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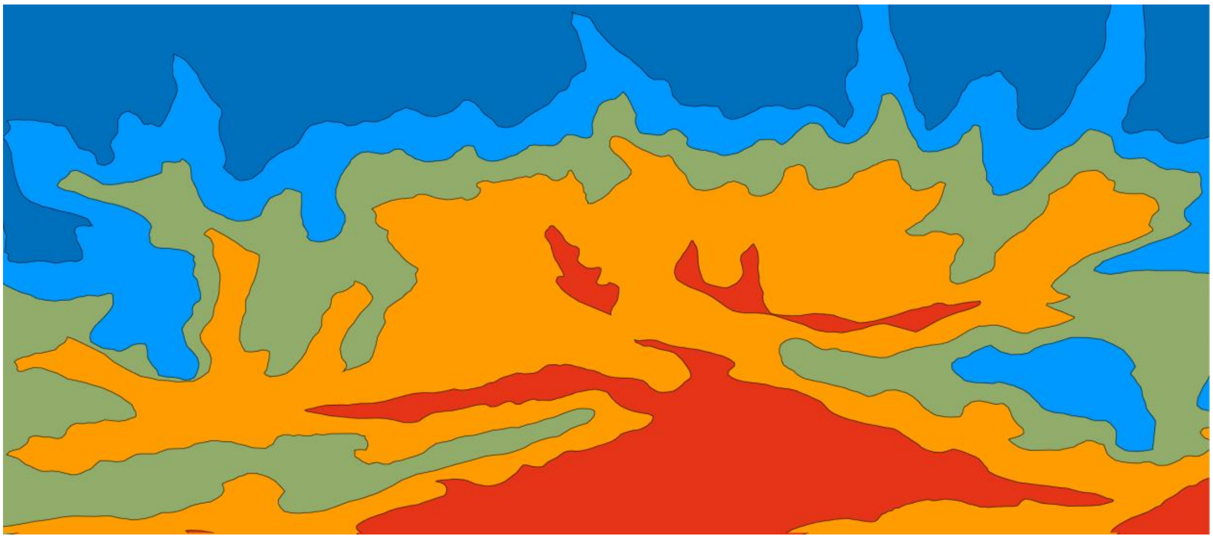

Dissertation

Climate responsive building design for low-carbon development in Nepal

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TECHNISCHE UNIVERSITÄT MÜNCHEN

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Abstract

With the uprising awareness for climate change and environmental protection, climate responsive building design is recognised to be a key factor for a sustainable and secure global energy future. Although the developed world has done some progress to implement innovative strategies to reduce the energy demand of buildings, developing countries are only starting to tap into saving potentials. In the future, energy demand will increase in developing countries because of population growth, fast urbanisation and increasing welfare. Energy will be consumed more and more by buildings in the fast growing urban centres. Like other developing countries, Nepal's weak energy supply system cannot fulfil the growing demand, which, consequently, leads to regular power cuts and supply shortages. This has an adverse impact on daily life and economic growth. The lack of awareness and regulations on energy efficiency is worsening the energy demand-supply gap. On the other hand, the knowledge about effective measures to reduce building energy consumption through climate-responsive design and efficient technologies is low. The aim of this PhD research is to fill this knowledge gap by providing recommendations for transforming the buildings sector of Nepal towards more energy efficiency. This study lays important groundwork for developing standards and regulations on energy efficiency in buildings for Nepal by focusing on three essential areas: 1. Vernacular knowledge, 2. Climate and design, 3. Energy-efficient design.

The results of this research show that vernacular architecture of Nepal is very well adapted to the local climate. Traditional houses within the same climate zone have similar passive design features that should be also applied to modern buildings in order to reduce the energy demand for heating and cooling. The climatic diversity within the Nepalese territory led to the development of a bioclimatic zoning which is an essential prerequisite for the introduction of a building energy conservation code. Using the bioclimatic approach, five elevation-based bioclimatic zones were identified. A simulation-based study on energy saving potentials through passive design in hotel buildings quantified energy and cost savings. Average energy savings of 37% can be reached by optimising design features like window-to-wall ratio, orientation, shading and thermal mass. Increasing insulation of the exterior building envelope up to a cost-effective level can result into energy savings between 26% and 50% depending on the climate zone. The results of the simulation study also led to the development of a catalogue of important passive design strategies and optimum insulation levels for each bioclimatic zone. Finally, the energy efficiency scenario for the residential sector in Nepal estimates a reduction in energy demand growth for space conditioning by 23% until 2040. This has shown that the consideration of climate-responsive design and energy efficiency can slow down the energy demand growth of the fast growing building sector. Concluding, a wide catalogues of suitable policy strategies is proposed to foster energy efficiency in buildings in Nepal that will ensure a resource-efficient and sustainable development path for the country.

Zusammenfassung

Die Folgen des Klimawandels und steigendes Umweltbewusstsein haben dazu geführt, dass Energieeffizienz und klimagerechtes Bauen als Schlüsselfaktor für eine nachhaltige globale Energiezukunft gesehen werden. Obwohl die Industrieländer schon einige Fortschritte in der Umsetzung innovativer Strategien zur Reduzierung des Gebäudeenergiebedarfs gemacht haben, beginnen die Entwicklungsländer erst langsam solche Einsparpotenziale zu erschließen. Der globale Energiebedarf wird aufgrund des Bevölkerungswachstums, der stetigen Urbanisierung und des zunehmenden Wohlstandes vor allen in Entwicklungsländern steigen. Energie wird dabei mehr und mehr von Gebäuden in den schnell wachsenden urbanen Zentren verbraucht. Wie andere Entwicklungsländer, kann Nepals schwache Energieversorgung die wachsende Nachfrage nicht erfüllen, was zu regelmäßigen Stromausfällen und Energielieferengpässen führt. Dies hat einen negativen Einfluss auf das tägliche Leben und das Wirtschaftswachstum. Das Fehlen von Bestimmungen und Standards für Energieeffizienz und das mangelnde Bewusstsein für diese Fragen werden langfristig die Versorgungslücke verschlechtern. Auf der anderen Seite, ist die Wissensbasis über wirksame Maßnahmen zu Reduzierung des Gebäudeenergieverbrauchs durch klimagerechtes Bauen und effiziente Technologien sehr gering. Das Ziel dieser Doktorarbeit ist es, mit der Entwicklung von technischen und regulativen Empfehlungen diese Wissenslücke zu füllen. Mit dem Fokus auf traditionellem Wissen, Klimazonierung und energieeffizientem Gebäudedesign legt diese Forschungsarbeit wichtige Grundlagen für die Entwicklung von Standards und Vorschriften zur Energieeffizienz in Gebäuden im Kontext des Entwicklungslandes Nepal.

Die Ergebnisse dieser Forschung zeigen, dass die traditionellen Bauweisen in Nepal sehr gut an das lokale Klima angepasst sind. Traditionelle Häuser in der gleichen Klimazone verwenden ähnliche passive Designkonzepte, die auf moderne Gebäude übertragen werden könnten, um deren Energiebedarf für Raumklimatisierung zu senken. Die klimatische Vielfalt innerhalb des Landes erforderte die Entwicklung einer bioklimatischen Zonierung für das Bauen, die zur Einführung einer Energieeinsparbauverordnung unbedingt notwendig ist. Mit Hilfe des bioklimatischen Ansatzes und der anschließenden Validierung durch thermische Gebäudesimulation, wurden fünf Klimazonen nach topografischer Höhe vorgeschlagen. Eine simulationsbasierte Studie zur Energieeffizienz in Hotelgebäuden ergab erhebliche Energie- und Kosteneinsparpotenziale. Durch die Optimierung des Fensterflächenanteils, der Ausrichtung, Verschattung und thermischen Masse können durchschnittlich 37% der Heiz- und Kühlenergie gespart werden. Kosteneffektive Dämmmaßnahmen führen abhängig von der Klimazone zu Energieeinsparungen zwischen 26% und 50%. Die Ergebnisse der Simulationsstudie geben auch Aufschluss über die wichtigsten passiven Maßnahmen und die optimalen Dämmwerte für jede Klimazone. Des Weiteren wurden Energieeffizienz-Szenarien für den Wohngebäudesektor entwickelt. Die Umsetzung von Energieeffizienzmaßnahmen könnten den steigenden Energieverbrauch für die Raumklimatisierung in 2040 um 23%

senken. Somit wurde aufgezeigt, dass die Verbesserung der Gebäudeeffizienz das Wachstum des Energiebedarfs in Nepal verlangsamen kann. Zum Abschluss wurde ein breiter Katalog von geeigneten Politikstrategien diskutiert und es wurden regulative Maßnahmen zur Förderung der Energieeffizienz in Gebäuden erarbeitet. Deren Umsetzung kann einen wesentlichen Beitrag zur ressourceneffizienten und nachhaltigen Entwicklung des Landes leisten.

