conservation Building Code (ECBC) 2017, India. Compliance with this code requires a minimum daylit area of 40%. This method utilizes the Daylight Extension Factor (DEF), which is provided in Table 15, and is most effectively applied using an AutoCAD plan. DEF is a factor to manually calculate the daylight area on floor plates. It is to be multiplied by the head height of windows. It is dependent on orientation and glazing VLT, shading devices adjacent to it and building location.

Table 15: Value of Daylight Extension Factor (DEF) for Different Directions

Shading	Latitude	Window Type	VLT of glass<0.3				VLT of glass ≥ 0.3			
			North	South	East	West	North	South	East	West
No shading or PF≥0.4	≥15°N	All window types	2.8	2.0	0.7	0.5	2.8	2.2	1.1	0.7
Shading with PF≥0.4	All Latitudes	All window **types** (Without light shelf)	2.5	2.3	1.5	1.1	3.0	2.5	1.8	1.5

(Source: Energy Conservation Building Code ECBC (2017). Bureau of Energy Efficiency, Ministry of Power, Government of India (GOI))

The Daylit Area is calculated as follows:

- In a direction perpendicular to the fenestration (refer to Figure 65):
    - Multiply the Daylight Extension Factor (DEF) by the head height/lintel height of the fenestration or until the opaque partition surpasses the head height of the fenestration. Choose the lesser of the two.
- In the direction parallel to the fenestration (refer to Figure 65), the daylit area extends to:
    - A horizontal dimension equal to the width of the fenestration plus either 1 meter on each side of the aperture,

      OR
    - The distance to an opaque partition of 2 m high,

      OR
    - One-half the distance to an adjacent fenestration.

  Choose the least of the above three.
- For skylights, the daylit area is determined as shown in Figure 66.
- For overlapping daylit areas, such as windows on different orientations or in the case of skylights, subtract the overlapping daylit area from the sum of daylit areas.

Figure 64: Head Height (Section)

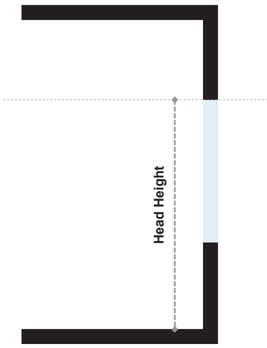
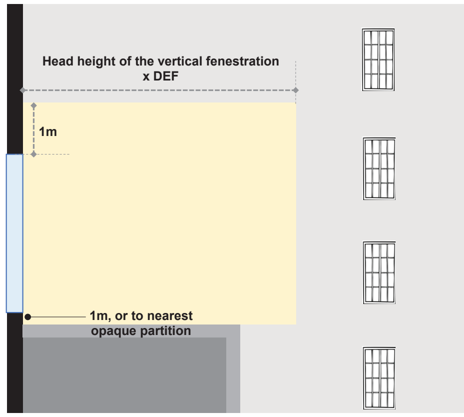
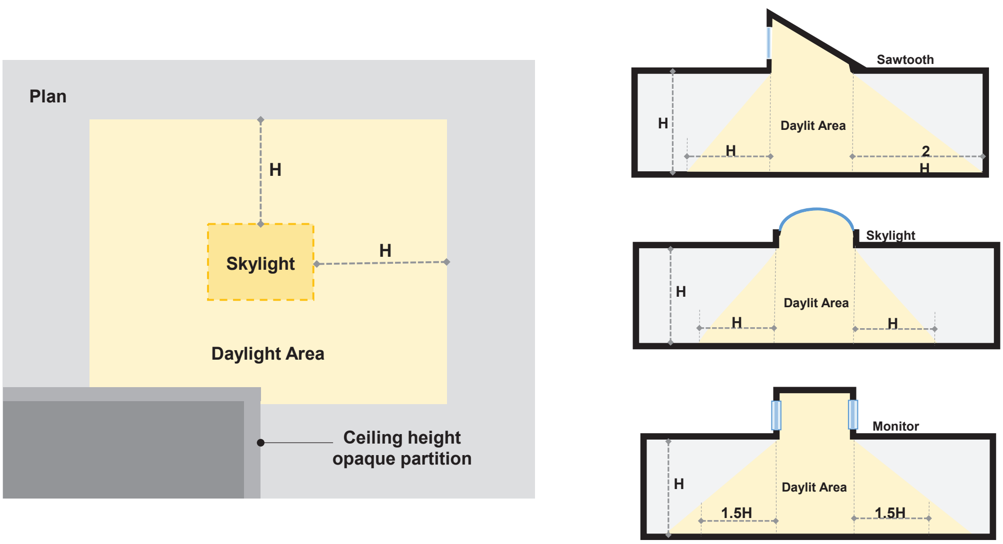


Figure 65: Daylit Area for Windows



Source: (Bureau of Energy Efficiency M. o., Energy Conservation Building Code, 2017)

Figure 66: Illustration of Daylit Area for Skylight



Source: (Bureau of Energy Efficiency M. o., Energy Conservation Building Code, 2017)

Summary

- The quantity of light is defined by terms such as luminous flux, illuminance, luminance, and reflectance. The quality of light is characterized by brightness, contrast, and glare.
- Daylighting strategies encompass various considerations:
  - Window orientation for optimal daylight.
  - Shallow planform depth to enhance light penetration.
  - High placement of windows on walls.
  - Optimization of window area for daylight while balancing solar heat gains.
  - Utilization of reflective finishes inside and incorporation of light shelves.

7

HEAT TRANSFER THROUGH FENESTRATION

What's in this Section?

Heat Transfer Through Fenestration

Windows are essential for daylight, ventilation, and outdoor views, enhancing both visual comfort and energy efficiency. However, they also allow significant solar heat gain and losses, which can be used beneficially in Nepal's different climatic zones. In case of colder climates (Temperate, Cool Temperate and Cold climatic zones), it is imperative to store the heat gained through the windows and store it within the building to maintain optimum temperatures and reduce the heating load. However, in the case of the Warm-temperate climate where the summers may see temperatures upto 40 degrees, excessive solar gain, combined with internal heat from occupants, lighting, and equipment can lead to thermal discomfort and increased cooling loads.

Achieving the right balance between daylight and heat ingress is crucial when designing windows. Early design decisions play a key role in optimizing natural light while limiting unwanted heat gains. This can be effectively managed through shading devices -elements of the building envelope or external additions that block direct solar radiation from striking glazed surfaces. It also helps protect windows from rain and snow.

This chapter introduces the concepts of building orientation, window positioning, window sizing, and the associated heat gains and losses through fenestration across different climatic zones of Nepal. It then examines the key principles and strategies for effectively incorporating shading into building design.

7.1 Building Orientation and Windows

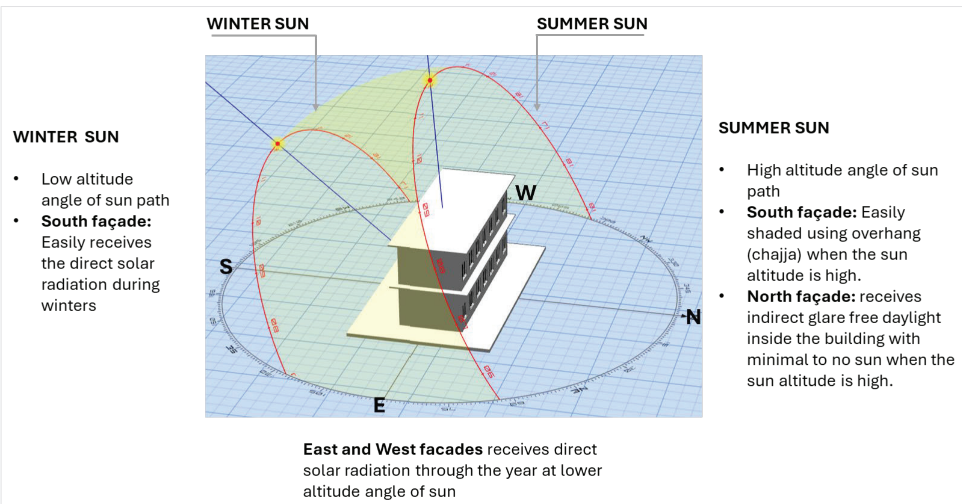
7.1.1 Massing and Orientation

As a first step towards effective massing, it is recommended that the longer facades of a building be oriented along the north–south axis (Refer Figure 67) in all climates. In cold climates, however, the longer façade can be oriented slightly (15°) east of south to maximize passive solar heat gain. These orientation helps to optimize overall solar heat gain and loss through the building envelope with respect to climatic zones.

In case of **warm-temperate climate**, during the summer months, when the sun's altitude is high, south-facing windows can be easily shaded using horizontal overhangs (chajjas), thereby reducing direct solar heat gain. In winter, when the sun is lower in the sky, these overhangs allow sunlight to penetrate inside the spaces to give warmth. The north façade, which receives minimal direct sunlight (mostly from north-east and north-west) throughout the year, typically does not require extensive shading. Any occasional solar gain from these directions can be easily managed with vertical shading devices. Additionally, the north-facing windows provide good quality natural daylight without significant heat gain, making them ideal for daylighting strategies.

However, in case of the **temperate, cool temperate and colder climatic zones** the lower altitude of the sun during extreme winter ensures direct solar heat gain through longer façade facing south. The windows can be shaded with minimal overhangs or chajjas, primarily to prevent rain entering the building while allowing adequate heat entering the building when the sun angle is higher.

Figure 67: Longer Façade Facing North and South Orientation and Depiction of Summer and Winter Sun in Case of Warm-Temperate Climate



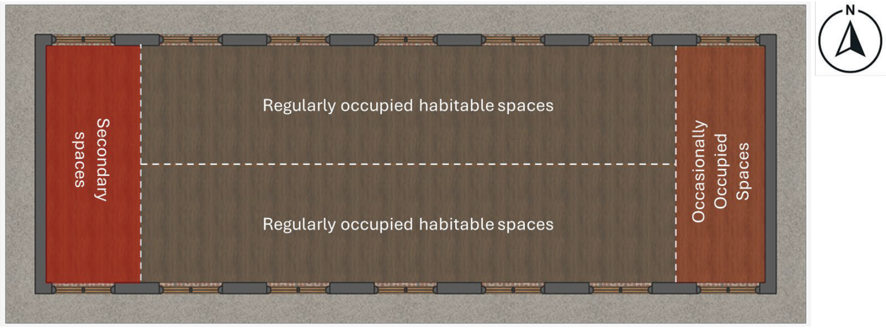
7.1.2 Windows Position and Its Size

After determining the building orientation, window positioning and sizing become crucial aspects of design. These decisions are closely linked to the spatial layout of interior functions.

In case of **Warm-temperate climate**, it is advisable to place regularly occupied habitable spaces, such as living rooms, bedrooms, and work areas, along the north and south facades to ensure good daylight access and effective solar control (on south) through shading. (Refer Figure 68). Other occasionally used habitable spaces like meeting rooms, conferences can be positioned on the east, benefiting from morning light. Less frequently used or secondary spaces, such as staircases, corridors, restrooms, storage, and service areas, are best located on the west, where late-afternoon lower angle sun is difficult to shade, with outdoor temperatures typically higher. (Refer Figure 68).

Additionally in this climatic zone, window should be placed towards north and south, with minimal window on east and no windows towards the west. Double-glazed windows with a lower SHGC to limit unwanted solar gains, combined with a low U-value to reduce conductive heat gains, are recommended for enhanced thermal performance.

Figure 68: Spatial Configuration for the Warm Temperate Climate Zone

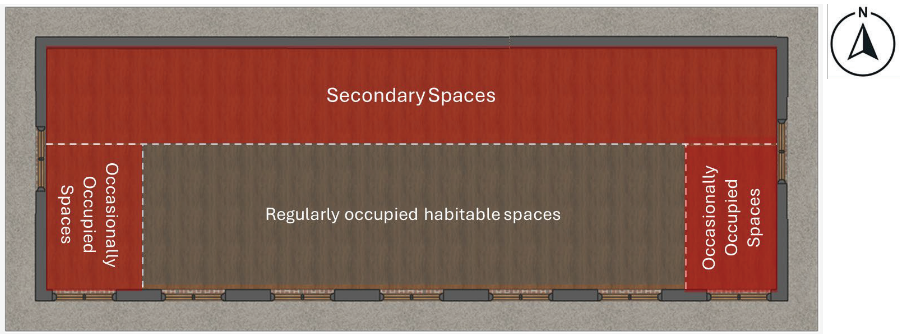


Building Plan View

However, in case of **temperate, cool temperate and colder climatic zones,** it is recommended to place regularly occupied habitable spaces, such as living rooms, bedrooms, and work areas, along the south facades and the secondary spaces such as staircases, corridors, restrooms, storage, and service areas, are best located on the north side, where there is minimal or no sun exposure. These spaces also function as a buffer zone at night, when outside temperatures are lower, thereby reducing heat loss for habitable spaces. (Refer Figure 69).

Additionally, in this climate zone higher distribution of window should be towards south, east and west to capture the maximum heat, with minimal or no window towards the north façade to avoid heat loss through fenestration. Double-glazed or triple glazed windows with a higher Solar Heat Gain Coefficient (SHGC), to allow more solar gains, and a lower U-value, to reduce heat loss, are recommended in such climates.

Figure 69: Spatial Configuration for the Warm Temperate Climate Zone



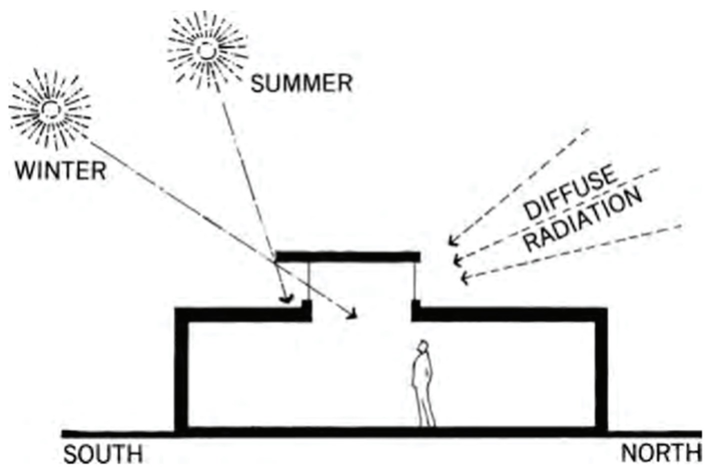
Building Plan View

Skylights (horizontal glazing systems) should generally be avoided, as they admit excessive solar radiation during summer and contribute to increased heat loss in winter. Where skylights are necessary, the Skylight-to-Roof Ratio (SRR) specified in Section 6.2.5 should be carefully considered and complied with.

Clerestory windows should be used instead of skylights because they allow the sun to enter in a controlled manner, and south facing clerestories collect more sun in the winter than the summer, thereby being suitable for both the warm-temperate and colder climates. (Refer Figure 70)

During the early design phase, a general guideline is to allocate glazing as per the GFR thresholds discussed in Section 6.2.4 and Annex 03. However, this rule should be applied in conjunction with considerations of building orientation, window placement, and the specific daylight requirements of each space. Integrating these factors helps achieve an optimal balance between adequate daylight, controlled solar heat gains and minimise losses.

Figure 70: Clerestory Windows Should be Used Instead of Skylights Because they Allow the Sun to Enter in a Controlled Manner, and South Facing Clerestories Collect More Sun in the Winter Than the Summer.



Building Section View

Source: Reproduced from Heating, Cooling Lighting sustainable method for the architects, Norbert Lechner

Window to Wall Ratio (WWR)

The Window-to-Wall Ratio (WWR) is a key design metric that defines the proportion of window area to the total exterior wall area of a building.