Table of contents

List of figures

List of tables

Acronyms

a	Anually
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CDD	Cooling degree days
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH
GWh	Gigawatthour
HDD	Heating degree days
HDI	Human development index
HVAC	Heating, ventilation and air conditioning
IEA	International Energy Agency
IFC	International Finance Corporation
kg	Kilogram
km	Kilometer
kWh	Kilowatthours
LCC	Life-cycle cost
LCCA	Life-cycle cost analysis
LPG	Liquefied petroleum gas
m	Metre
m^2	Square metre
masl	Metres above sea level
Mio	Million
mm	Millimetre
NGO	Non-governmental organisation
PF	Projection factor
SHGC	Solar heat gain coefficient
toe	Tons of oil equivalent
TWh	Terrawatthour
TMY	Typical meteorological year
yr	Year
UN-Habitat	United Nations Human Settlements Programme
UNDP	United Nations Development Programme
UNEP	United Nations Environmental Programme
USD	US-Dollar
W/m^2K	Watt per square metre per degree Kelvin
WWR	Window-to-wall ratio

Chapter 1

Introduction

1.1 Background and problem statement

Buildings are responsible for over one third of final energy consumption worldwide and are an equally important source of carbon emissions [1]. New inefficient buildings being built today will be in operation and will continue to consume energy for the next decades. In the business-as-usual scenario, energy consumption in buildings will increase by 50% in 2050 compared to 2010 [2]. Consequently, total carbon emissions will more than double and the average global temperature is projected to rise by at least 6°C worsening the adverse effects of climate change [2]. Most of the added demand is coming from developing countries due to the growth of population, rapid urbanisation and rising living standards.

There is a widespread agreement that access to reliable and affordable energy sources is fundamental for economic development [2–4]. However, the development model of the industrialised countries, which is based on cheap fossil fuels and environmental degradation,

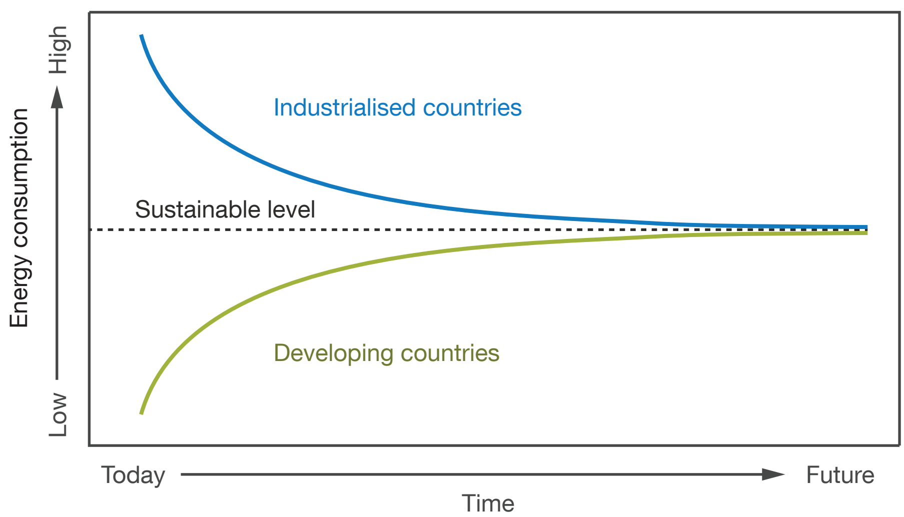


Figure 1.1: Sustainable development model of contraction and convergence (adapted from [3])

cannot ensure a sustainable future for further generations. The most important strategy for sustainable development is to decouple quality of life from consumption of natural resources and carbon emissions [3]. Developing countries should switch to the low-carbon development path while the industrialised countries have to reduce their resource and energy consumption (Figure 1.1).

The energy consumption of buildings can be significantly reduced through climate-responsive building design and energy efficiency. Building energy regulations and standards can play a vital role to reduce the energy use in buildings [5]. By setting minimum requirements, they enhance energy efficiency and contribute to a more sustainable construction sector. However, it is essential to understand the local context in order to find the most effective measures to transform the sector towards higher energy efficiency and, thus, sustainability.

Almost all developed countries' governments have introduced standards and regulations to enhance energy efficiency in buildings. More and more developing countries are currently introducing such legislation [6]. Unlike other Asian countries, Nepal has not developed standards or regulations regarding energy efficiency in buildings. Beside few small NGO initiated activities, the awareness about energy efficiency in general and particularly for buildings among policy makers and all stakeholders of the construction sector is low. Academic institutions have so far conducted little research on this topic. Consequently, there is a lack of well-documented information about effective measures to drive the sector towards higher energy efficiency.

Beside few studies on climate-responsive design for individual buildings in specific locations, no data about passive and active strategies to reduce energy consumption in buildings in Nepal is available. Due to the geographic and climatic diversity of the country, there is the need to conduct a comprehensive study to identify regions with similar climate design strategies. Furthermore, those strategies have to be evaluated in regards to its importance and cost-effectiveness in order to develop effective building energy regulations and policy measures.

1.2 Research objectives

Due to the fact that the state of research about climate-responsive building design and energy efficiency in Nepal is at the starting point, this doctoral thesis is going to lay some groundwork in this field. Therefore, a rather horizontal approach was used investigating few selected important aspects. The overall objective of this study was to develop recommendations for transforming the building sector towards higher energy efficiency.

Thus, this PhD research is focusing on three main areas:

1. Following the principles *Learning from past experiences*, the study aims to investigate the passive design concepts used by vernacular architecture in Nepal.

2. The development of a bioclimatic zoning presents a required basis for building energy conservation policies because of the climatic diversity within Nepal.

3. Finally, it is envisaged to analyse the effectiveness of passive design measures for each climate zone and estimate energy saving potentials.

The main hypothesis of the research states:

The consideration of climate-responsive design and energy efficiency strategies can slow down the energy demand growth of Nepal's fast growing building sector.

The hypothesis asserts that energy efficiency measures can achieve considerable energy savings in buildings. Consequently, building energy regulation and energy conservation measures can contribute to a resource-efficient and low-carbon development path for the country to embark on.

1.3 Methodology

In order to achieve the objectives, this research was designed as illustrated in Figure 1.2. Analysing the Nepalese building sector concerning energy efficiency was required to identify the gaps and develop adequate strategies. Three focus areas were identified as crucial to develop recommendations for driving the building sector towards more energy conservation:

1. Learning from the past,

2. Climate and design, and

3. Energy-efficient design.

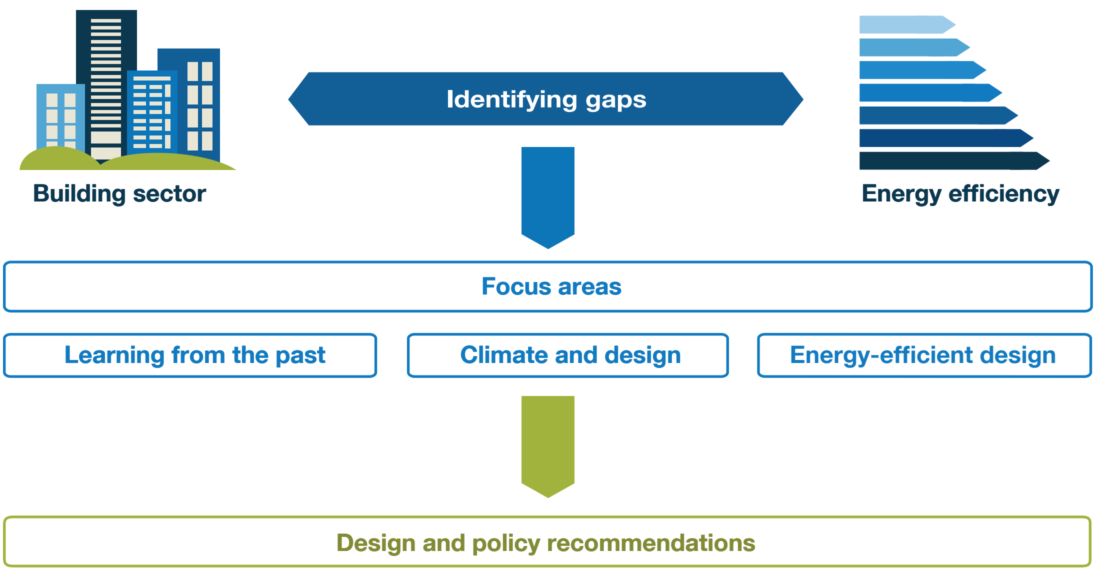


Figure 1.2: Research design

Figure 1.3 illustrates problem statement, methods, scope and contribution of each focus area. Although each focus area stands independently, a systematic learning effect was induced. Investigating on vernacular architecture led to a large catalogue of passive design measures for each climate. The geographic diversity of the country required a comprehensive study of the climate conditions and its implications for passive design resulting in the development of bioclimatic zoning for Nepal. The hotel sector was selected to investigate the effectiveness of the design measures and quantify energy saving potentials for heating and cooling. As a result, a catalogue of priority design strategies and cost-effective insulation measures were developed for each bioclimatic zone.

Finally, the synthesis of the outcomes from the three focus areas led to the comprehensive understanding of building design and energy efficiency in the context of Nepal. As a result, design recommendations and policy actions are suggested to ensure the low-carbon development for the building sector.

1.4 Structure of the thesis

The thesis is organised into four chapters as follows. This chapter, *Chapter 1 - Introduction* provides the background of the research, the problem statement, objectives, research design and framework, and the structure of the thesis report.

	I. Learning from the past	II. Climate and design	III. Energy-efficient design
Research problem	Climate-responsive design strategies of traditional buildings are unknown.	Nepal has a large diversity of climate conditions. The effective passive design strategies for the different climates are not identified.	Quantitative evaluation of passive design strategies and insulation measures to reduce building energy demand.
Methods	Field research, literature review	Climate data analysis, climate maps, bioclimatic approach	Field research, building energy simulation, regression analysis, life cycle cost analysis
Scope	Vernacular buildings	Whole building sector	Hotel building sector
Contribution	Identification of passive design strategies of vernacular architecture in Nepal	Development of bioclimatic zoning for Nepal and corresponding passive solar strategies	Priority passive design strategies and cost-effective insulation measures for hotel design in all bioclimatic zones

Figure 1.3: Research framework

Chapter 2 - Results presents the findings of the three focus areas of this cumulative dissertation. The first sub-chapter titled *Learning from the past* contains the study on vernacular architecture of Nepal and how it follows climate-responsive design strategies (published in [7]). The second sub-chapter *Climate and design* reveals the first proposal for a bioclimatic zoning (published in [8]). The results of a quantitative analysis for energy saving potentials in one building sub-sector lead to passive design strategies for each climate zone that are summarised in the third sub-chapter *Energy-efficient design* (published in [9]).

In *Chapter 3 - Design and policy recommendations* the findings of chapter 2 are brought together leading to a comprehensive catalogue of climate-responsive design strategies for the different bioclimatic zones of Nepal. The bioclimatic zoning for Nepal is further developed considering the results of the building simulation study. Furthermore, policy implications are discussed in detail and required interventions are suggested.

Chapter 4 - Building energy conservation for low-carbon development highlights the importance of the key findings of this PhD research to ensure a sustainable development path for Nepal. Scenarios for the whole building sector estimate considerable energy saving potentials during the next decades if proper policy strategies are implemented.

Chapter 2

Results

2.1 Learning from the past

Traditional building design is the result of hundreds of years of building optimisation through trial and errors. Due to the absence of mechanical means, natural sources like the sun and the wind and locally available materials are used for the buildings to create the most comfortable indoor climate [10–13]. Passive techniques applied in vernacular houses are often very effective in the local climatic context and do not rely on energy-intensive and expensive active systems.

Through the modernisation of the construction sector, traditional knowledge of climate-responsive building construction is disappearing slowly. In many regions of the world, vernacular houses have been analysed thoroughly to understand the passive design techniques [13–16]. In Nepal, there is a lack of proper documentation and analysis of this

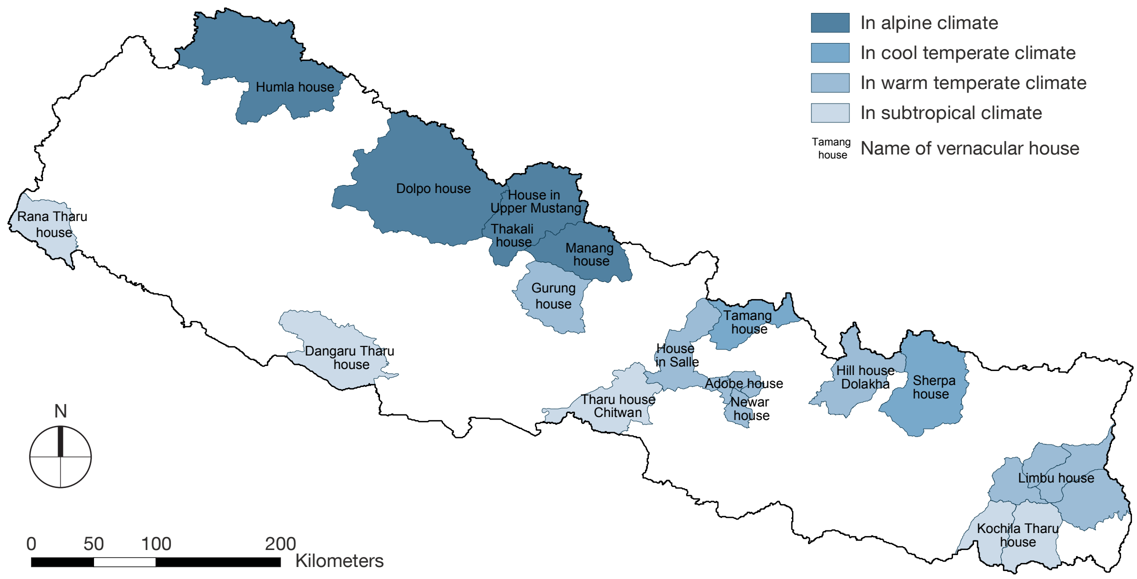


Figure 2.1: Nepal map with the location of analysed vernacular houses

traditional knowledge of climate-smart building design which can be helpful in developing cost-effective low-energy design strategies for the fast growing construction sector.

Following the principle of “Learning from the past”, a crucial and comprehensive study analysing the design of vernacular buildings in different climate zones of Nepal was first conducted for this PhD research (published in [7], see also appendix *Publication I* on page 83).

Using the bioclimatic approach of [10] and the Mahoney table of [11] climate design strategies for the four predominant climates were identified (Figure 2.2). In the following, nineteen different traditional houses from all over Nepal were analysed regarding the identified design strategies (Figure 2.1).

The comparison of all traditional houses in the same climate zone shows clearly that they have similar design features. Table 2.1 summarises the characteristics of all vernacular houses by zone and shows that the climatic context is generally considered.

It can be seen that settlement density increases in colder climate zones. In Nepal’s subtropical climate, traditional houses are arranged in a rather loose and scattered pattern to enhance natural ventilation. However, in the cooler climates, villages and towns have a moderate building density. Houses in the cool temperate and alpine climate are attached to each other creating a system of small alleys and courtyards to protect from the harsh climate condition.

The building form of vernacular houses in the warmer climates of Nepal is rather elongated, while in colder climate, houses are more compact. Elongated floor plans with the long axis from east to west reduce the solar gains into the building and enhance the possibility of natural

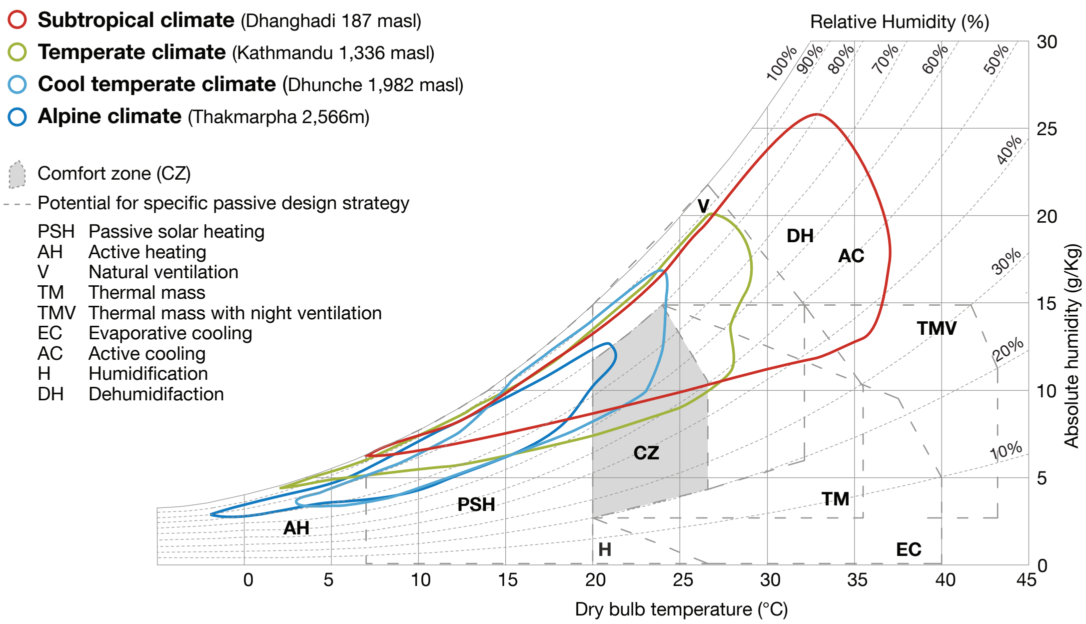


Figure 2.2: Bioclimatic chart for the four predominant climate zones of Nepal: the perimeter was plotted based on monthly minimum and maximum mean outdoor air temperature and relative humidity (adapted from [7])

Table 2.1: Characteristics of vernacular houses by climatie zone (adopted from [7])

	Subtropical climate	Warm temperate climate	Cool temperate climate	Alpine climate
Settlement pattern	loose, scattered	moderate dense	rather compact, attached houses	compact
Building form	elongated	rectangular elongated, courtyard, round shape	compact to rectangular layout	rectangular to square floor plan, attached houses
Building orientation	long axis east-west	longer façade south, south-east of south-west	longer/main façade south-wards facing	facing south
Stories	1-2	1.5-3.5	2	2-3
Internal space arrangement	horizontally with no or few divisions	vertically or horizontally	vertically, elevated ground floor for thermal buffer	vertically and horizontally, creating buffer zones to the exterior
Semi-open spaces	veranda, open courtyard	closed and shaded veranda or balcony	veranda and balcony	courtyard, roof terrace
Wall material	wattle-and-daub, straw and bamboo plastered with mud	plastered stonework, mud-brick, burned clay brick and/or mud-covered timber	unplastered or plastered stonework	stone, mud, sun-dried bricks
Wall thickness	thin	28-70 cm	40-100 cm	40-50 cm
Roof material	thatch, bamboo	stone slates, thatch, burned clay bricks	stone or wood slates	mud layers over wood
Roof type	pitched or hipped roof	gable, pitched or saddleback roof	pitched roof	flat
Roof overhang	wide	wide		maximum 50cm
Foundation	slightly raised stone plinth	stone plinth	built into the slope	stone
Floor	compacted earth with mud layer	compacted earth with mud layer	wooden lathwork, eventually covered by carpet	mud covered, timber
Ceiling	high	low, wooden structure with lathwork and mud layer	low, double wooden ceiling	low, timber beam and pillar structure
Openings	few and small openings but thin walls are made of loose material to enhance air flow	medium sized openings	small openings with shutters	very small to small

Table 2.2: Passive design strategies of vernacular houses in subtropical climate zone (adapted from [7])

Recommended passive design strategy for subtropical climate zone	
Natural ventilation essential	✓
Elongated layout with long axis east-west	(✓)
High thermal mass for hot and dry season	–
Low thermal mass for hot and humid season	✓
Light well insulated roof	✓
Medium sized openings	(✓)
Shading of openings	✓
Passive solar heating	–
Rain protection	✓
Legend: ✓applied, (✓) partially applied, – not applied	

ventilation. These both passive design strategies are needed in this climate to keep the indoor at a comfortable level. In the colder climate zones of the country, the building form is more compact often with an almost square floor layout to reduce the surface of the exterior envelope and, thus, the heat loss.

In subtropical climate, internal spaces are arranged horizontally. The floor plan has no or very few internal division walls to enhance air flow within the buildings. In contrast, in Nepal's colder climate zones internal space arrangement is vertical to create buffer zones towards the exterior and protect from the cold weather conditions. The main living area in traditional houses in the coldest climate is located in the centre of the second floor enclosed by rooms of secondary use. Animals are housed in the ground floor and storage rooms are located in the third floor, creating an effective buffer zone.

Thermal mass of traditional houses increases the colder the climate conditions are. In subtropical climate, buildings have walls and roofs made of lightweight material leading to

Table 2.3: Passive design strategies of vernacular houses in warm temperate climate zone (adapted from [7])

Recommended passive design strategy for warm temperate climate	
Natural ventilation diserable	✓
Elongated layout with long axis east-west	(✓)
High thermal mass for passive heating and cooling	✓
Light well insulated roof	(✓)
Medium sized openings	✓
Shading of openings	✓
Passive solar heating	✓
Protection from the cold	(✓)
Rain protection	✓
Legend: ✓applied, (✓) partially applied, – not applied	

Table 2.4: Passive design strategies of vernacular houses in cool temperate climate zone (adapted from [7])

Recommended passive design strategy in cool temperate climate	
Passive solar heating	(✓)
Protection from the cold	✓
Compact settlement and building layout	✓
Natural ventilation diserable	(✓)
High thermal mass for passive heating and cooling	✓
Light well insulated roof	(✓)
Medium sized openings	✓
Rain protection	✓
Legend: ✓applied, (✓) partially applied, – not applied	

low thermal building mass as recommended for hot and humid climates. In the other climate zones, buildings have a medium to high thermal mass using materials like natural stone, mud and clay bricks.

Although window and door openings in vernacular houses in subtropical climates are rather small, the permeable wall material allows the air to flow through the building envelope. Window openings in warm temperate climate are of medium size as compared to small openings in the colder climate zones. While medium sized windows can be effectively used for natural ventilation in the hot season, small openings are better as they reduce heat loss under cold conditions. Additional shutters applied in vernacular houses in the colder climate zones, increase the tightness and insulation level of the envelope.

Shading is very important in hot climates. Therefore, openings in the envelope are shaded by a large roof overhang of a balcony or veranda in subtropical and warm temperate climate. Often, shaded semi-open spaces are provided by the building layout. In contrast, windows in colder climate regions of Nepal have shutters and sunny semi-open spaces are provided in form of a roof top terrace or a wind-protected small courtyards.

Concluding the analysis of vernacular architecture in different climate regions of Nepal, it can be said that most of the passive design strategies are applied (Table 2.2, Table 2.3,

Table 2.5: Passive design strategies of vernacular houses in alpine climate zone (adapted from [7])

Recommended passive design strategy in alpine climate	
Passive solar heating	–
Protection from the cold	✓
Compact settlement and building layout	✓
High thermal mass for passive heating	✓
Small openings	✓
Legend: ✓applied, (✓) partially applied, – not applied	

Table 2.4, Table 2.5). The identified strategies for each climate zone can be used to design modern climate-responsive buildings with low energy demand for active cooling and heating. However, it is clear that even if a new building is designed accordingly, new lifestyles and increased thermal comfort requirements might lead to the need of mechanical systems or the need of modern low-energy building technologies like the application of better insulation materials or double glazing windows.