WWR is defined as given in Equation 21.

$$\textbf{\textit{Window to Wall Ratio}}(\%) = \frac{\textbf{\textit{Window Area}}}{\textbf{\textit{Area of Envelope}}} \times \mathbf{100} \quad \text{.............Equation 21}$$

Where

Window Area (m^2) : It is the total glass area of the façade

Area of Envelope (m^2): It is the gross Wall Area of the façade

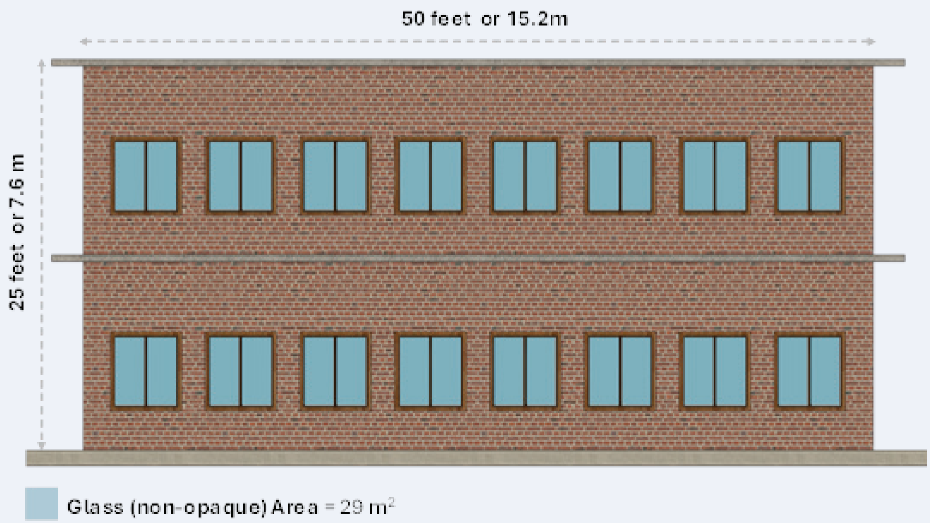
In warm-temperate climates, it is generally recommended to maintain a Window-to-Wall Ratio (WWR) of less than 40% for the building. A higher WWR increases solar heat gains, leading to greater cooling loads and, consequently, higher cooling electricity consumption.

In the case of the cold climate zone, the same recommendation (WWR < 40%) applies, however, a greater proportion of the window area should be distributed along the south façade to maximize passive solar gain. Additionally, provisions of dynamic external shading are recommended to mitigate the risk of overheating.

Example Calculation of Window-to-Wall Ratio (WWR) in Building Design

Figure 71: shows the south façade of the building. The overall dimension of the façade and the total glass area (shaded in blue) has been given.

Figure 71: Example of the Window to Wall Ratio



The WWR calculation for the south façade will be:

Facade Width: 15.2 m

Facade Height: 7.6 m

Facade Area = 15.2 m × 7.6 m = 115.5 m^2

Total Glass Area (shaded in blue) = 29 m^2

Hence,

$$\boldsymbol{Window\ to\ Wall\ Ratio}(\%) = \frac{\mathbf{29}}{\mathbf{115.5}} \times \mathbf{100 \approx 25\%}$$

Therefore, the WWR is approximately 25%, which is below the 40% threshold recommended for energy-efficient design.

Note: *The area below the plinth and the parapet (a low wall along the edge of a roof) should be excluded when calculating the total façade area.*

7.2 Shading Devices: Type and Orientation

This section focuses on shading strategies and the various types of shading devices commonly used in buildings. Each type performs differently in response to solar angles and is best suited for specific façade orientations.

Understanding which shading device is appropriate for which orientation is essential for optimizing solar heat gains inside the building. While it is recommended to avoid placing windows on the east and west due to high solar heat gains, site constraints may make their placement unavoidable. This section also discusses how to mitigate these heat gains using appropriate shading devices and design interventions.

However, these shading strategies are not a substitute for proper orientation and well considered window placement and sizing, they should complement them.

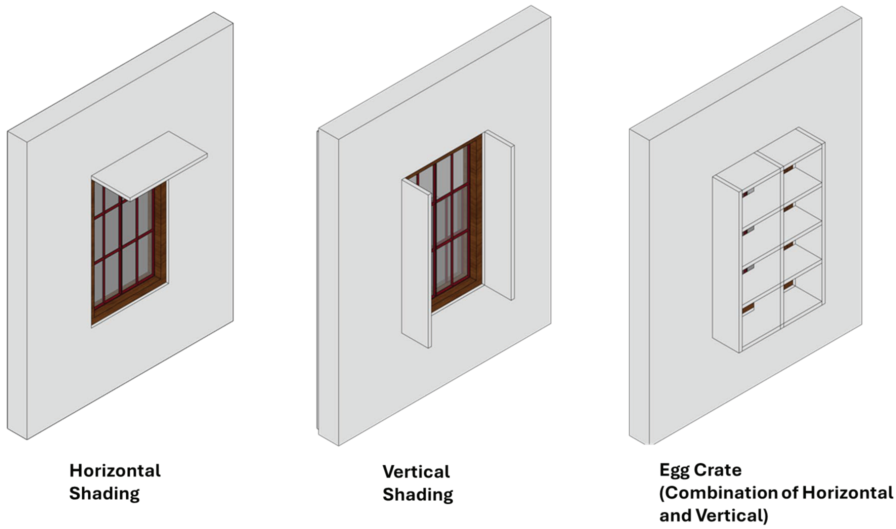
7.2.1 Type of Shadings

Shading devices can be broadly categorized into two main types based on their functionality and integration with the building envelope:

1. **Fixed Exterior Shading Devices:** These shading devices are permanent architectural elements integrated into the building envelope. They are designed to block solar radiation based on the building's orientation and solar angles.

   Common examples include Horizontal Shading (overhangs or chajjas), Vertical Shading, and Egg-crate shading (combination of horizontal and vertical shading). These kinds of shading devices require minimal maintenance. (Refer to Figure 72).

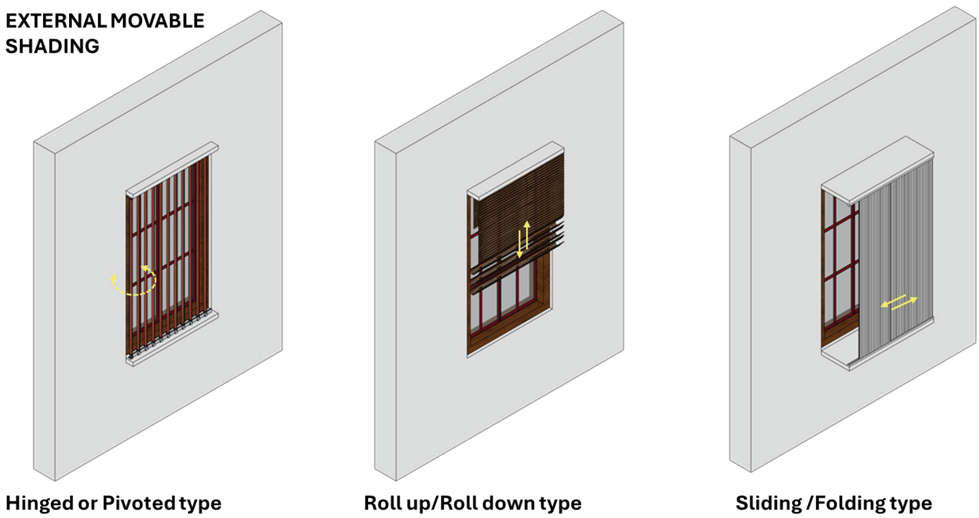
Figure 72: Fixed Exterior Shading Devices



2. **External Movable Shading Devices:** Movable shading devices are adjustable systems installed on the exterior of the building. They allow occupants or automated systems to control the amount of sunlight entering the building based on season, time of day, or user preference. These shading devices must be designed to withstand outside environmental extremities and ensure durability under varying climatic conditions.

   Common examples include hinged/pivoted louvers, retractable awnings or roll up-roll down shades, and operable shutters or blinds (Refer to Figure 73). Suitable shading device for each orientation has been discussed in next section. down shades, and operable shutters or blinds (Refer to Figure 73). Suitable shading device for each orientation has been discussed in next section.

Figure 73: External Movable Shading Devices



7.2.2 Shading by Façade Orientation and Climatic Zone

This section presents various shading strategies for facades facing the eight cardinal directions.

Warm-Temperate Climatic Zone

7.2.2.1 Shading on the North Façade

The northern façade receives limited direct sunlight, primarily during early mornings and late afternoons around the summer solstice when the sun altitude is at its highest (summer solstice). While vertical fins can be used on the east and west sides of windows to provide shade, they are generally not necessary on the north façade due to the oblique angle and minimal intensity of solar radiation. However, horizontal overhangs may be provided to protect windows from rain.

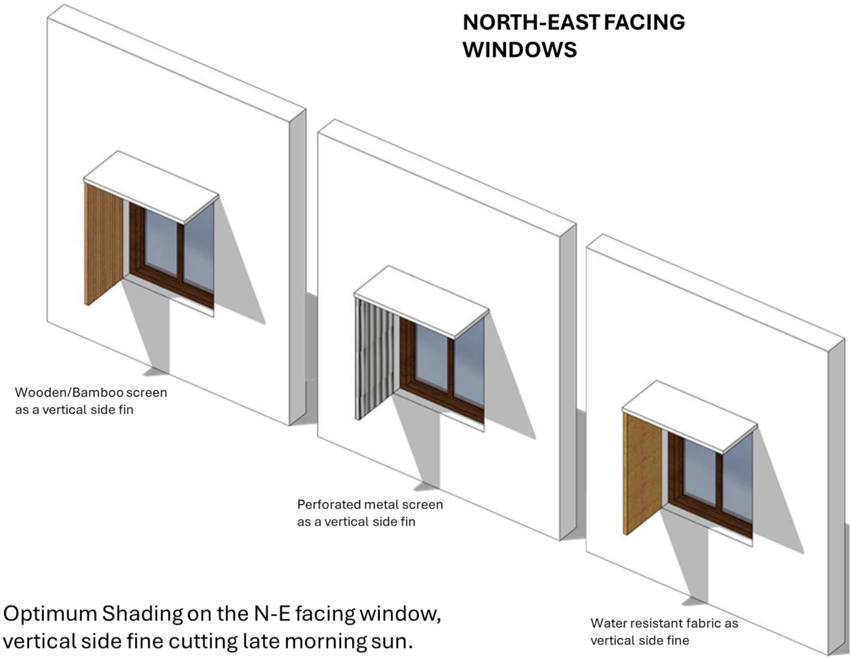
Figure 74: Vertical Side Fins on the North Facing Window to Shade from Early Morning (On Left) and Late Evening Sun (On Right)

7.2.2.2 Shading in North-East/North-West Façades

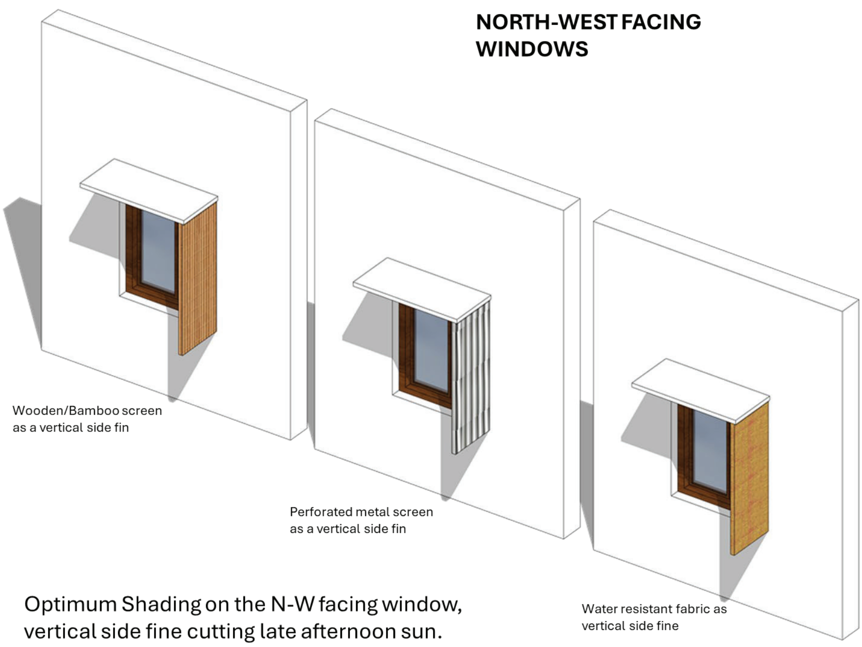
The north-east and north-west façades are exposed to the rising and setting sun, respectively, during the hottest part of the year. Due to the low sun angle during these times, direct solar radiation enters the building, increasing indoor heat gains. This effect is particularly critical on the north-west façade, as it coincides with peak afternoon temperatures. Vertical fins can be used on either side of the window to mitigate this.

For windows facing north-east, vertical fins should be placed on the east side, while for north-west-facing windows, fins should be on the west side. A combination of horizontal overhangs and vertical fins can effectively shade windows on both façades, as illustrated in Figure 75 .

Figure 75: Optimum Shading Combination of Horizontal Overhangs and Vertical Fins Effectively Shading Windows Facing Northeast (Top) and Northwest (Bottom)



Optimum Shading on the N-E facing window, vertical side fine cutting late morning sun.

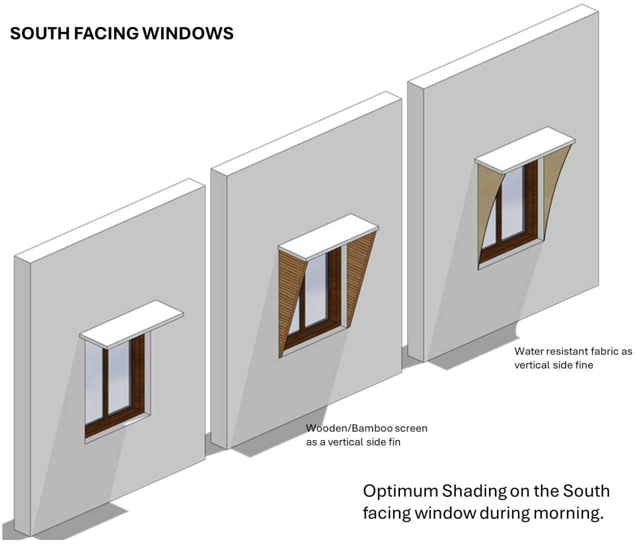


Optimum Shading on the N-W facing window, vertical side fine cutting late afternoon sun.

7.2.2.3 Shading in South Façades

The southern façade receives sunlight from a high solar altitude angle during summer. In this orientation, an overhang above the window plays a crucial role in blocking direct solar radiation during peak sun hours. Vertical fins on either side of the window help reduce solar gains during early mornings and late afternoons. These fins can be designed in a triangular shape, as illustrated (Refer Figure 76), and can be constructed using materials such as wooden or bamboo panels, metal screens, or water-resistant fabrics.

Figure 76: Optimum Shading Combination of Horizontal Overhangs and Vertical Fins Effectively Shading Windows Facing South



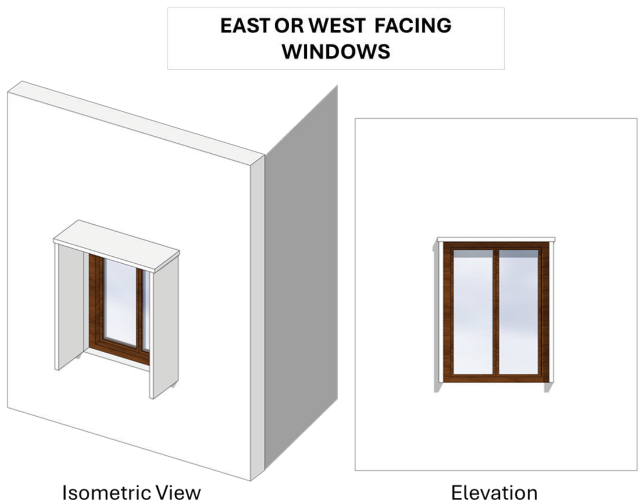
Optimum Shading on the South facing window during morning.

Optimum Shading on the South facing window during afternoon.

7.2.2.4 Shading in East/West Façades

The east and west façades are exposed directly to the strong radiation of the sun for the entire morning on the east face and for the entire afternoon on the west face. Thus, the sun penetrates deeper directly from the front of the window. In such cases, a single overhang or vertical fin alone is often insufficient, as they do not effectively block the low-angle sun penetrating from the front as shown in Figure 77 below.

Figure 77: East and West-Facing Windows Receive Intense Direct Solar Radiation During Early Morning and Late Afternoon Hours. Overhangs or Vertical Fins Alone are Often Ineffective, as the Low-Angle Sun Penetrates Directly from the Front.