2.2 Climate and design

Bioclimatic or climate-responsive building design is one of the major drivers to reduce energy consumption and, thus, carbon emissions from the building sector [17]. Although buildings in developing countries like Nepal are not yet as energy-intensive as in the developed world, increasing thermal comfort requirements and changing lifestyles combined with population growth and rapid urbanisation will lead to an increased energy demand in the building sector.

Low energy consumption in buildings can only be achieved if the local climate conditions are considered during the early stage of the design. Therefore, many countries with large climatic diversity have developed a bioclimatic zoning for building construction which is necessary to introduce energy conservation standards and building energy codes [18–25]. Nepal has not yet developed any bioclimatic zoning nor has it established any standard with regards to building energy conservation. The National Building Code is mainly concerned about structural and earthquake safe design [26].

The lack of a climate classification for the building construction sector was identified as a major gap towards more energy efficiency in buildings in Nepal. Therefore, a study analysing the climate of Nepal was conducted with the objective to develop a bioclimatic zoning for Nepal. Using the bioclimatic approach, this study is an important part of the PhD research (published in [8], see also appendix *Publication II* on page 101).

Climate data being the most important input of this study has to be carefully chosen. A typical meteorological year (TMY) is often used in climate-responsive building design for analysing design strategies and conducting building energy simulation. The TMY is generated based on weather observations over a longer period (at least 20 years) by the national meteorological institutions of a country. The lack of TMY data sets for Nepal made it necessary to generate such data sets by using the software tool Meteonorm [27]. Monthly climate normals (temperature, precipitation) from 26 weather stations, either directly collected from Department of Hydrology and Meteorology Nepal [28] or derived from United Nation's Food and Agriculture Organisation climate database [29], were imported into the software to achieve more accurate results.

The comparison of the generated data sets with measured climate observations is needed to check the plausibility of data. Therefore, weather observations (temperature and relative humidity) from recently installed automated weather stations were analysed and compared with the TMY data set. Figure 2.3 and Figure 2.4 illustrate the exemplary comparison for the location Pokhara. The density of the data points for 2013, 2014 and 2015 is lower than for the generated TMY data set because the weather station only records observations five times a day. Nevertheless, it can be seen that both daily averages and hourly values are in a similar range (see also appendix *Comparison of climate data sets* on page 143). Consequently, the generated TMY data sets are used for the following analysis.

The climate data was plotted on the bioclimatic chart of [10] with the objective to identify locations with similar passive design strategies. In this chart the comfort zone is defined

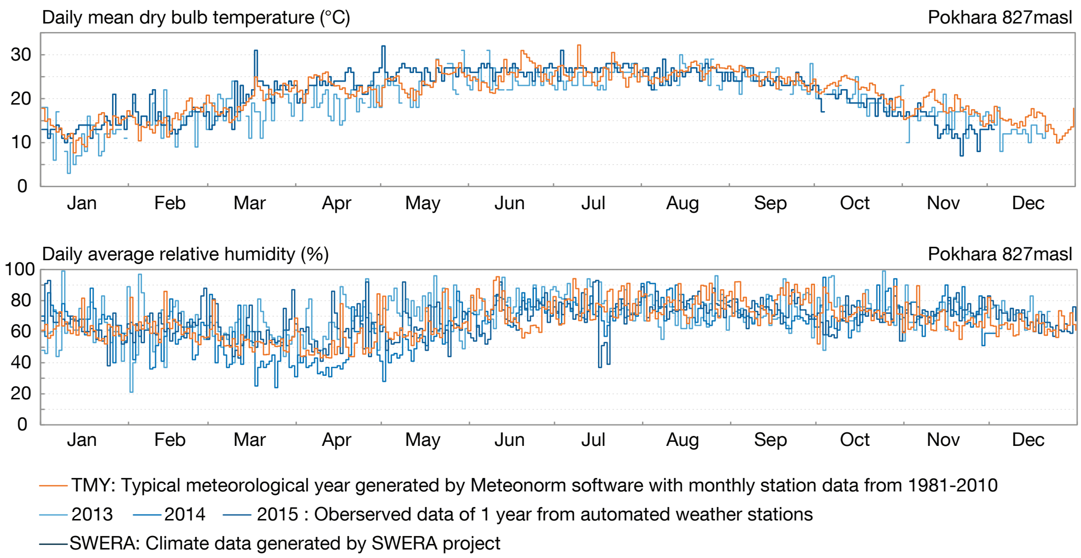


Figure 2.3: Comparison of daily climate data from Pokhara (Data sources: [27–30])

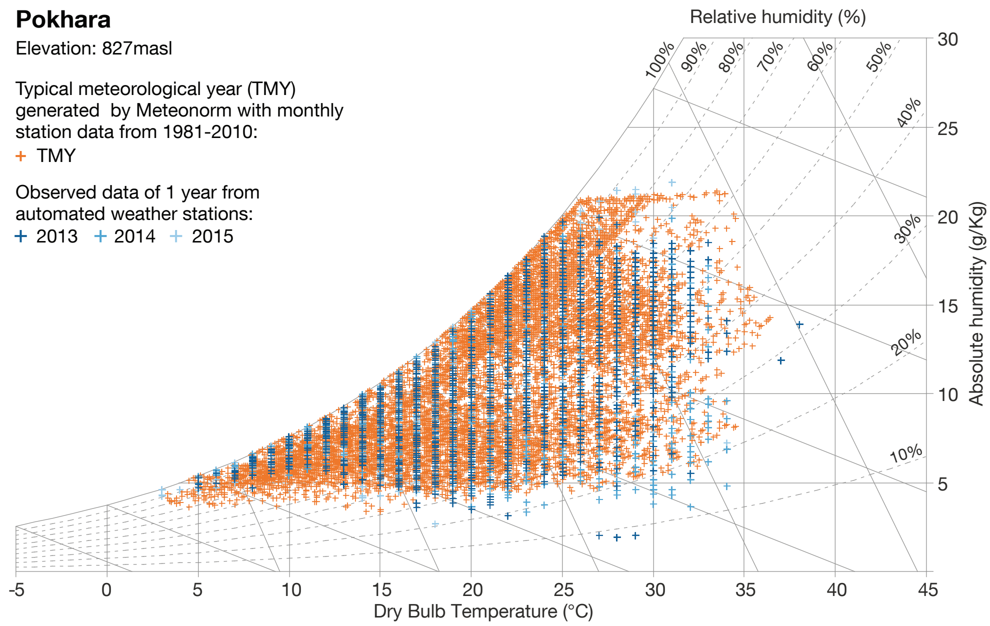


Figure 2.4: Comparison of hourly climate data from Pokhara (Data sources: [27–30])

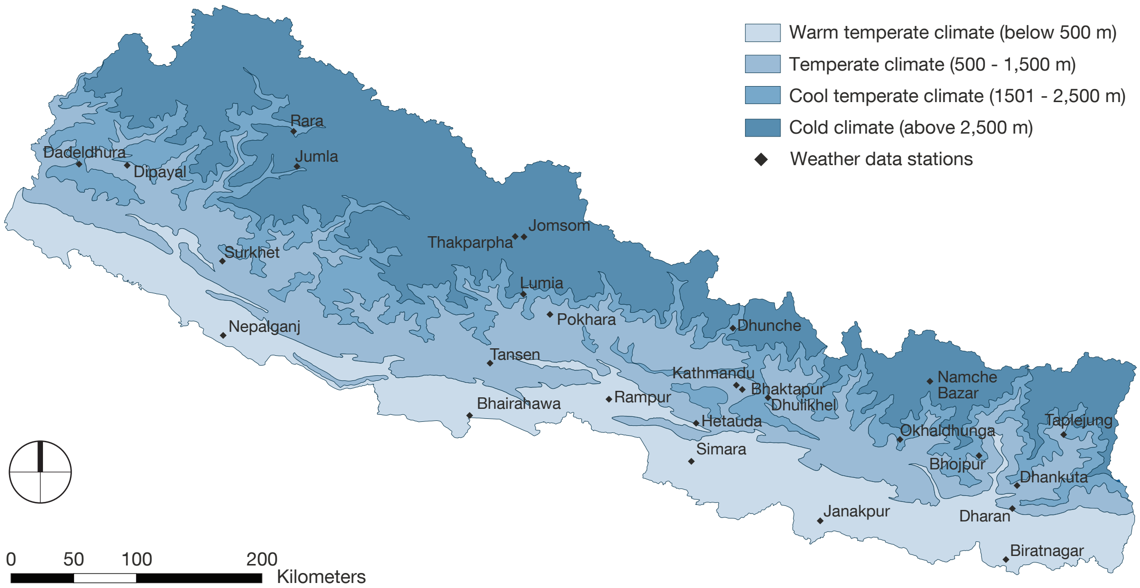


Figure 2.5: First proposal of bioclimatic zoning for Nepal (adopted from [8]