The east-facing window requires protection from the sun during the morning hours, while the west-facing window needs shading during the afternoon. To block direct solar radiation effectively, a screen or shutter across the face of the window is essential. Since this protection is only needed for a portion of the day, a practical solution is to use a movable shading system. This can be achieved through the following options:

1. **A hinged or pivoted shutter with optimum size perforations/cut-outs/openings, etc. (Refer Figure 78) It can be made of various materials such as the following:**

    a. *Punched galvanised steel louver panel*

    b. *Painted louvre wooden panel*

    c. *Perforated metal/plastic screens*

    d. *Water-resistant boards*

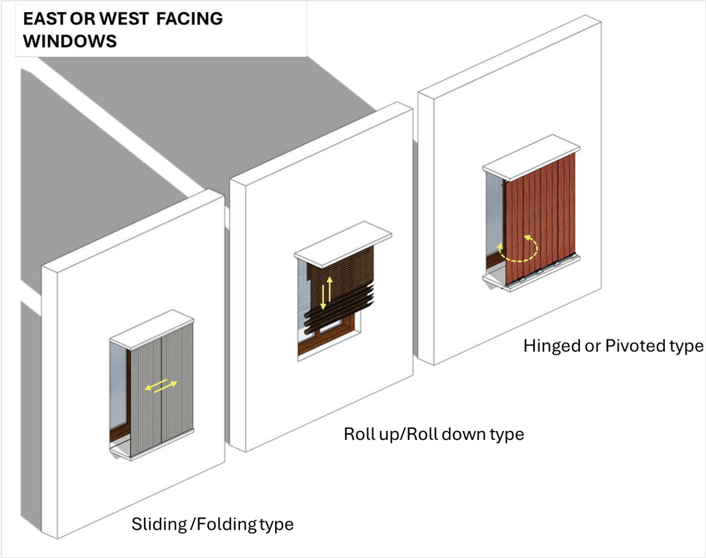
    e. *Treated bamboo curtains*

2. **A retractable system with a breathable and translucent membrane could be further classified in two categories. (Refer Figure 78)**

   a. **Sliding/Folding (horizontal movement): I**n these stretchable, durable, and abrasion-resistant nylon and polyester fabrics/curtains can be slided along two rods fixed on top and bottom of the fabric.

   b. **Roll-up/roll-down (vertical movement): I**n these materials like bamboo curtains, foldable fabrics, and cloth could be used. Movable shading system across the face of the window.

Figure 78: East and West-Facing Windows Receive Intense Direct Solar Radiation During Early Morning and Late Afternoon Hours. Overhangs or Vertical Fins Alone are Often Ineffective, as the Low-Angle Sun Penetrates Directly from the Front.

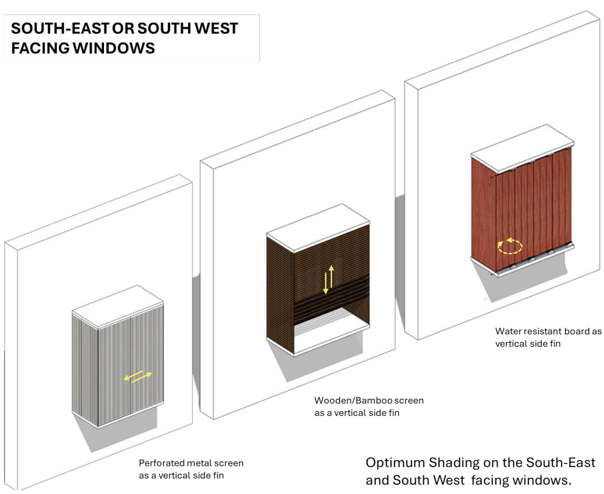


7.2.2.5 Shading in South-East/South-West Façades

The south-east and south-west façades are exposed to both the lower altitude sun and the overhead sun. Thus, it gets solar radiation from both sides and front (Refer Figure 79). So, it is necessary to have a shading provision on sides and front as well. This could be achieved by having fixed side-fins and a movable front screen as shown in Figure 80.Movable shading screens can operate in the different way as discussed Section 7.2.2.4.

Figure 79: Windows Facing SE-SW Receives Direct Low Altitude Sun During Early Morning and Late Afternoon.

Figure 80: Optimum Shading with Fixed Side-fins and a Movable Front Screen for the SE and SW Facing Windows



It is important to note that these are not the only possible shading solutions; However, the principles of type of shading which should be used as per the climate and orientation remains the same. The designers have the choice of design shading devices based on the needs and keeping the context of the building in mind. The shading through the surrounding building and other microclimate factors as discussed in Section 3.2.3 should also be considered.

Temperate, Cool Temperate and Cold Climatic Zones

In cold climates, windows can be left unshaded to allow maximum solar radiation to enter the building. However, overhangs with smaller depths are recommended on south to protect windows from snow and rain, while also blocking the high-angle summer sun to prevent overheating. Movable external shading devices or hinged shutters (as shown in Figure 81) can also be used. During the day, when there are cold draughts, these shutters help restrict the cold wind while still allowing sufficient daylight to enter. At night, they can be closed completely to retain the heat gained during the day and reduce cold draughts, thereby improving indoor comfort in cold climates.

Figure 81: External Shutters for Cold Climates

7.3 Available Tools for Shading Design

This chapter talk about the various available tool for the shading design. Some of the available tools for shading design and sun path analysis are the following:

Installation Tools:

1. **Andrew Marsh's Online Webtools:** Andrew Marsh has developed several interactive tools for solar access, shading mask, and sun path analysis. These tools are browser-based and useful for quick assessments during early design stages. They are widely used in both academic and professional settings. https://andrewmarsh.com/software/
2. **Sustainable by Design (Web tool):** Sustainable by Design is tool developed by Christopher Gronbeck, a freelance consultant in the renewable energy and green building fields. https://www.susdesign.com/tools.php
3. **Ecotect:** Autodesk Ecotect analysis is a sustainable design analysis software as a concept to detail sustainable building design tool.
4. **Rhino & Pollination:** Rhino, coupled with the Grasshopper visual programming interface and Pollination plugins, enables detailed parametric modelling and advanced shading analysis.

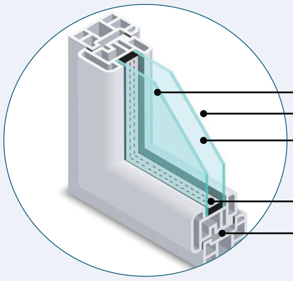
5. **Revit by Autodesk:** Revit provides basic solar study features that allow users to simulate sun paths and analyse shading at different times of the year. When used with the Insight plugin, it allows for more in-depth environmental performance analysis, including solar exposure and shading optimization.

6. **SketchUp (with Shadow Tool and Plugins):** SketchUp is a widely-used 3D modelling tool that includes a simple but effective Shadow Tool to visualize sun paths and shading for different times and dates. Additional plugins such as Skelion or Sefaira extend SketchUp's capabilities for solar and energy analysis.

High Performance Windows:

High-performance windows are advanced glazing systems that reduce heat transfer, improve energy efficiency, and enhance thermal comfort. They typically feature double or triple glass panes with insulating spacers and cavities filled with gases like air, argon or krypton. Set in thermally insulated frames made of non-conductive materials such as fiberglass or vinyl, these windows often include low-emissivity (low-E) coatings that reflect solar radiation, minimizing solar heat gains in summer.

Figure 82: Typical Double-Glazed Window/ High Performance Window



Source: A&E Glazing

When the WWR is greater than 40%, the following minimum performance specifications are recommended for the high-performance windows:

- ***U Value:*** U-value ≤ 2.8 W/m^2.K for all climate zone, this ensures reduced heat loss or gain through the glazing.

- ***Shading Coefficient (SC):***
  SC ≥ 0.31 for Cold, Cool Temperate, and Temperate climates
  SC ≤ 0.70 for Warm Temperate climates

- Visible Light Transmittance (VLT):
  Visible Light Transmittance (VLT) ≥ 0.3, for all climate zone, this ensures adequate daylight while minimizing glare

Using glazing that meets these specifications enhances thermal comfort, reduces reliance on active systems, and maintains daylight without excessive heat gain or loss.

Summary

- Early design decisions play a key role in optimizing the right balance between daylight, ventilation and heat ingress, which is crucial when designing windows.
- Buildings should be oriented based on the climatic zones they fall in:
    - Warm-Temperate Climate: Longer facades along the north–south axis. South-facing windows can be shaded easily with horizontal overhangs to block high summer sun while allowing winter sunlight for warmth. The north façade requires minimal shading and offers good daylight with little heat gain.
    - Temperate, Cool-Temperate and Cold Climates: Longer facades along the east-west axis. All windows can have a combination of horizontal overhangs and dynamic shading/ fixed shutters
- Placement of Windows:
    - Warm-Temperate Climate: It's recommended to place windows on north and south facades for better solar control. East and west windows, especially west-facing, should be minimized due to difficult shading and heat gain.
    - Temperate, Cool-Temperate and Cold Climates: It's recommended to place windows on east and west facades for better solar retention. North and South windows, especially north-facing, should be minimized due to heat losses.
- Habitable Spaces
    - Warm-Temperate Climate: Habitable spaces to be placed on the north and south for optimal daylight and minimal heat gains. Use east for occasional use spaces, and west for secondary spaces like staircases or storage due to high heat gain from the low altitude angle sun.
    - Temperate, Cool-Temperate and Cold Climates: Habitable spaces to be placed on the east and west to optimise heat gains.
- Shading devices are of two types: fixed (e.g., overhangs, vertical fins) requiring minimal maintenance, and movable (e.g., louvers, retractable shades) offering adjustable sun control based on orientation and user needs.
- Shading strategies vary by façade orientation to manage solar heat gain effectively. Fixed shading like overhangs and vertical fins work well for N,S,NE and NW facades of the building while external movable shading is essential for E,W,SE and SW facades due to low-angle sun.
- Combining horizontal and vertical elements based on sun angles and orientation is key. Shading complements but does not replace the requirement of proper orientation and window placement. Design should also consider local microclimate and building context.

8
PASSIVE STRATEGIES FOR COMFORT AND ENERGY EFFICIENCY

What's in this Section?

Passive Strategies for Comfort and Energy Efficiency

Passive design strategies refer to design approaches that focus on utilizing the natural environment to provide thermal and visual comfort in a building, unlike active design strategies that rely on mechanical systems and processes. They take advantage of the climate, site conditions, materials, and design elements to provide comfort. A building with passive design features will be able to maintain suitable indoor conditions for greater time without resorting to the use of electricity or other forms of energy, thus making the building energy efficient. For example, passive design features avoid or reduces electricity use for cooling or heating as well as ventilating a building and avoids use of artificial lighting when ample daylight is available. Natural ventilation strategies and daylighting strategies, which are addressed in detail in Chapters 5 and 6, are also passive strategies. This chapter details those passive strategies that help improve thermal comfort and reduce energy use for cooling and heating.

One way of describing passive strategies is that they help in "load avoidance". Passive strategies in warm and hot climates help in cooling load avoidance. In cold places, they help in heating load avoidance. Generally, in climates that are "cooling dominated", passive strategies should:

- Reduce solar radiation falling on the building envelope.
- Reduce external heat gains through the building envelope.
- Remove excess heat that has built-up inside through ventilation.

In "heating dominated" climates, passive strategies should:

- Optimize solar access inside the building during the day.
- Reduce heat loss from inside to outside through the building envelope.
- Prevent cold draughts in the building.

In moderate climates, cooling strategies should be used in summer and heating strategies in winter.

Vernacular architecture, which refers to the traditional, indigenous native architecture of a particular place, often takes advantage of passive strategies to enhance living conditions. Vernacular architecture is inherently climate-responsive and follows passive design principles, as it has developed over time when there were no electricity, mechanical heating and cooling. It was developed over time through a process of trial and error, rather than being designed by professional architects, and thus includes passive design using local materials and construction techniques. This is also the reason why vernacular architecture changes as the environment and climate changes. This is evident in Nepal, where homes in the warmer Terai region have larger windows for better wind movement, larger overhangs to shade the windows, verandas, and were made of bricks that were made of local soil. In contrast, homes in cold Himalayan locations were compact, the living spaces faced the south to allow sun, the walls were made with thick walls of local stone, the windows were small to keep out the cold winds and some form of insulation was provided on the roof with wood and mud.

However, with changing social structures, increasing densities and modern requirements of living, vernacular architecture is being replaced. This change is not just happening in terms of aesthetics but, more crucially, in terms of the basic principles of passive design.

The following examples of vernacular architecture from different climatic zones demonstrate traditional passive design strategies.

Examples:

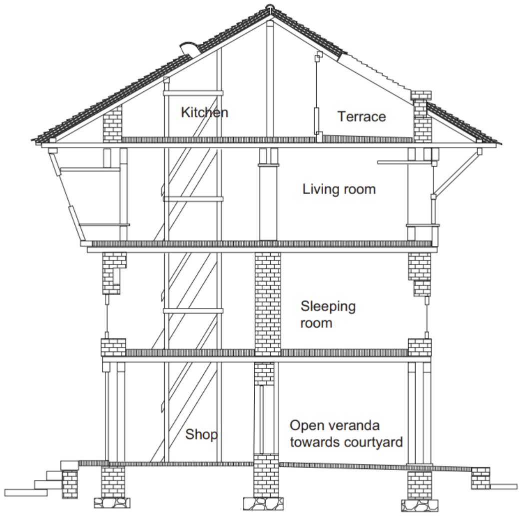
Vernacular Tharu houses in the **warm temperate climate** of Chitwan, Nepal, are well-adapted to their environment. Arranged in scattered clusters, they promote ventilation and open space. These single-storied, rectangular houses are oriented north-south to minimize sun exposure. The layout is horizontal with minimal divisions and includes semi-open verandas for airflow and social interaction. Walls are built with local materials like wattle and daub, straw, mud, timber, and bamboo, with thin wall thickness. Roofs are thatched and pitched with wide overhangs to protect from sun and rain. Houses are raised on stone or earthen plinths to prevent flooding, and high ceilings to enhance ventilation. Floors are made of compacted earth, clay tiles, or stone. Small, low windows and roof openings support airflow, while shading is provided by roof overhangs and surrounding trees.

Figure 83: Chitwan House in Warm Temperate Climate

Source: (Susanne Bodach, 2014)

Newari houses in Temperate climate of Kathmandu showcase a climate-responsive and culturally rich architecture. Built in dense settlements, they feature interconnected courtyards that allow solar access and create warm outdoor spaces in winter (Refer Figure 84). These rectangular, elongated buildings are oriented on sunny slopes with the longer façade facing south, southeast, or southwest to maximize solar gain. Large, ornately carved wooden windows on these facades enhance passive heating. Walls made of burnt clay bricks outside and sun-dried bricks inside, with thicknesses of 28–70 cm, provide high thermal mass. Gable roofs with wide overhangs and stone foundations (60–80 cm deep) provide rain protection. A notable feature is the water-inclusive roof design, where burnt clay tiles are laid over a 4–10 cm thick mud layer for improved insulation and waterproofing.

Figure 84: Typical Section of the Newar House



Source: (Susanne Bodach, 2014)

Tamang houses in Nepal's Langtang region are well adapted to the cool temperate and cold climate zone. Built in compact, attached clusters forming terrace-like structures, they help reduce heat loss (Refer Figure 85). These two-story houses have a rectangular plan, often oriented southwest to maximize solar gain. The elevated ground floor serves as the main living area with kitchen, dining, and sleeping spaces, while the upper floor is used for storage. Verandas and balconies enhance comfort, and a central open hearth provides warmth during winter. Constructed with thick dry stone outer walls and timber-clad entry facades, these houses feature wooden lath floors, low ceilings, and small entry-side windows to retain heat. Their vertical layout creates thermal buffer zones, and foundations are adapted to the slope, ensuring stability. Overall, they use local materials and passive design to maintain indoor comfort.