at temperatures between 18°C and 29°C and at an absolute humidity between 4 g/kg and 17 g/kg according to the recommendation for developing countries [31]. The zones for passive design strategies are defined by [32] for warm and humid climate (see also [8]). The analysis of the climate data identified elevation as the main factor for climate design. Therefore, a classification by elevation with a total of four bioclimatic zones was suggested (Figure 2.5).

Figure 2.7, Figure 2.8, Figure 2.9 and Figure 2.10 show the bioclimatic charts for the four proposed climate zones. Each line on these charts was derived from the monthly minimum and maximum mean outdoor temperature and relative humidity of all the weather stations in one zone. Hourly temperature and humidity levels in one month move around this line. While the blue lines represent the climate conditions during the winter months, the red lines stand for the summer (monsoon period). The green lines show the conditions in pre- and post-monsoon. Additionally, a blue, red and green perimeter line (cloud) was added representing the area of hourly temperature and humidity values for each season.

According to the analysis of the bioclimatic charts, the temperate zone has the most comfortable climate as the majority of line segments fall within the comfort zone. While heat stress is the most important concern in warm temperate climate, cold stress is dominant in the cold climate zone of the country. Natural ventilation, high thermal mass for cooling and passive solar heating are the three predominant passive design strategies. Depending on the season and the climate zone, it is recommended to apply one or more of these strategies (Figure 2.6).

In warm temperate climate zone (above 500 masl) passive solar heating strategy can avoid the use of active heating completely. However, some active cooling might be necessary in the hot and humid monsoon season. Thermal mass for cooling is useful for the hot and dry weather in spring and autumn.

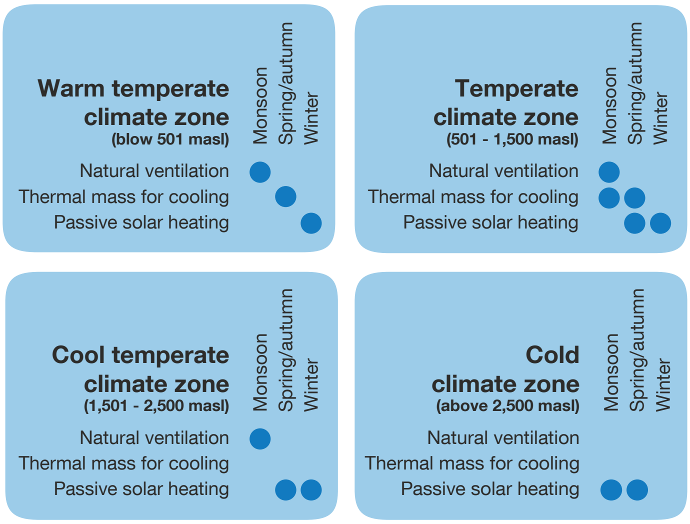


Figure 2.6: Predominant passive design strategies for proposed bioclimatic zones by season (adapted from [8]

In temperate climate zone (501 - 1,500 masl) cooling is not required if the building has a high thermal mass and is optimised for natural ventilation cooling. Passive solar heating can keep indoor temperature at a comfortable level in spring and autumn and has the potential to reduce active heating in winter to almost zero.

Buildings in cool temperate zone (1,501 - 2,500 masl) should be designed to enhance natural ventilation during the monsoon season. Passive solar heating is essential for spring and autumn and can considerably reduce the need of active heating in winter. However, some mechanical heating might always be required in winter.

Due to the low summer temperature, natural ventilation for cooling is not necessary in Nepal's cold climate (above 2,500 masl). However, passive solar heating is recommended and useful throughout the year. It can replace the need of active heating in summer and reduce it during the other seasons of the year.

The development of a bioclimatic zoning based on climate data has its limitations especially in composite climates like Nepal. Therefore, the effectiveness of conflicting design strategies can be only evaluated using thermal building simulation. Thus, the bioclimatic zoning was further adjusted (see section *Adaption of bioclimatic zoning for Nepal* on page 25).

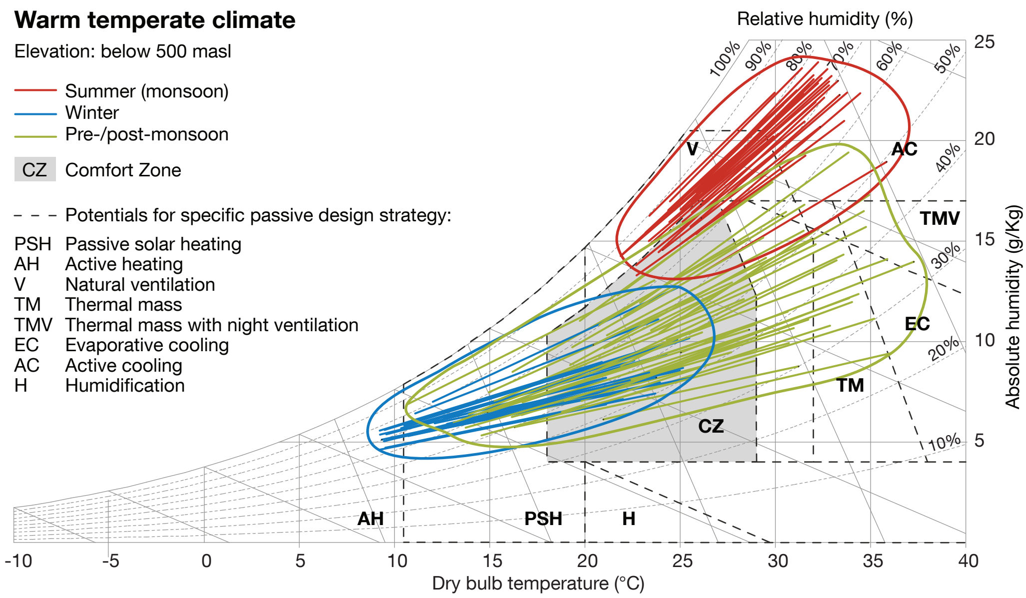


Figure 2.7: Bioclimatic chart for warm temperate climate zone (adopted from [8]

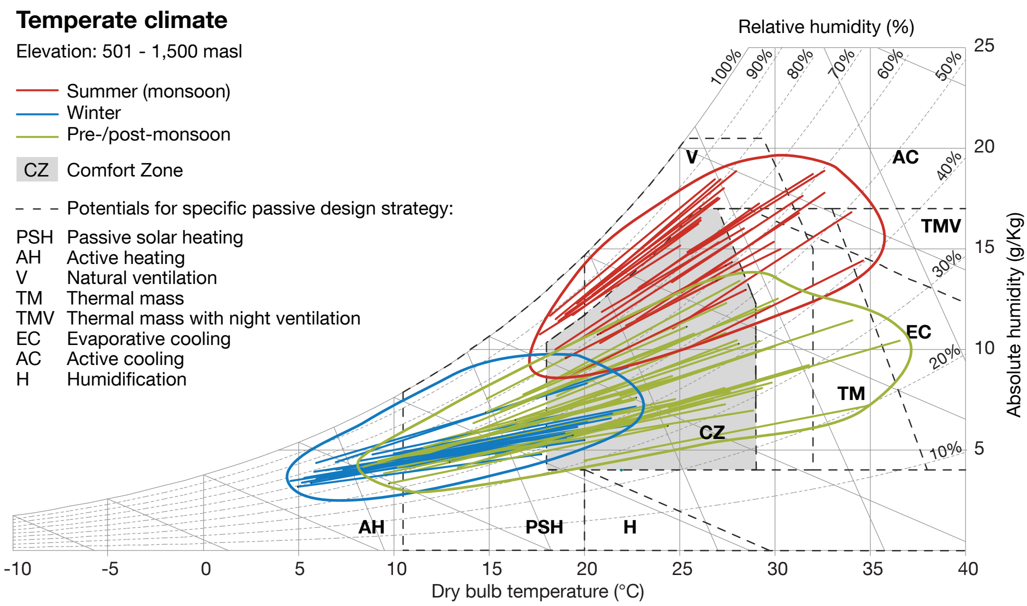


Figure 2.8: Bioclimatic chart for temperate climate zone (adopted from [8]

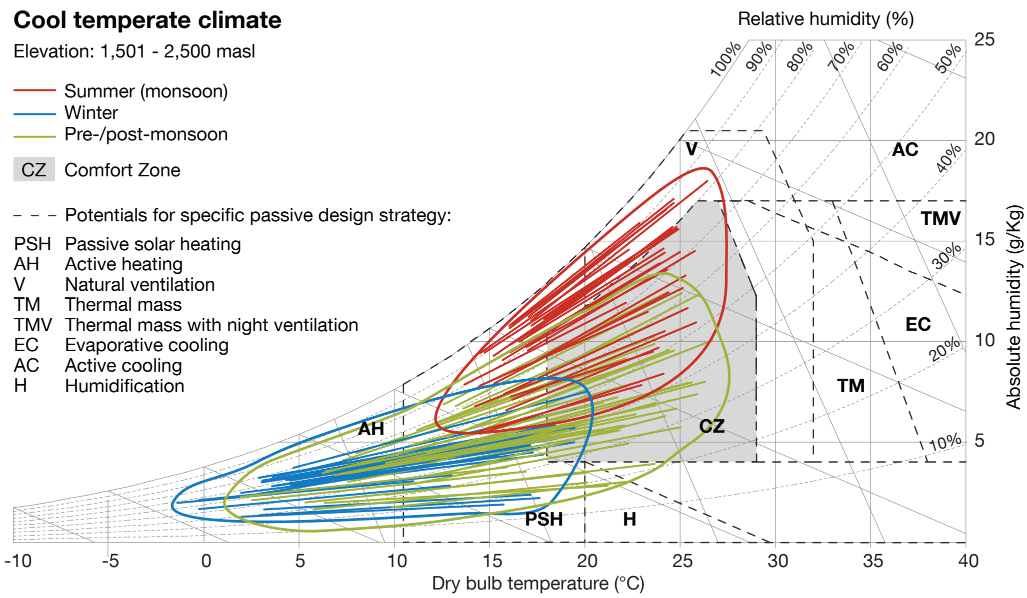


Figure 2.9: Bioclimatic chart for cool temperate climate zone (adopted from [8])

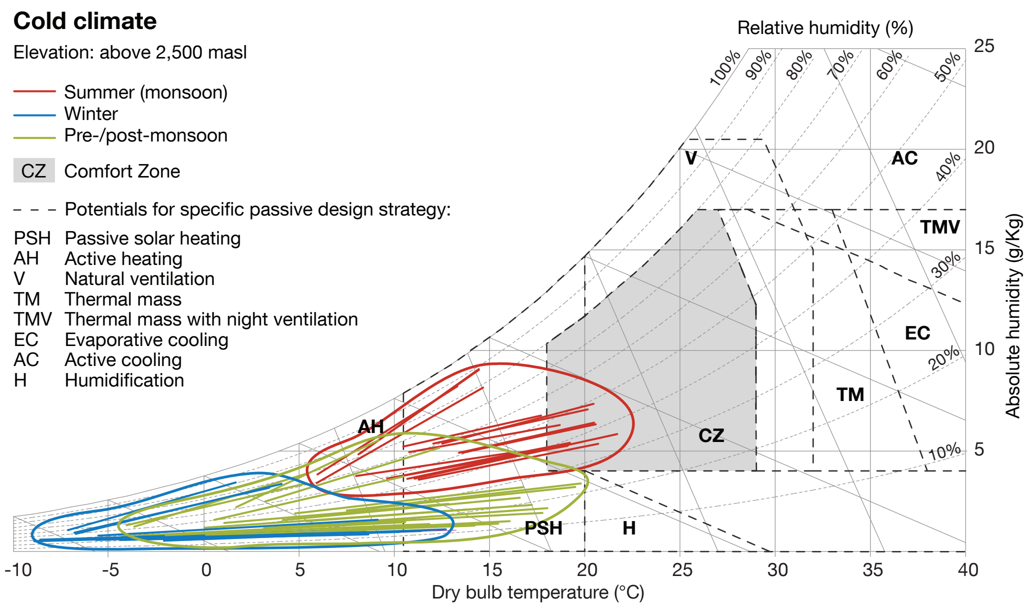


Figure 2.10: Bioclimatic chart for cold climate zone (adopted from [8])

2.3 Energy-efficient design

By analysing nineteen vernacular houses in different climate regions of Nepal, various suitable passive design strategies could be identified for each climate zone [7]. The study of the climate data from 26 Nepalese weather stations resulted into the development of a bioclimatic zoning with its main climate-responsive design strategies [8]. However, there is the need to evaluate the importance of each strategy in order to develop effective passive design guidelines and building energy regulations for the country.

Moreover, some identified design strategies are conflicting each other due to the composite character of Nepal's climate. For example, traditional buildings in subtropical climate of Nepal have low thermal mass [7]. In contrast, high thermal for passive cooling was identified using the bioclimatic chart [7]. Solely, hourly building energy simulation can help to evaluate the effectiveness of the thermal mass strategy.

Therefore, a building energy simulation study for Nepal was conducted with the objective to evaluate the effectiveness of different design strategies and to estimate energy saving potentials (published in [9], see also appendix *Publication III* on page 111). It is the first comprehensive study that assesses energy-efficient building design in Nepal.

The building sector is complex and there exist a large variety of building types. Thermal comfort requirements of local people in Nepal are still very low and, thus energy-intensive active heating and cooling systems are commonly not yet installed in residential buildings. However, there is an increasing trend to install these systems in commercial buildings. Therefore, hotels were selected for the simulation study as they are an important sub-sector of commercial buildings.

The hospitality industry is one of the most important sectors for economic development in Nepal. The number of tourists has almost grown by 400 percent in the last decade and the travel and tourism industry corresponds to 8.2 percent of Nepal's Gross Domestic Product

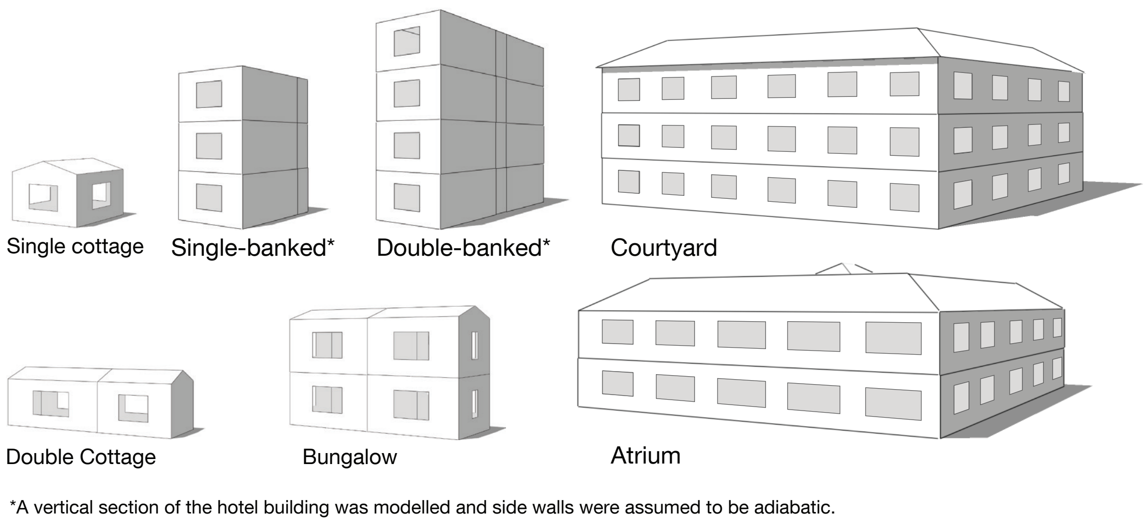


Figure 2.11: Reference models for simulation study on hotel design

(GDP) in 2013 [33]. From 2009 to 2013, the hotel and restaurant business experienced an annual growth rate of over 6 percent per year [34]. The growing numbers of tourists and the boom in the tourism sector have led to more hotels being built by investors. Furthermore, there is an increasing trend to install mechanical heating and cooling systems to achieve the thermal comfort requirements of international tourists.