Figure 85: Tamang Houses in Nepal's Langtang Region

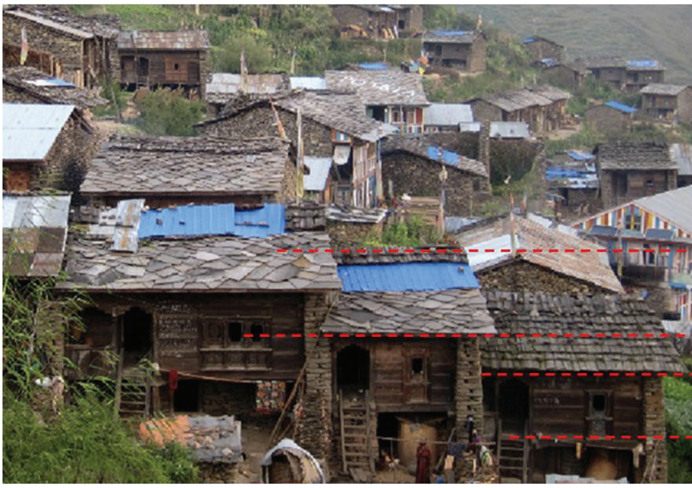
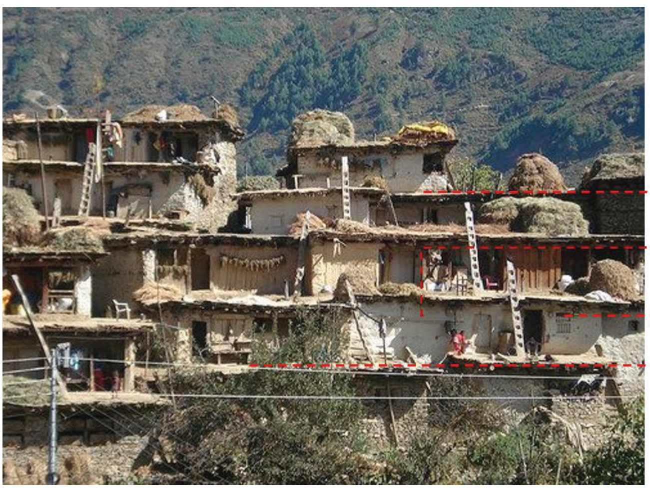


Figure 86: Humla Houses in Cold Climate



Vernacular Humla houses in Nepal's far-western cold climate region are designed to withstand extreme cold and high-altitude conditions. Found in densely scattered settlements, some units are partly attached (Refer Figure 86). These three-story houses have an almost square floor plan and are oriented south to maximize sunlight and warmth. The multi-story design creates a compact volume that reduces heat loss, while internal spaces are arranged with buffer zones for thermal insulation. Built with stone and mud mortar, the 45 cm thick walls provide strong thermal mass. Flat mud roofs with 50 cm overhangs offer limited weather protection, and rooftops serve as semi-open spaces. Low ceilings help retain warmth, and small openings minimize heat loss. These houses use local materials and passive design to ensure thermal comfort in the harsh alpine climate.

The following sections explore the basic principles of passive design orientation, massing, spatial configuration, and the building envelope (including walls, roof, fenestration, and floors) - which are rooted in the principles of vernacular architecture.

8.1 Building Orientation, Massing, and Spatial Configuration

In the context of this manual,

- Orientation refers to the direction that the larger walls and glazed windows face
- Building massing refers to the compactness of a building,
- Spatial configuration is how buildings are arranged about each other defining built and open spaces.

Building orientation determines the amount of solar radiation that the exposed surfaces receive. In all four climatic zones in Nepal:

- The roof receives the greatest intensity.
- Any exposed wall or window facing south receives the highest intensity in winter (when the sun is low and is positioned largely in the south) but it receives very little in summer (as the sun is high when shining from the south).
- East and west facing walls receive large intensities in summer and less intensities in winter compared to south facing walls.
- North facing walls receive the least intensity in both summer and winter.

Table 16 shows the favourable orientation for energy efficiency for the different climate zones. Figure 87 shows sun path on summer solstice (June 21st) and Figure 88 shows the winter solstice (December 21st) for Kathmandu. This will be generally the same all over Nepal.

Table 16: Favourable Orientation for Energy Efficiency for the Different Climate Zones

File Type	
Warm-temperate	Longer exposed walls and major windows face north and south
Temperate	Longer exposed walls face north and south. Habitable spaces and large windows facing south
Cool-temperate	
Cold	

Figure 87: Sun Path on Summer Solstice (June 21st) (Tool Used: Andrew Marsh)

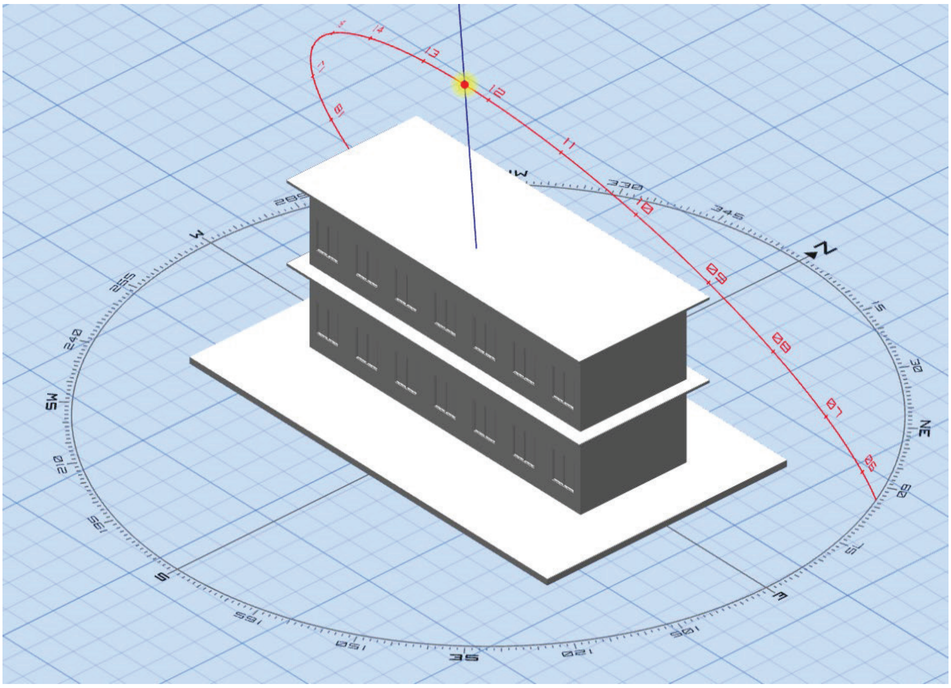
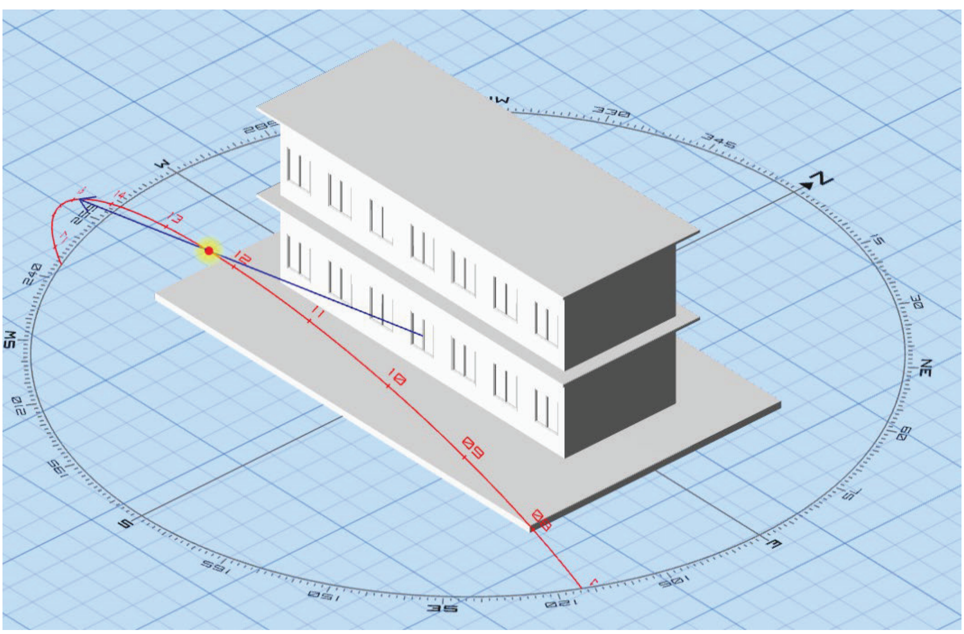


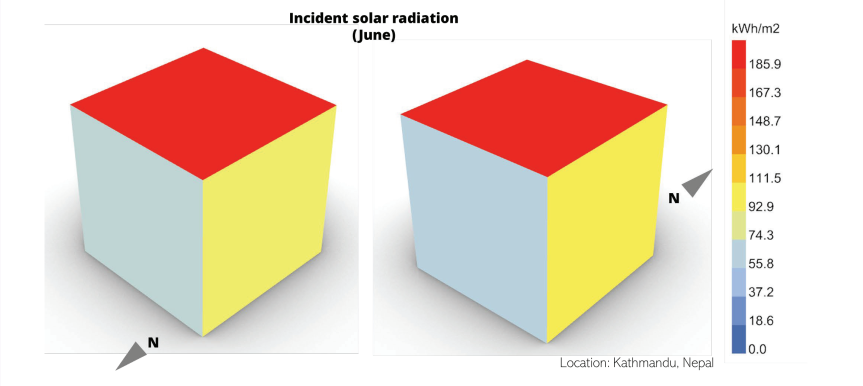
Figure 88: Sun Path for Winter Solstice (December 21st) (Tool Used: Andrew Marsh)



Solar Radiation and Orientation

Figure 89 shows the incident solar radiation on the roof and walls of a cuboidal building in the temperate climate in June.

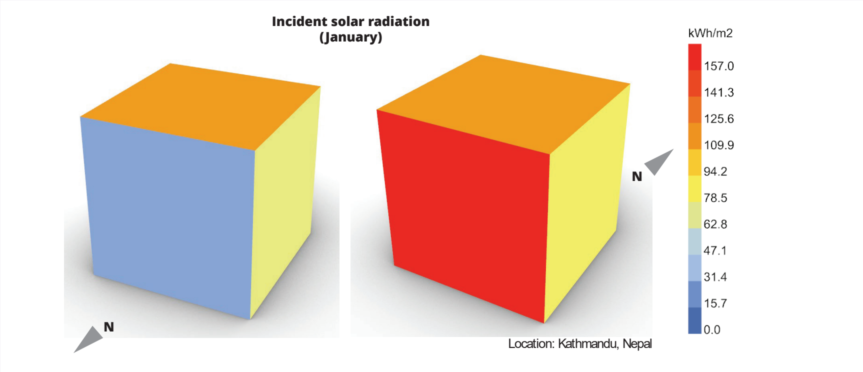
Figure 89: Incident Solar Radiation on Roof and Walls (June)



The roof receives the maximum amount of radiation. The west and east façades receive high amounts of solar radiation due to the low-altitude afternoon and morning sun, respectively. In contrast, the north façade receives the least amount of radiation. Similarly, the south façade also receives a lower amount of solar radiation due to the higher altitude of the sun in the south during summer

Figure 90 illustrates the incident solar radiation on the roof and walls of a cuboidal building in a temperate climate during January.

Figure 90: Incident Solar Radiation on Roof and Walls (January)



The highest radiation is received by the south façade and the roof, followed by the west and east façades. The south façade receives high solar radiation, particularly due to the low altitude of the sun in winter. In contrast, the north façade receives the least amount of radiation.

Building massing is a crucial factor influencing heat loss and gain, often measured by the surface area to volume (S/V) ratio. A greater surface area results in more heat gain or loss. Therefore, smaller S/V ratios imply minimal heat gain and loss. However, this may not always ensure comfort in all climates or for all types of buildings. For instance, in warm climates where natural ventilation is essential and heating demand is low, a small S/V may not be the optimal choice. Similarly, a building prioritizing daylight may not be designed with a small S/V.

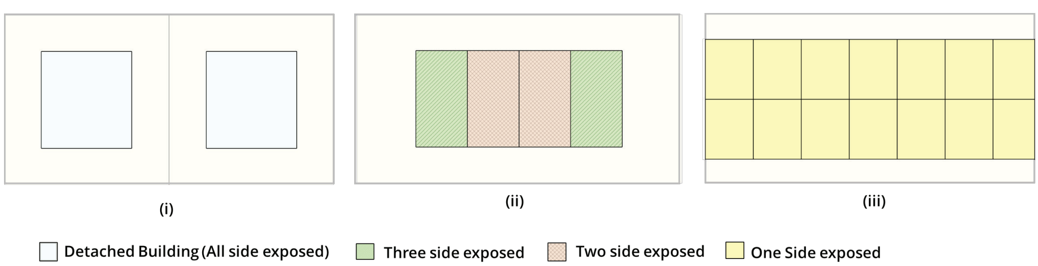
In the cold climate zone of Nepal, a small S/V or a compact building design proves beneficial. However, in the remaining climate zones, where natural ventilation is essential to prevent overheating and remove heat during the summer, a compact building may not effectively utilize natural ventilation as a strategy.

The spatial configuration of a building plays a crucial role in determining the amount of solar radiation it receives and its potential for utilizing natural ventilation. Broadly, building configurations may fall into one of the following categories (refer to Figure 91):

- Detached buildings: These are exposed on all sides.
- Three-side exposed buildings (e.g., buildings at the end of a row).
- Two-side exposed buildings, usually the front and back (e.g., buildings in the middle of a row).
- Buildings with only one side exposed.

The greater the number of exposed walls, the higher will be the potential for heat gains or losses. Simultaneously, the ventilation potential will also be greater.

Figure 91: Different Building Spatial Configurations



Orientation, massing, and spatial configuration are not the only passive design aspects that determine the heating and cooling loads of a building. These factors, along with the properties of the building envelope, collectively influence the amount of energy the building will consume for heating and cooling.

8.2 Building Envelope

The building envelope serves as the interface between the indoor spaces of the building and the outdoor environment. It essentially comprises two components: the opaque component (roof, external walls, and slab-on-grade) and the non-opaque or fenestration component (external glazed windows, doors, ventilators, etc.).

Regardless of the spatial configuration or exposure of the building (i.e., whether it's a detached building, two-side exposed building, etc.), the properties of the building envelope components play a crucial role in regulating interior temperatures and influencing the energy consumption required to maintain thermal comfort.

Sections 8.3 to 8.6 describe the impact of different building envelope properties on the heating and cooling loads of a simple "detached" building in the four climate zones of Nepal. This building model was simulated to assess the impact of applicable passive strategies compared to the baseline construction[3] of each respective climate zone. The simulation of the building model included the following inputs:

- Detached building, rectangular with longer facades facing north and south.
- 3-4 storey building (all except cold climate). Single-storey building (cold climate).
- Cooling set point temperature (°C): 24°C (for all climates).
- Heating set point temperature (°C): 22°C (for all climates).
- No internal heat gains were considered in the model. It's important to note that in real-life scenarios, varying amounts of internal heat gains will be generated based on the use and occupancy of the building.

The simulations were conducted with a strict expectation of comfort (cooling set point 24°C, heating set point 22°C) based on the assumed user preferences, and consequently, the Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) comfort model were considered. This decision was made to optimize simulation time to present in this manual. It's important to note that using the adaptive comfort model would yield similar recommendations for passive strategies and a comparable trend in annual and heating load reduction. The main difference would be in the absolute values of the loads, with the adaptive comfort model resulting in lower absolute heat load values.

3 The baseline construction in each zone has been created by using the inputs from a baseline study done in 2023 by the BEEN project in the respective climate zone. The construction used is for residential buildings.

8.3 Building Envelope for Warm Temperate Zone in Nepal

8.3.1 Climate Characteristics

The warm temperate climate zone in Nepal is characterized by a monsoon-influenced humid subtropical climate with a dry winter (Dec – Feb). There is a short dry summer period in April – May, with the remaining year being warm and humid. This climate is considered "cooling-dominated," emphasizing the importance of reducing external heat gains and removing built-up heat inside the space.

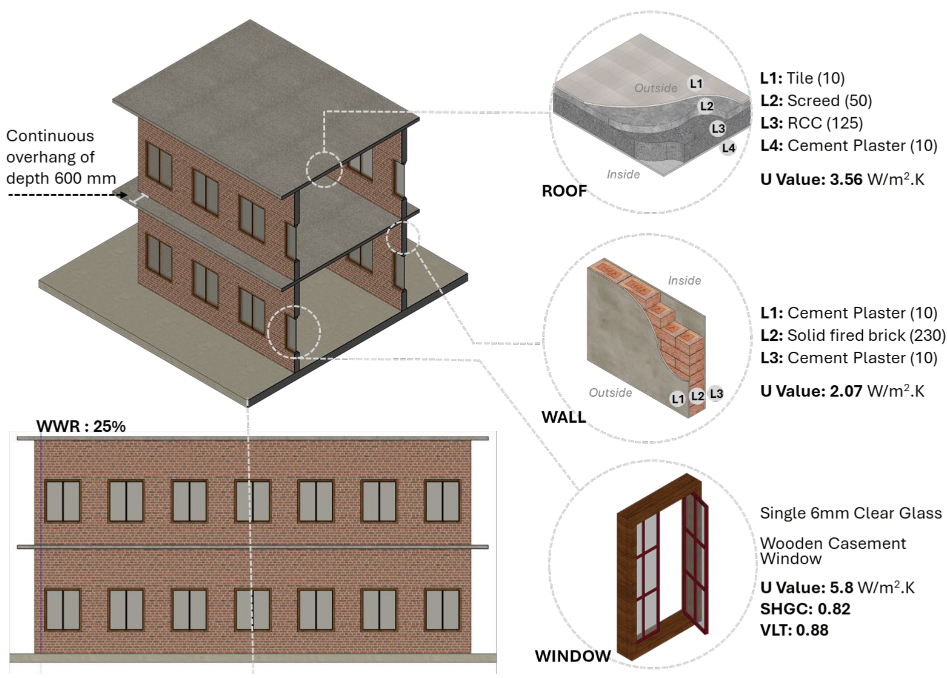
For this example, the climate file of Siddharth Nagar was used to represent this climate zone.

8.3.2 Baseline Construction

The typical construction in the warm temperate climate zone consists of the constructions as shown in Figure 92.

In the warm temperate climate zone, multi-storey buildings are common. Therefore, the building model was simulated for both an intermediate floor and a top floor to capture the varying conditions experienced at different levels.

Figure 92: Baseline Construction (Warm Temperate Zone)



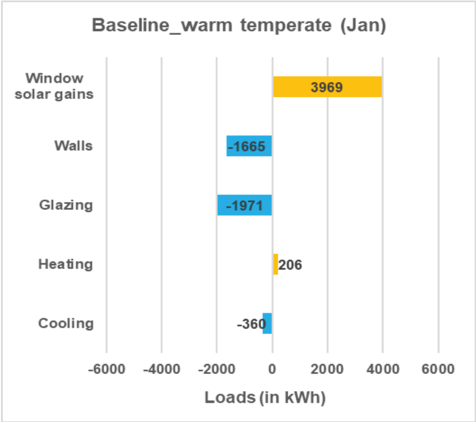
8.3.2.1 Heat Balance of the Baseline Construction

Figure 94 illustrates the heat gains and losses from the envelope for an intermediate floor during a typical summer month (June) and winter month (January) in the warm temperate climate zone. In this climate, the summer cooling load is more critical. Heat gains on an intermediate floor primarily occur through solar gains from glazed windows, conduction through the walls, and conduction through the glass.

In January, there is a minimal heating requirement, which can be adequately compensated by the internal gains from occupants and appliances. Additionally, a small cooling requirement is observed, which can be effectively addressed through natural ventilation by opening the windows.

Figure 93 demonstrates that on the top floor, the roof significantly influences heat gains during the summer and heat losses during the winter.

Figure 93: Heat Gains & Losses Through Baseline Building Envelope in Warm Temperate Climate (Intermediate Floor)



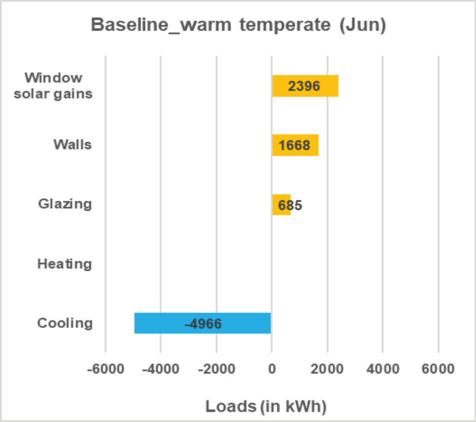
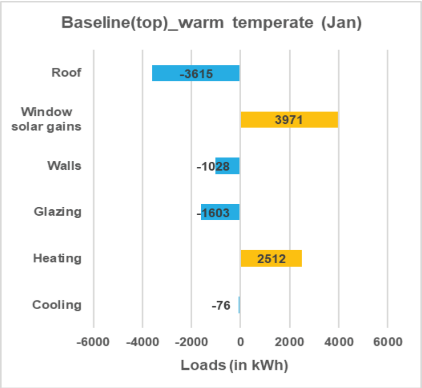
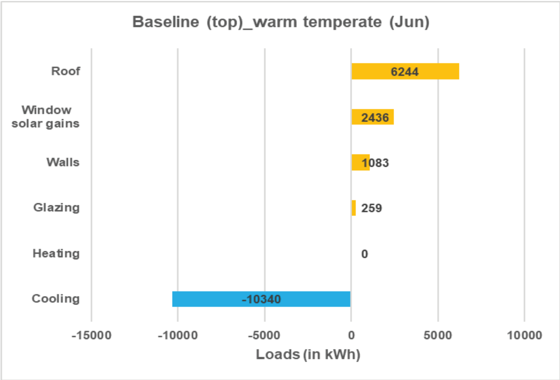


Figure 94: Heat Gains & Losses Through Baseline Building Envelope in Warm Temperate Climate (Top Floor)





8.3.3 Impact of Passive Strategies

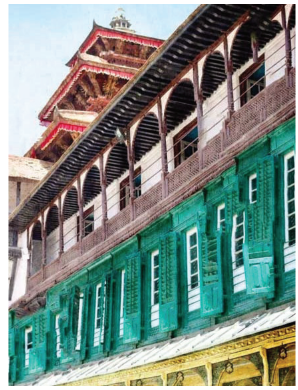
To mitigate heat gains through the windows and walls, the following strategies were analysed:

- Implementing better shading for glazed windows on the south, west, and east sides to reduce solar gains in the summer. This could involve deeper fixed shading or external movable shading (EMSyS). The latter provides superior shading in the summer compared to fixed shading but can be moved to allow solar gains in the winter when needed.
- Utilizing a roof assembly with a lower U-value to decrease conduction heat gains and losses through the roof.
- Leveraging the full potential of natural ventilation during the cooling period by opening windows whenever the outside temperature is cool.
- Employing a wall assembly with a lower U-value to minimize heat gains and losses through the walls.
- Using glass with a lower U-value to reduce conduction heat gains and losses through the glass.

An example of Examples of External Movable Shading is shown in Figure 95 and an example of Traditional Examples of Good Solar Shading in Nepal is shown in Figure 96.

Figure 95: Examples of External Movable Shading (EMSyS)

Figure 96: Traditional Examples of Good Solar Shading in Nepal



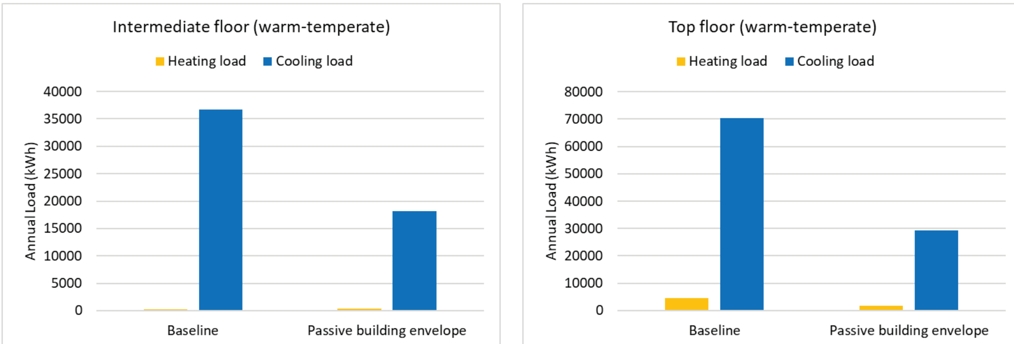
The above passive building envelope strategies can be applied in different ways in the building. Table 17 shows the passive building envelope options taken as an example for analysis in this manual.

Table 17: Baseline Construction and Passive Building Envelope Strategies for Warm-Temperate Climate

	Baseline	Passive Building Envelope
Exterior Wall Assembly	10mm internal plaster + Solid fired brick wall (230 mm thk) + 10 mm external plaster (U-value: 2.07 W/m².K)	10mm internal plaster + Hollow brick wall (240 mm thk) + 10 mm external plaster (U-value: 1.6 W/m².K)
Roof Assembly	10mm internal plaster + RCC Slab (125 mm thk) + 50 mm Screed +Tile, (U-value: 3.564 W/m².K)	10mm internal plaster + RCC Slab (125 mm thk) + 25 mm XPS insulation + 50mm Screed +Tile, (U-value: 0.8 W/m².K)
Window Assembly	6mm clear glazing (SHGC: 0.82, U-value: 5.8 W/m².K, VLT: 88%) with wooden frame	Double glazed Unit (SHGC: 0.54, U-value: 2.8 W/m².K, VLT: 58%) with wooden frame
Window-to-Wall Area Ratio (WWR)	25%, uniformly distributed on all directions	25% Overall. Higher distribution on north façade, followed by south façade.
Window Openability	Casement windows, but windows kept closed	Same as baseline
Shading	Continuous overhang of depth 600 mm	Continuous overhang of 600 mm + EMSyS on south, west and east facing windows

Figure 97 shows a comparison of the annual cooling and heating loads of the baseline construction and the passive building envelope strategies used.

Figure 97: Annual Heating and Cooling Loads for an Intermediate Floor and Top Floor, with Baseline Construction and Passive Strategies (Warm Temperate Climate)



In this cooling-dominated climate, the implementation of passive building envelope strategies has resulted in a notable reduction of more than 50% in the cooling load for both the intermediate and top floors. Additionally, the small annual heating load of the top floor has been reduced by almost 60%.

8.4 Building Envelope for Temperate Zone in Nepal

8.4.1 Climate Characteristics

The temperate climate zone in Nepal, like the warm temperate climate, is characterized as a monsoon-influenced humid subtropical climate. However, both summer and winter temperatures are lower than those of the warm temperate climate zone. This climate experiences a slightly longer winter period (mid-Nov to mid-Mar) with January and December being the more intense cold months. There is a short dry summer period in April – May, with the remaining year being warm and humid. The climatic conditions could be termed comfortable for most of the year, with some cold stress in winter and heat stress in summer. Buildings in this climate will require both cooling and heating to varying extents depending on the building design. There is also good potential for thermal comfort with natural ventilation in this climate.

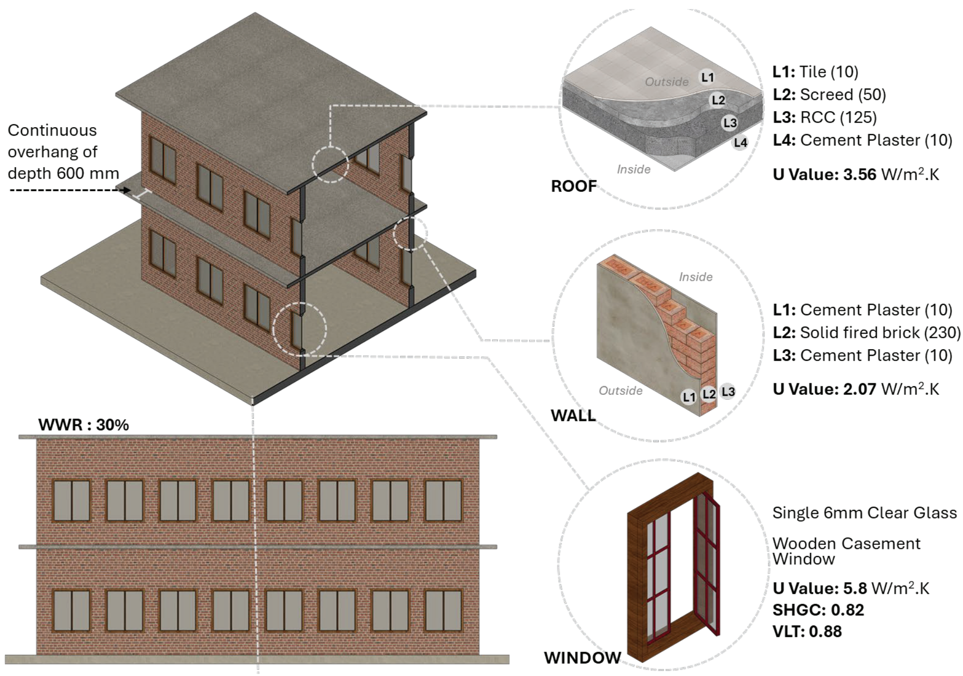
The climate file of Kathmandu was used as an example of this climate.

8.4.2 Baseline Construction

The typical construction in the temperate climate zone consists of the constructions as shown in Figure 98.

Multi-storey buildings are also common in this climate; therefore, the building model was simulated for both an intermediate floor and a top floor.

Figure 98: Baseline Construction (Temperate Zone)

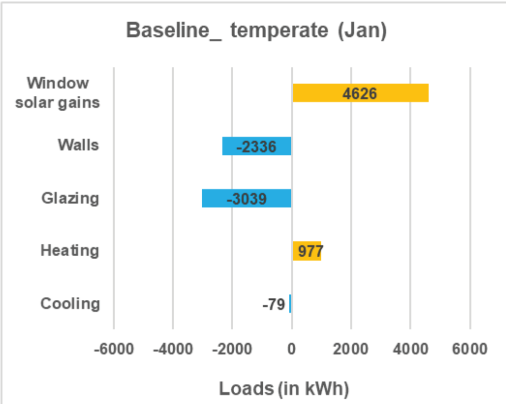


8.4.2.1 Heat Balance of the Baseline Construction

Figure 99 illustrates the heat gains and losses from the envelope for an intermediate floor in a typical summer month (June) and winter month (Jan). Meanwhile, Figure 100 presents the same information for the top floor. Notably, heat loss in winter primarily occurs through the roof (specifically for the top floor), conduction through the walls, and conduction through the glass.

In summer, heat gain predominantly occurs through transmission from glazed windows and conduction through the roof (specifically for the top floor).

Figure 99: Heat Gains & Losses Through Baseline Building Envelope in Temperate Climate (Intermediate Floor)



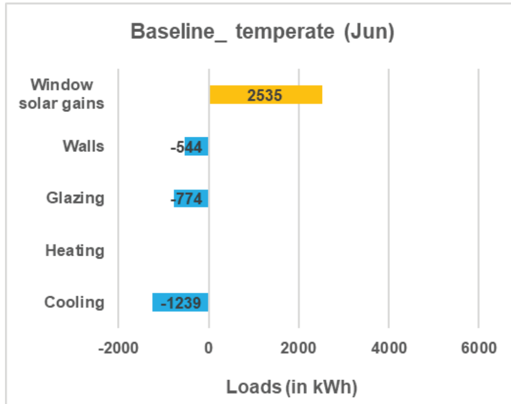
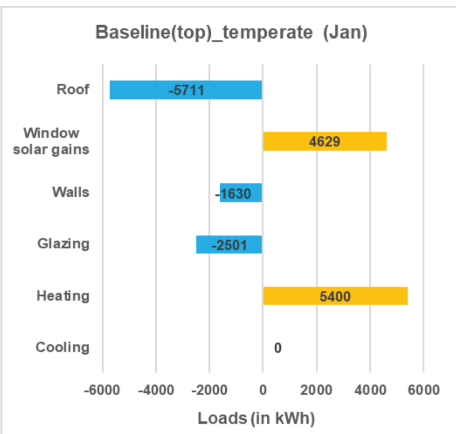
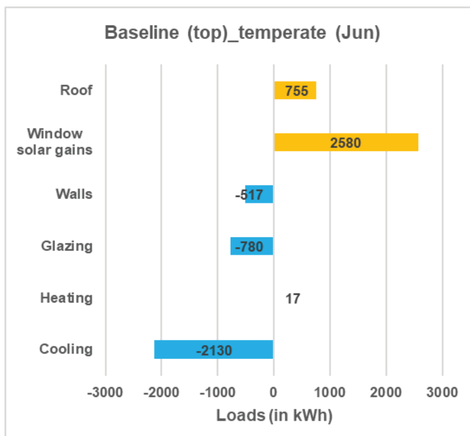


Figure 100: Heat Gains & Losses Through Baseline Building Envelope in Temperate Climate (Top Floor)





8.4.3 Impact of Passive Building Envelope Strategies

Taking the above considerations into account, the following strategies were analyzed:

- Using a roof assembly with a lower U-value to reduce conduction heat gains and losses through the roof.
- Implementing better shading for glazed windows on the south, west, and east sides to minimize solar gains through the windows in summer.
- Maximizing the potential of natural ventilation during the cooling period by opening windows when the outside temperature is cool.

- Utilizing a wall assembly with a lower U-value to reduce heat gains and losses through the walls.
- Choosing glass with a lower U-value to minimize conduction heat gains and losses through the glass.

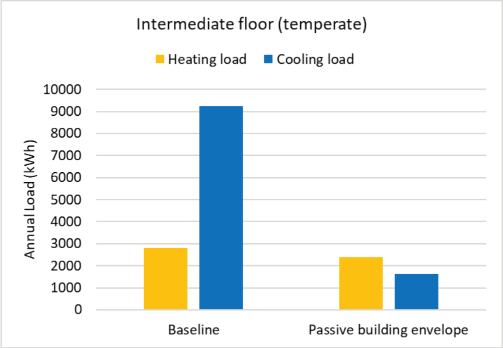
Table 18 shows the passive building envelope options taken as an example for analysis in this manual.

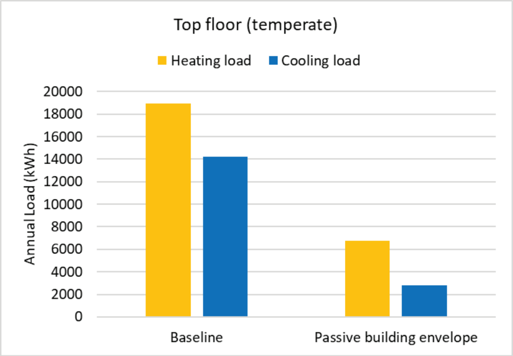
Table 18: Baseline Construction and Passive Building Envelope Strategies for Temperate Climate

	Baseline	Passive Building Envelope
Exterior Wall Assembly	10mm internal plaster + Solid fired brick wall (230 mm thk) + 10 mm external plaster (U-value: 2.07 W/m².K)	10mm internal plaster + Hollow brick wall (240 mm thk) + 10 mm external plaster (U-value: 1.6 W/m².K)
Roof Assembly	10mm internal plaster + RCC Slab (125 mm thk) + 50 mm Screed +Tile, (U-value: 3.564 W/m².K)	10mm internal plaster + RCC Slab (125 mm thk) + 25 mm XPS insulation + 50mm Screed +Tile, (U-value: 0.8 W/m².K)
Window Assembly	6mm clear glazing (SHGC: 0.82, U-value: 5.8 W/m².K, VLT: 88%) with wooden frame	Double glazed Unit (SHGC: 0.54, U-value: 2.8 W/m².K, VLT: 58%) with wooden frame
Window-to-Wall Area Ratio (WWR)	30%, uniformly distributed on all directions.	30% Overall. Higher distribution on south façade.
Window Openability	Casement windows, but windows kept closed	Casement windows, and windows are kept open when there is natural ventilation potential
Shading	Continuous overhang of depth 600 mm	Continuous overhang of 600 mm + EMSyS on south, west and east facing windows

Figure 101 provides a comparison of the annual cooling and heating loads between the baseline construction and the passive building envelope strategy options employed.

Figure 101: Annual Heating and Cooling Loads for an Intermediate Floor and Top Floor, with Baseline Construction and Passive Strategies (Temperate Climate)





The cooling load can dominate in this climate if natural ventilation is not utilized during the summer months. However, with the passive envelope features outlined in Table 18, there is an 80% decrease in the cooling load for both the intermediate and top floors. This significant reduction can be attributed to the effective implementation of shading, natural ventilation, and roof insulation (specifically for the top floor).

The annual heating load reduction is almost 15% on the intermediate floor and 60% on the top floor. The impact of roof insulation in decreasing winter heat losses from the top floor is particularly noteworthy. To further minimize the heating load on the intermediate floor, one or more of the following strategies can be considered:

- Using a double-glazed unit (DGU) with a low U-value but a high Solar Heat Gain Coefficient (SHGC). The DGU mentioned in this manual has a U-value of 2.8 W/ $m^2 \cdot K$ and SHGC of 0.54. While this glass is effective in reducing conductive heat transfer, it also diminishes desirable solar radiation gains in winter. Hence, a glass with a low U-value and high SHGC may offer better performance. However, it's essential to ensure adequate shading for all windows during the summer months.
- Reducing the wall U-value, it is crucial to providing good natural ventilation; otherwise, it might be counterproductive in the summer.

8.5 Building Envelope for Cool Temperate Zone in Nepal

8.5.1 Climate Characteristics

The cool temperate climate zone in Nepal experiences a longer winter period, extending from November to March. However, the climatic conditions during the remaining months are generally comfortable. Buildings in this climate may require cooling in these months if heat gains during the summer are unchecked and natural ventilation is not utilized.

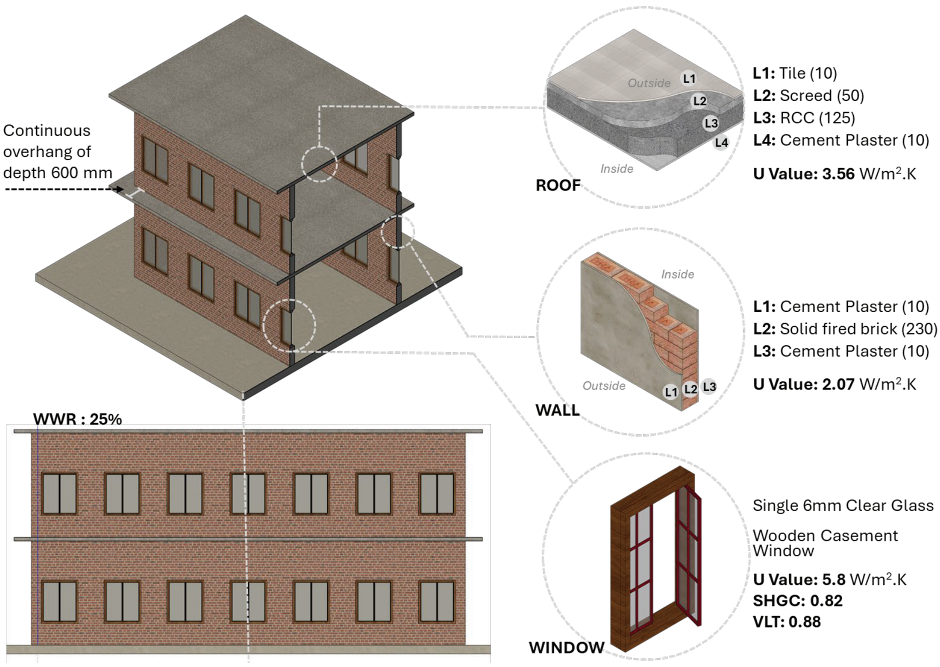
For this climate, the climate file of Gosaikunda rural municipality headquarters was created and used as an example.

8.5.2 Baseline Construction

The typical construction in the cool temperate climate zone consists of the constructions as shown in Figure 102.

Multi-storey buildings are common in this climate; therefore, the building model was simulated for both an intermediate floor and a top floor.

Figure 102: Baseline Construction (Temperate Climate)



8.5.2.1 Heat Balance of the Baseline Construction

Figure 103 illustrates the heat gains and losses from the envelope for an intermediate floor in a typical summer month (June) and winter month (Jan). Meanwhile, Figure 104 presents the same information for the top floor. Notably, heat loss in winter primarily occurs through the roof (specifically for the top floor), conduction through the walls, and conduction through the glass.

In summer, heat gain predominantly occurs through transmission from glazed windows and conduction through the roof (specifically for the top floor).

Figure 103: Heat Gains & Losses Through Baseline Building Envelope in Cool Temperate Climate (Intermediate Floor)

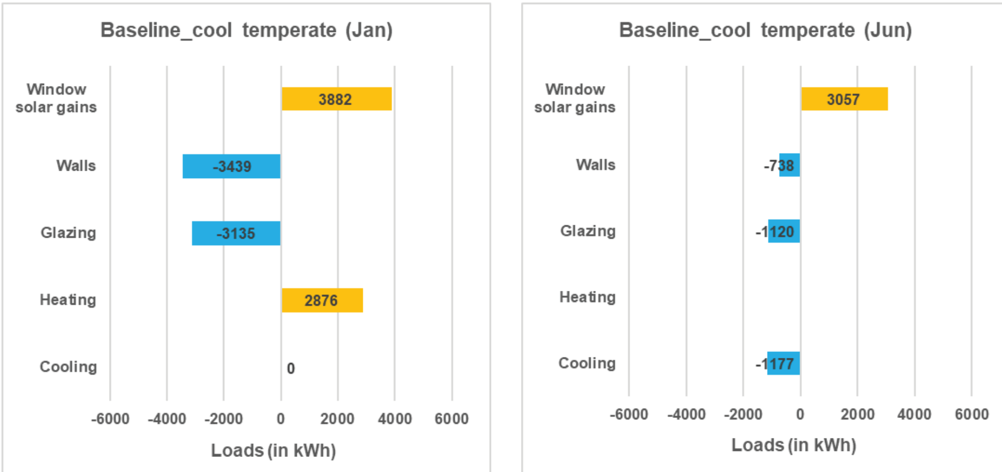
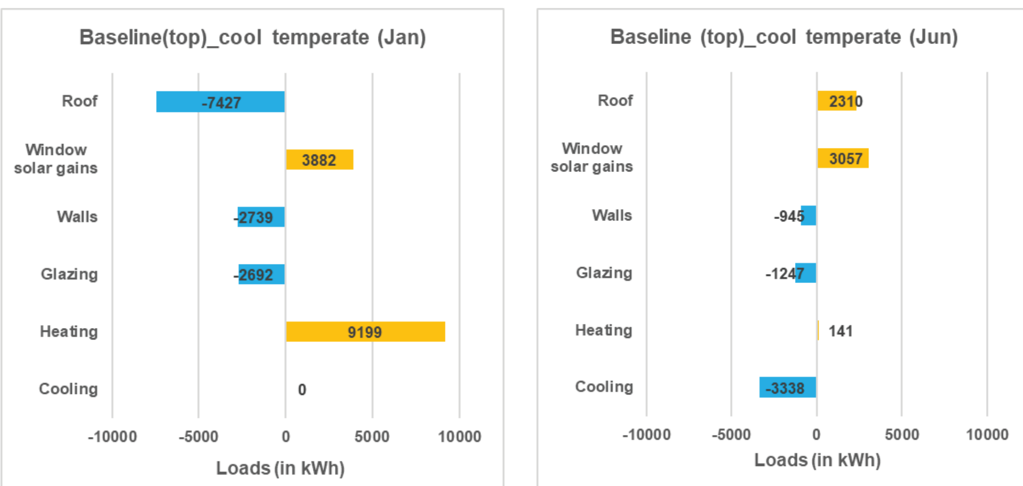


Figure 104: Heat Gains & Losses Through Baseline Building Envelope in Cool Temperate Climate (Top Floor)



8.5.3 Impact of Passive Strategies

The strategies mentioned in Section 8.4.3 can be applied here as well.

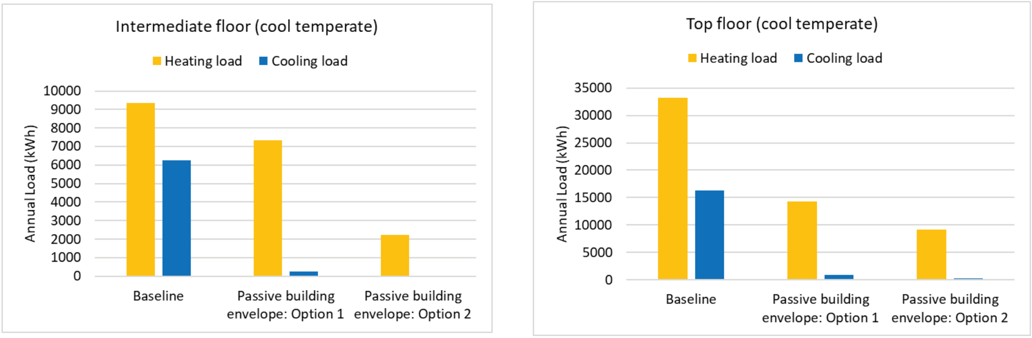
Table 19 presents the passive building envelope options used as examples for analysis in this manual. Two sets of building envelope strategies were analysed.

Table 19: Baseline Construction and Passive Building Envelope Strategies For Cool-Temperate Climate

	Baseline	Passive Building Envelope	Passive Building Envelope
Exterior Wall Assembly	10mm internal plaster + Solid fired brick wall (230 mm thk) + 10 mm external plaster (U-value: 2.07 W/m².K)	10mm internal plaster + Hollow brick wall (240mm thk) + 10 mm external plaster (U-value: 1.6 W/m².K)	10mm internal plaster + Solid fired brick wall (230 mm thk) + 25 mm XPS + 10 mm external plaster (U-value: 0.8 W/m2.K)
Roof Assembly	10mm internal plaster + RCC Slab (125 mm thk) + 50mm Screed +Tile, (U-value: 3.564 W/m².K)	10 mm internal plaster + RCC Slab (125 mm thk) + 25mm XPS insulation + 50mm Screed +Tile, (U-value: 0.8 W/m².K)	Same as option 1
Window Assembly	6mm clear glazing (SHGC: 0.82, U-value: 5.8 W/m².K, VLT: 88%) with wooden frame	Double glazed Unit (SHGC: 0.54, U-value: 2.8 W/m².K, VLT: 58%) with wooden frame	Same as option 1
Window-to-Wall Area Ratio (WWR)	25%, uniformly distributed on all directions.	25% Overall. Higher distribution on south façade.	Same as option 1
Window Openability	Casement windows, but windows kept closed	Casement windows, and windows are kept open when there is natural ventilation potential	Same as option 1
Shading	Continuous overhang of depth 600 mm	Continuous overhang of 600mm + EMSyS on south, west and east facing windows	Same as option 1

Figure 101 provides a comparison of the annual cooling and heating loads between the baseline construction and the passive building envelope strategy options employed.

Figure 105: Annual Heating and Cooling Loads for an Intermediate Floor and Top Floor, with Baseline Construction and Passive Strategies (Cool Temperate Climate)



Cooling loads can be nearly negated for both the intermediate and top floors, primarily attributed to the effectiveness of natural ventilation, shading, and roof insulation.

Regarding the heating load, Passive Building Envelope Option 1 results in a nearly 20% reduction on the intermediate floor and a 50% reduction on the top floor. With Option 2, the heating load can be reduced by more than 70%. It's crucial to ensure the full potential of natural ventilation is utilized in the summer months to prevent the building from overheating.

8.6 Building Envelope for Cold Zone in Nepal

8.6.1 Climate Characteristics

The cold climate zone in Nepal is characterized as a "heating-dominated" climate, experiencing winter from October to April. The remaining months are generally cool and comfortable, with slightly warm daytime temperatures from June to August due to intense solar radiation. The primary focus in this climate should be on reducing heat losses and optimizing solar gains during winter.

For this climate, the climate file of Jomsom was created and used as an example.

8.6.2 Baseline Construction

The typical construction in the cold climate zone consists of the constructions as given in Figure 106.

The baseline roof assembly in cold climates is shown in Figure 107. Single-storey buildings are common in this climate; therefore, the building model was simulated as a single floor.

Figure 106: Baseline Roof Assembly in Cold Climate

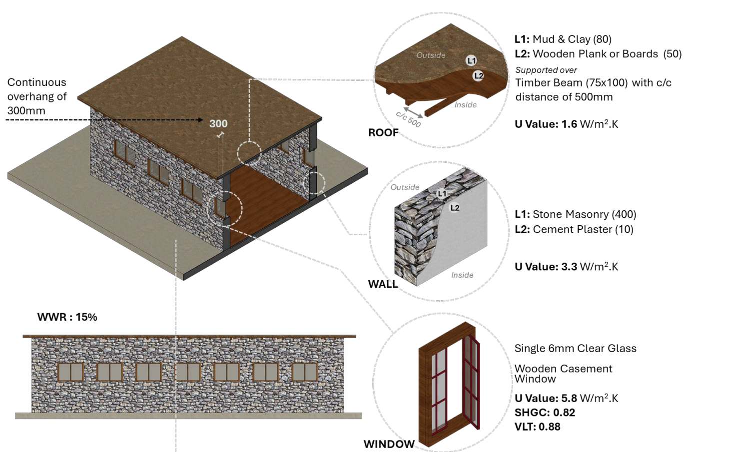
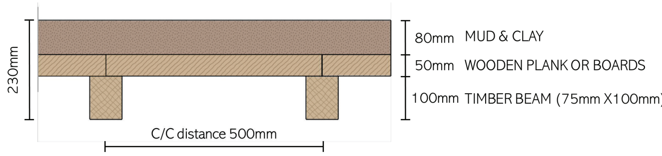


Figure 107: Baseline Roof Assembly in Cold Climate

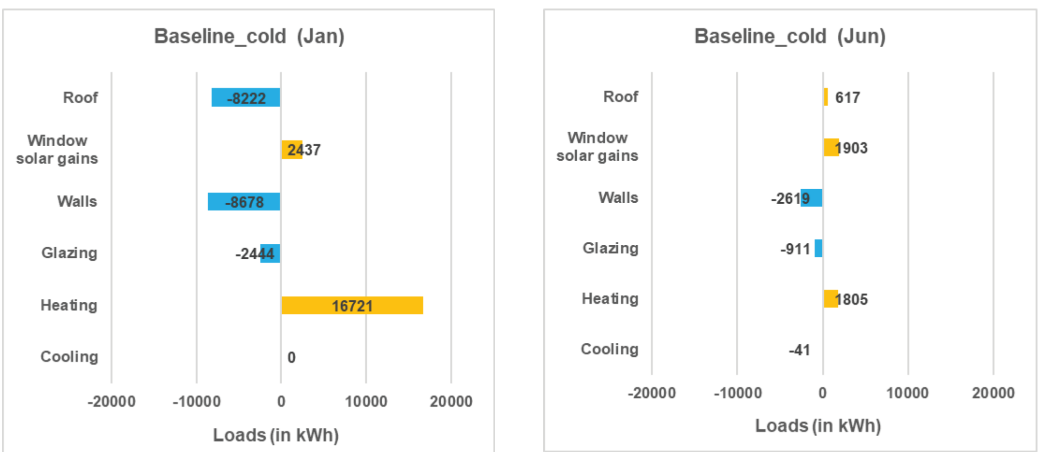


8.6.2.1 Heat Balance of the Baseline Construction

Figure 108 illustrates the heat gains and losses from the envelope in a typical winter month (Jan) and summer month (Jun). The cooling load in June is negligible and can be effectively managed with natural ventilation by opening the windows.

In this climate, the heating load is critical. Heat losses primarily occur through the roof and conduction through the walls. Conduction heat loss through the glass is less significant as the Window-to-Wall Ratio (WWR) in this climate is low (around 15%).

Figure 108: Heat Gains & Losses Through Baseline Building Envelope in Cold Climate



8.6.3 Impact of Passive Strategies

To mitigate heat losses, the following strategies were analyzed:

- Implementing a roof assembly with a lower U-value to reduce conduction heat loss through the roof.
- Choosing glass with a lower U-value to minimize conduction heat loss through the glass.
- Employing a wall assembly with a lower U-value to reduce heat loss in winter.

Table 20 shows the passive building envelope options taken as an example for analysis in this manual. Two sets of building envelope strategies were analysed.

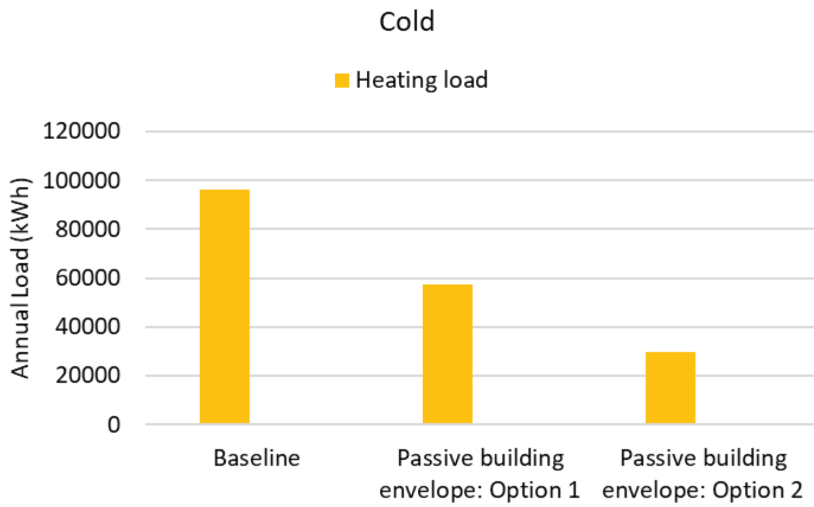
Table 20: Baseline Construction and Passive Building Envelope Strategies for Cold Climate

	Baseline	Passive Building Envelope	Passive Building Envelope
Exterior Wall Assembly	10mm internal plaster + Stone masonry (400 mm thk) (U-value: 3.3 W/m².K)	10 mm internal plaster + Hollow brick wall (240 mm thk) + 10 mm external plaster (U-value: 1.6 W/m².K)	10 mm internal plaster + Solid fired brick wall (400 mm thk) + 25 mm XPS + 10 mm external plaster (U-value: 0.8 W/m².K)
Roof Assembly	Mud over wooden planks (Figure 107) (U-value: 1.6 W/m².K)	10mm internal plaster + RCC Slab (125 mm thk) + 25 mm XPS insulation + 50 mm Screed +Tile, (U-value: 0.8 W/m².K)	Same as option 1
Window Assembly	6 mm clear glazing (SHGC: 0.82, U-value: 5.8 W/m².K, VLT: 88%) with wooden frame	Double glazed Unit (SHGC: 0.54, U-value: 2.8 W/m².K, VLT: 58%) with wooden frame	Triple glazed unit (SHGC: 0.6, U-value: 0.6 W/m².K, VLT: 69%)
Window-to-Wall Area Ratio (WWR)	15%, uniformly distributed on all directions.	15% Overall. Higher distribution on south façade.	Same as option 1
Window Openability	Casement windows, but windows kept closed	Same as baseline	Same as baseline
Shading	Continuous overhang of depth 300 mm	Same as baseline	Same as baseline

Unlike in the other climate zones, the roof taken in the baseline construction here is not a simple 125 mm RCC slab (U-value 3.5 W/m².K), but a more traditional roof made of mud and wood (U-value 1.6 W/m².K). To reduce heat losses further, the roof value must be lower than this. An RCC slab with 25 mm XPS insulation has a U-value of 0.8 W/m².K. In no circumstance should an un-insulated RCC roof be used in the cold climate.

Figure 109 shows a comparison of the annual cooling and heating loads of the baseline construction in the two options of passive building envelope strategies.

Figure 109: Annual Heating and Cooling Loads with Baseline Construction and Passive Strategies (Cold Climate)



Being a heating-dominated climate with negligible cooling load, Option 1 results in a 40% decrease in the annual heating load. Option 2, with a more insulated wall and a more stringent glass specification, can achieve a reduction of nearly 70% in the annual heating load.

Summary

- Passive design strategies involve design approaches that leverage the natural environment to achieve comfort.
- Depending on the climate and desired thermal comfort, passive strategies aim to:
  - Reduce or optimize solar radiation falling on the building envelope.
  - Minimize heat gains or losses through the building envelope.
  - Enable cooling through natural ventilation and reduce infiltration losses through the building envelope.
- The orientation, massing, spatial configuration of a building, along with the properties of the building envelope, are the key passive design aspects that influence the building's energy consumption for heating and cooling.

9
RESOURCE EFFICIENT MATERIALS AND CONSTRUCTION TECHNOLOGIES

What's in this Section?

Resource Efficient Materials and Construction Technologies

9.1 Resource Efficient Materials

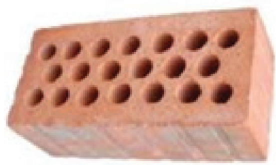
While addressing resource-efficient construction materials, the document focuses on a selected group of materials that are considered to have the most significant impact on the current construction landscape of Nepal. This targeted approach ensures practical relevance and easier adoption within the local context. Hence, the discussion in this chapter will primarily centre around the following key materials:

1. **Hollow /Perforated Bricks**
2. **Hollow Concrete Blocks (HCB)**
3. **Compressed Stabilized Earth Blocks (CSEB)**

These materials have been selected for their ability to minimize material usage, improve thermal performance, reduce construction expenses, and support sustainable building practices in the context of Nepal. Therefore, the following section will briefly discuss these resource-efficient materials.

1. **Hollow /Perforated Bricks:** are a type of brick that has a tubular, hollow structure created within the brick. The perforated brick has numerous small-sized holes, while the hollow brick has a smaller number of larger holes. Since hollow /perforated bricks require less clay, they also require less water during the production of green bricks. Additionally, during firing, they consume less fuel, making them a more resource-efficient building material. Likewise, the reduced fuel consumption in the production of hollow bricks leads to lower emissions, making it an environmentally friendly option. Furthermore, hollow bricks possess better insulation properties, contributing to the creation of energy-efficient buildings.

Table 21: Categorization of the Clay Bricks

Solid Brick	Perforated Bricks	Hollow Bricks
		
Bricks without any holes passing through the bricks surface.	Containing a pattern of small holes passing through the brick removing not less than 15% of the brick volume. Small holes have an area less than 500 mm^2. The hole may be circular, square, rectangular or any other regular shape.	Containing a pattern of large holes removing not less than 15% of the brick's volume.

2. **Compressed Stabilized Earth Blocks (CSEB):** CSEB are building blocks made by compacting a mixture of soil, sand, a small amount of cement or lime, and water in a manual or mechanical press. Unlike traditional fired bricks, CSEBs are cured naturally, which significantly reduces energy consumption and carbon emissions. These blocks are locally produced using available soil, making them cost-effective and sustainable. CSEBs offer good thermal insulation, structural strength, and durability, making them suitable for various building applications — especially in rural and climate-sensitive regions. Their use supports resource efficiency, reduces dependence on fired bricks, and promotes environmentally responsible construction practices. BEEN has been promoting CSEB as one of the resource efficient construction materials.

Figure 110: Compressed Stabilized Earth Blocks (CSEB)

3. **Hollow Concrete Block (HCB):** HCB are precast masonry units composed of cement, aggregates, and water, featuring one or more hollow cores. These cores make HCBs lighter than solid concrete blocks while offering improved thermal and acoustic insulation. Their consistent shape, structural strength, and ease of installation make them suitable for both load-bearing and non-load-bearing walls. Additionally, HCBs require less mortar, accelerate construction time, and reduce material waste which additionally make it resource efficient during application. It also contributes to lowering the overall deadload of structures and enhancing the energy efficiency of buildings. However, widespread adoption in Nepal remains limited due to inconsistent production quality.

Figure 111: Hollow Concrete Block (HCB)

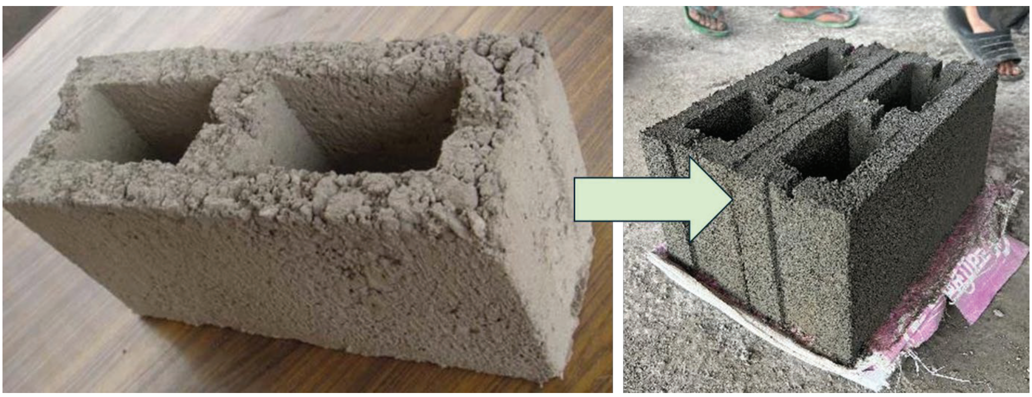


Table 22: Advantages of Resource-Efficient Materials

	Hollow/Perforated Bricks	Compressed Stabilized Earth Blocks (CSEB)	Hollow Concrete Block (HCB)
Resource Efficiency	• Less natural clay and energy compared to traditional solid bricks. • Because of their reduced mass, the energy required to fire green hollow bricks is lower compared to solid bricks	• Uses locally available soil, resulting in lower transportation costs. • Low embodied energy • Can be recycled at the end of lifecycle • The quality of CSEB requires salient attention on soil quality	• No firing needed • Can be recycled and reused at the end of their lifespan
Thermal & Sound Insulation	Improved thermal and sound insulation compared to solid bricks. Keep's the interiors of buildings cooler during hot summers and warmer during cold winters.	Better thermal insulation as compared to bricks	Good sound and thermal insulation properties
Energy Conservation	Reduced Energy Costs	Reduced Energy Costs	

	Hollow/Perforated Bricks	Compressed Stabilized Earth Blocks (CSEB)	Hollow Concrete Block (HCB)
Cost	Reduced Structural Cost	• Significantly lower construction costs • Low dependency on external materials	Cement-based concrete blocks are relatively affordable
Sizes & Customization	Various sizes and perforations available	Can be easily moulded into different shapes and sizes	Come in various shapes, sizes, and configurations
Aesthetics	Exposed brickwork is aesthetically pleasing		Low maintenance
Strength	Compressive strength similar to solid bricks	• Depends on grade and type of soil	Cement-based concrete blocks are known for their high compressive strength
Seismic Strength	Reduced Structural Cost	• The seismic force acting on a structure is directly proportional to its mass. Hollow Brick walls have a reduced mass compared to solid bricks, resulting in a smaller lateral force during an earthquake. • Lighter weight of the structure reduces load on foundations	

9.2 Resource-Efficient Construction Techniques

Resource-efficient construction techniques aim to minimize the use of materials and energy while enhancing the overall performance and sustainability of buildings. Through the BEEN Project, only selected key construction techniques have been promoted — those that not only reduce construction costs and environmental impact but also support climate-resilient, energy-efficient, and resource-conscious building practices. These approaches are particularly relevant in the context of Nepal, where both affordability and sustainability are critical considerations.

1. **Rat-Trap Bond:** Rat-Trap Bond is a modular masonry technique where bricks are placed on edge, forming a continuous cavity within the wall. This cavity enhances the wall's thermal performance while reducing the overall consumption of bricks and mortar. Rat-Trap Bond masonry is suitable for both partition walls and load-bearing structures. Since it follows a modular layout, careful attention is required during the design phase — particularly in determining the wall's length and height. To ensure structural stability, the inclusion of horizontal bands, vertical reinforcements, corner ties, and reinforcements at T-junctions is essential.

Figure 112: Rat-Trap Bond and Cavity Wall (with Insulation)

Ratrap Bond **Cavity Wall**

2. **Cavity Walls:** Cavity Walls consist of two parallel walls (an inner and an outer layer) separated by a gap or cavity. This construction method is designed to enhance thermal insulation and prevent moisture penetration, making it a sustainable and efficient choice for building envelope.

   In Nepal, with its diverse climate ranging from hot plains to cold mountainous regions, cavity walls offer significant advantages. In hot climates, the air gap reduces heat transfer, keeping interiors cooler and reducing energy consumption for cooling. In colder regions, the cavity minimizes heat loss, helping maintain warmer indoor temperatures and reducing heating costs. Cavity walls are an ideal solution for sustainable and climate-responsive construction, particularly in Nepal's varied environmental conditions.

Table 23: Advantages of Resource-Efficient Construction Techniques

	Rat-Trap Bond	Cavity Wall
Material & Resource Efficiency	Saves up to 30-40% on bricks and up to 45% on cement mortar	
Thermal & Sound Insulation	Good thermal and sound insulation	Good thermal and sound insulation
Energy Conservation	Reduced Energy Costs	Reduced Energy Costs
Cost	Cost of masonry is reduced by 25-30%	Slightly higher cost
Structural Stability	Reduced dead load makes it suitable for earthquake prone areas	Enhances the lifespan of buildings by protecting against weather-induced damage.
Moisture Resistance	Prevents seepage & moisture related issues	Prevents seepage & moisture related issues

Table 24: Comparative Properties of Materials and Walling Techniques

Description	Dimensions (mm)	Density (kg/m³)	CO2 emission (t CO2/m3)	Thermal Conductivity (W/m.K)	U value (W/(m²K))	Number Per m3	Brick Equivalent	Compressive strength (Mpa)	Water Absorption
Resource Efficient Material									
Solid Bricks	240 x 115 x 57 (varies as per location)	1660-1900	0.15-0.22	0.85-0.98		477	1	Min–3.5	<15%
Hollow / Perforated Bricks	240 x 115 x 57 (available in wide variety)	1520	0.11-0.14	0.63		477	1	NA 12.2-17.4	NA (11-16%)
Hollow Concrete Blocks (HCB)	400x 200x 100/ 150/ 200	700-900	0.08-0.1	0.7 to 0.9		105/ 72/ 55	4.5/ 6.6/ 8.6	5	< 10 %
CSEB	300 x 150 x 100 mm (available in various shape and sizes)	1700-1900	0.05	0.46-0.93		183	2.6	>5 MPa (1st Class) 2-5 MPa (2nd class)	<10% (1st Class) 10-20% (2nd class)
Resource Walling Technique									
Solid Brick walls	230 mm				2.0 W/m²K				
Hollow Brick Walls	230 mm				1.6 W/m²K				
Rat Trap Bond Wall	230 thick walls				1.37 W/m²K				
Cavity Wall	The cavity 40 to 70 mm				1.6 W/m²K				

Table 25: Code Compliance

Walling Material	Code, Standard, Norms and Specification	District Rates	Remarks
Resource Efficient Material			
Brick	NS 1-2035	✓	For load bearing and non-load bearing walls
Hollow Bricks	IS: 3952-1988	N/A	For load bearing and non-load bearing walls
HCB	NS: 119/2042	✓	For load bearing and non-load bearing walls
CSEB	N/A	✓	For load bearing and non-load bearing wall
Resource Walling Technique			
Brick masonry	NS 578, NBC 201, 202, 203, 205	✓	Design catalogue for reconstruction, DUDBC For load bearing and non-load bearing walls
Hollow Brick	Under progress	N/A	For non-load bearing walls For load bearing walls depends upon type of hollow bricks, type of structure Green Masonry Module to be added in CTEVT
HCB masonry	NBC 202	✓	Design catalogue for reconstruction, DUDBC For load bearing and non-load bearing walls
CSEB walls	NBC 203	N/A	In NBC, it is mentioned as Stabilized Earth Block, for low strength masonry only. Design catalogue for reconstruction, DUDBC For load bearing and non-load bearing walls
Rat Trap Bond	N/A	✓	Design catalogue for reconstruction, DUDBC Only for single brick thick walls For load bearing and non-load bearing walls Green Masonry Module to be added in CTEV
Cavity Wall	N/A	N/A	Only for non-load bearing walls Green Masonry Module to be added in CTEVT

ANNEX

Annex 1

Table 26: Thermal Properties of Building and Insulating Materials (Bureau of Energy Efficiency, Eco-Niwas Samhita 2018, (Energy Conservation Building Code for Residential Buildings), Part I: Building Envelope, 2018)

S.N.	Type of Material	Density (kg/m^3)	Thermal Conductivity (W/m.K)	Specific Heat Capacity (kJ/kg.K)
1	Solid burnt clay brick	1920	0.81–0.98	0.80
2	Solid burnt clay brick	1760	0.71–0.85	NA
3	Solid burnt clay brick	1600	0.61–0.74	NA
4	Solid burnt clay brick	1440	0.52–0.62	NA
5	Resource efficient hollow brick	1520	0.631	0.99
6	Fly ash brick	1650	0.856	0.93
7	Solid concrete block 25/50	2427	1.396	NA
8	Solid concrete block 30/60	2349	1.411	NA
9	Aerated autoclaved concrete (AAC) block	642	0.184	0.79
10	Cement stabilized soil block (CSEB)	1700–1900	1.026	1.03
11	Cement stabilized soil block (CSEB)	1800	1.201	1.07
12	Cement stabilized soil block (CSEB)	1900	1.303	1.07
13	Dense concrete	2410	1.740	0.88
14	Reinforced concrete cement (RCC)	2288	1.580	0.88
15	Brick tile	1892	0.798	0.88
16	Lime concrete	1646	0.730	0.88
17	Mud Phuska	1622	0.519	0.88
18	Cement mortar	1648	0.719	0.92
19	Cement plaster	1762	0.721	0.84
20	Gypsum plaster	1120	0.512	0.96
21	Cellular concrete	704	0.188	1.05
22	AC sheet	1520	0.245	0.84
23	GI sheet	7520	61.060	0.50
24	Timber	480	0.072	1.68
25	Timber	720	0.144	1.68
26	Plywood	640	0.174	1.76
27	Glass	2350	0.814	0.88
28	Tar felt (2.3 kg/m^2)		0.479	0.88

S.N.	Type of Material	Density (kg/m³)	Thermal Conductivity (W/m.K)	Specific Heat Capacity (kJ/kg.K)
II. Insulating Materials				
1	Expanded polystyrene	16.0	0.038	1.34
2	Expanded polystyrene	24.0	0.035	1.34
3	Expanded polystyrene	34.0	0.035	1.34
4	Foam glass	127.0	0.056	0.75
5	Foam glass	160.0	0.055	0.75
6	Foam concrete	320.0	0.070	0.92
7	Foam concrete	400.0	0.084	0.92
8	Foam concrete	704.0	0.149	0.92
9	Cork slab	164.0	0.043	0.96
10	Cork slab	192.0	0.044	0.96
11	Cork slab	304.0	0.055	0.96
12	Rock wool (unbonded)	92.0	0.047	0.84
13	Rock wool (unbonded)	150.0	0.043	0.84
14	Mineral wool (unbonded)	73.5	0.030	0.92
15	Glass wool (unbonded)	69.0	0.043	0.92
16	Glass wool (unbonded)	189.0	0.040	0.92
17	Resin bonded mineral wool	48.0	0.042	1.00
18	Resin bonded mineral wool	64.0	0.038	1.00
19	Resin bonded mineral wool	99.0	0.036	1.00
20	Resin bonded mineral wool	16.0	0.040	1.00
21	Resin bonded mineral wool	24.0	0.036	1.00
22	Exfoliated vermiculite (loose)	264.0	0.069	0.88
23	Asbestos mill board	1397.0	0.249	0.84
24	Hard board	979.0	0.279	1.42
25	Straw board	310.0	0.057	1.30
26	Soft board	320.0	0.066	1.30
27	Soft board	249.0	0.047	1.30
28	Wall board	262.0	0.047	1.26
29	Chip board	432.0	0.067	1.26
30	Chip board (perforated)	352.0	0.066	1.26
31	Particle board	750.0	0.098	1.30
32	Coconut pith insulation board	520.0	0.060	1.09
33	Jute fibre	329.0	0.067	1.09
34	Wood wool board (bonded with cement)	398.0	0.081	1.13
35	Wood wool board (bonded with cement)	674.0	0.108	1.13
36	Coir board	97.0	0.038	1.00

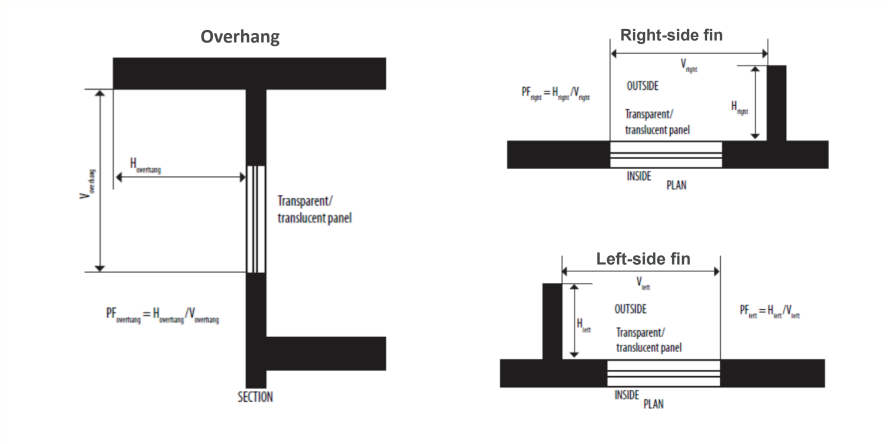
S.N.	Type of Material	Density (kg/m³)	Thermal Conductivity (W/m.K)	Specific Heat Capacity (kJ/kg.K)
37	Saw dust	188.0	0.051	1.00
38	Rice husk	120.0	0.051	1.00
39	Jute felt	291.0	0.042	0.88
40	Closed cell flexible elastomeric foam - NBR	40–55	0.043	1.20

Annex 2

Calculation of Equivalent SHGC

Equivalent Solar Heat Gain Coefficient (SHGC) is the SHGC of an opening that incorporates a permanent external shading projection, such as an overhang and side fins.

Step 1: Calculate projection factor (PF)



Step 2: Select the External Shading Factor (ESF) value for each shading element from the Table 22, Table 23, and Table 24, corresponding to the PF and the orientation.

Step 3: Calculate the total external shading factor (ESF_{total})

$ESF_{total} = ESF_{overhang} \times ESF_{sidefin}$ (A2-1)

where,

$ESF_{sidefin} = 1-[(1-ESF_{right}) + (1-ESF_{left})]$ (A2-2)

Step 4: Calculate the equivalent SHGC of the fenestration ($SHGC_{eq}$)

$SHGC_{eq} = SHGC_{unshaded} \times ESF_{total}$ (A2-3)

Table 27: External Shading Factor for Overhang (ESFoverhang) for LAT ≥ 23.5˚N. (Bureau of Energy Efficiency, Eco-Niwas Samhita 2018, (Energy Conservation Building Code for Residential Buildings), PART I: BUILDING ENVELOPE, 2018)

	External Shading Factor for Overhang ($ESFo_{verhang}$) for LAT ≥ 23.5˚N							
Orientation	North	North-east	East	South-east	South	South-west	West	North-west
$PF_{overhang}$	(337.6˚-22.5˚)	(22.6˚-67.5˚)	(67.6˚-112.5˚)	(112.6˚-157.5˚)	(157.6˚-202.5˚)	(202.6˚-247.5˚)	(247.6˚-292.5˚)	(292.6˚-337.5˚)
<0.10	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.10-0.19	0.955	0.930	0.922	0.906	0.881	0.905	0.922	0.930
0.20-0.29	0.922	0.876	0.855	0.824	0.789	0.823	0.853	0.875
0.30-0.39	0.897	0.834	0.796	0.755	0.719	0.753	0.794	0.834
0.40-0.49	0.877	0.803	0.745	0.697	0.665	0.695	0.743	0.802
0.50-0.59	0.860	0.779	0.702	0.652	0.626	0.650	0.700	0.778
0.60-0.69	0.846	0.761	0.666	0.617	0.598	0.614	0.663	0.760
0.70-0.79	0.834	0.747	0.635	0.590	0.580	0.587	0.632	0.746
0.80-0.89	0.825	0.737	0.609	0.569	0.569	0.566	0.606	0.736
0.90-0.99	0.817	0.729	0.587	0.554	0.563	0.551	0.585	0.728
≥1	0.810	0.722	0.569	0.542	0.559	0.539	0.566	0.721

Table 28: External Shading Factor for Side Fin-Right (ESF_{right}) for LAT ≥ 23.5˚N. (Bureau of Energy Efficiency, Eco-Niwas Samhita 2018, (Energy Conservation Building Code for Residential Buildings), PART I: BUILDING ENVELOPE, 2018)

	External Shading Factor for Side Fin-Right (ESFright) for LAT ≥ 23.5˚N							
Orientation	North	North-east	East	South-east	South	South-west	West	North-west
PF_{right}	(337.6˚-22.5˚)	(22.6˚-67.5˚)	(67.6˚-112.5˚)	(112.6˚-157.5˚)	(157.6˚-202.5˚)	(202.6˚-247.5˚)	(247.6˚-292.5˚)	(292.6˚-337.5˚)
<0.10	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.10-0.19	0.968	0.942	0.972	0.982	0.961	0.965	0.988	0.985
0.20-0.29	0.943	0.894	0.949	0.968	0.933	0.934	0.977	0.972
0.30-0.39	0.924	0.855	0.931	0.957	0.912	0.907	0.968	0.961
0.40-0.49	0.911	0.824	0.917	0.950	0.898	0.884	0.960	0.953
0.50-0.59	0.899	0.798	0.905	0.944	0.887	0.865	0.954	0.945
0.60-0.69	0.890	0.777	0.895	0.939	0.880	0.849	0.948	0.939
0.70-0.79	0.883	0.762	0.887	0.936	0.875	0.837	0.943	0.934
0.80-0.89	0.877	0.750	0.881	0.933	0.872	0.827	0.939	0.930
0.90-0.99	0.871	0.739	0.875	0.930	0.868	0.819	0.935	0.926
≥1	0.865	0.731	0.870	0.927	0.865	0.812	0.932	0.922

Table 29: External Shading Factor for Side Fin-Left (ESFleft) for LAT ≥ 23.5˚N. (Bureau of Energy Efficiency, Eco-Niwas Samhita 2018, (Energy Conservation Building Code for Residential Buildings), PART I: BUILDING ENVELOPE, 2018)

	External Shading Factor for Side Fin-Left (ESFleft) for LAT ≥ 23.5˚N							
Orientation	North	North-east	East	South-east	South	South-west	West	North-west
PF_{left}	(337.6˚-22.5˚)	(22.6˚-67.5˚)	(67.6˚-112.5˚)	(112.6˚-157.5˚)	(157.6˚-202.5˚)	(202.6˚-247.5˚)	(247.6˚-292.5˚)	(292.6˚-337.5˚)
<0.10	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.10-0.19	0.968	0.985	0.988	0.965	0.961	0.982	0.972	0.942
0.20-0.29	0.943	0.972	0.977	0.933	0.932	0.967	0.949	0.895
0.30-0.39	0.925	0.961	0.968	0.906	0.911	0.957	0.931	0.857
0.40-0.49	0.912	0.953	0.961	0.883	0.897	0.949	0.916	0.826
0.50-0.59	0.900	0.946	0.954	0.863	0.886	0.943	0.904	0.801
0.60-0.69	0.890	0.939	0.948	0.846	0.879	0.938	0.895	0.781
0.70-0.79	0.884	0.935	0.944	0.834	0.874	0.935	0.887	0.766
0.80-0.89	0.877	0.931	0.940	0.824	0.871	0.932	0.881	0.754
0.90-0.99	0.871	0.927	0.936	0.815	0.867	0.929	0.875	0.744
≥1	0.866	0.923	0.932	0.808	0.864	0.927	0.870	0.736

Annex 3

Table 30: Minimum Threshold of WFR_{op} for Each Climate Zone

Climatic Zone	Minimum WFR_{op} (%)
Warm Temperate*	16.66
Temperate	12.50
Cool Temperate	8.33
Cold climate	6.25

Source: Kathmandu valley Bye-laws 2064
NBC:206, 2024

Table 31: Minimum Threshold of GFR for Each Climate Zone

Climatic Zone	Minimum GFR_{op} (%)
All Climate Zone (Warm temperate, Temperate, Cool Temperate and Cold)	16.5

Source: Kathmandu valley Bye-laws 2064
NBC:206, 2024

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