Based on an extensive field study, reference models for typical hotel buildings ranging from small-scale resort hotels to large-scale multi-storey hotels were developed (see Figure 2.11). Using building energy simulation with parametric analysis, these reference designs were optimised by varying different design parameters. For each climate zone and hotel type, all design parameters were ranked in order to find the most important factor to reduce energy demand for heating and cooling. Two sets of simulation runs were conducted due to the huge number of design parameter combinations. The first set of runs (passive design optimisation) focused on the optimisation of parameters like window-to-wall ratio, thermal mass, orientation and shading devices. The objective of the second set of run (insulation level optimisation) was to find the cost-effective insulation level for each component of the building envelope.

The results of the passive design optimisation indicate that minimising solar gains by keeping the window-wall-ratio small and using shading devices is the most important design strategy in Nepal's warm climate zone. In all other climate zones, high thermal mass has priority because on the one side the passive cooling effect can reduce energy demand for mechanical cooling. On the other side, thermal mass is necessary to store solar heat gains

Table 2.6: Passive design recommendations for hotel buildings in Nepal ([9])

Bioclimatic zone Elevation (masl)	**Warm** <500	**Moderate warm** 501 – 1000	**Moderate** 1001 – 1500	**Moderate cold** 1501 – 2500	**Cold** >2500
Thermal mass	low to high	high	high	high	high
WWR South	20%[a] / 30%[b]	20%[a] / 30%[b]	20 – 60%	20 – 60%	20 – 40%
WWR North	20%[a] / 30%[b]	20%[a] / 30%[b]	10 – 20%	10 – 20%	0 – 20%
WWR East	0 – 20%	0 – 20%	10 – 20%	20 – 30%	0 – 20%
WWR West	0 – 20%	0 – 20%	10 – 20%	20 – 30%	0 – 20%
Orientation	South	South	South	South	–
Overhang South PF[d]	0.2 – 0.4	0.2 – 0.4	0.2[c]	flexible shading	– –
Fins East & West PF	0.4 – 0.6	flexible shading	flexible shading	flexible shading	– –

[a] For small-scale hotels with low case depth
[b] For large-scale hotels with large case depth
[c] For window-to-wall-ratio greater than 40% otherwise flexible shading device
[d] Projection factor

Table 2.7: Recommendations for window performance of hotel buildings in Nepal (adapted from [9])

Bioclimatic zone	**U-Value**		**SHGC**
	Minimum Comfort[a] W/m²K	Maximum Comfort[b] W/m²K	
Warm (<500m)	<3.0	<3.0	≤0.25
Moderate warm (501–1000m)	5.40	<3.0	≤0.3
Moderate (1001–1500m)	5.40	<3.0	≥0.6
Moderate cold (1501–2500m)	5.40	2.50	≥0.6
Cold (>2500m)	3.20	2.50	≥0.6

[a] Minimum comfort as defined in [9] for small-scale hotels
[b] Maximum comfort as defined in [9] for all other hotels

and, thus, can reduce energy demand for mechanical heating (passive solar heating effect). Large windows facing south are recommended for the moderate and moderate cold climate to enhance passive solar heating. In the cold climate zone passive solar heating can be only effective when the window area is moderate to balance heat losses in the cold season. Table 2.6 summarises the recommendations for energy-efficient hotel design in Nepal.

The insulation level optimisation concluded that insulation measures can be cost-effective in almost all climate zones over the building life time and are highly recommended (Table 2.9). Depending on the climate zone U-Values between 0.25 and 1.6 W/m^{2}K are recommended for exterior walls. The roof should have a thermal transmittance between 0.25 and 0.7 W/m^{2}K while the optimal ground floor insulation level is between 0.9 and 0.25 W/m^{2}K. The best insulation level of 0.25 W/m^{2}K is recommended for the whole exterior envelope of hotel buildings in the cold climate. Minimum ground floor insulation is necessary in warm, moderate warm and moderate climate.

Improving the performance of windows is not cost-effective in all climate zones when considering current investment prices. However, switching from single to double glazing to improve the building performance is recommended under most conditions (Table 2.7). It is important to consider that double glazing is a new building technology in Nepal and, therefore, very expensive. There are few suppliers with a limited range of double glazing windows available in the market. Furthermore, the double glazing available in the Nepalese market has a higher U-Value compared to European standards. According to the simulation results, double glazing windows is not recommended in the moderate warm, moderate and moderate cold climate zone from the cost-perspective when comfort requirements and energy consumption are low. For all others zones and for higher comfort requirements (e.g. hotels with international tourist) doubled-glazed windows with an U-Value of 3.2 W/m^{2}K are cost-effective. Assuming that with the dissemination of double glazing in the country, international production standards will be introduced, a window performance of less that 3.0 W/m^{2}K can be easily reached. In moderate cold and cold climate windows U-Values

Table 2.8: Energy saving potentials in hotel buildings through energy-efficient design by climate zone (adapted from [9])

Bioclimatic zone	**Eneryg saving potentials through**	
	Passive design[a]	**Insulation level**[b]
Warm climate (<500 masl)	22 – 38%	35 – 47%
Moderate warm (501–1000 masl)	39 – 50%	37 – 40%
Moderate (1001–1500 masl)	48 – 64%	26 – 50%
Moderate cold (1501–2500 masl)	14 – 73%	41 – 50%
Cold (>2500 masl)	9 – 23%	38 – 48%

[a] Considering following design parameter: window-to wall ratio, orientation, thermal mass, overhang and fins; relative savings of best performers (1st quartile) compared to worst performing case

[b] Considering cost-effective insulation level; relative savings of best performers (1st quartile) compared to uninsulated reference case

lower than 2.5 W/m^{2}K are recommended.

The optimisation of passive design and insulation level in hotels can lead to substantial energy and cost savings. Table 2.8 lists the energy saving potentials for heating and cooling by bioclimatic zone. In the moderate warm, moderate and moderate cold climate zone, highest relative savings can be achieved. However, it has to be considered that absolute savings might be lower compared to the warm and cold climate zone because the total energy demand for heating and cooling is lower due to the moderate temperatures.

Cost savings through passive design optimisation (except insulation) depend upon building typology and climate zone (Figure 2.12, Figure 2.13). For example in warm climate (Biratnagar) and moderate warm climate (Pokhara), annual electricity cost for air conditioning can be reduced to almost 50% by considering all important passive design strategies starting from optimal orientation, reducing WWR, and adding an overhang to the south oriented window. In the colder climate zone annual energy cost savings are considerable smaller.

Similarly, life cycle cost savings amounts to almost one third in Nepal's warm and moderate warm climate zone. In the moderate cold climate life cycle costs of the base case design and the optimised design are at a very similar level. In the cold climate no life cycle cost savings can be achieved because the initial investment costs are not payed back through reduced energy cost. There only adding a good insulation layer to the whole building envelope will reduce energy and life cycle cost [9].

Although the simulation study was conducted for hotel buildings, similar energy savings are expected to be achievable in the residential sector. The reason for this is that dwellings have a similar use pattern like hotels. Although today energy-intensive active heating and cooling systems are not common in residential buildings of Nepal, it can be anticipated that thermal comfort standards will rise and, thus, mechanical space conditioning systems will be installed. Therefore, the findings of this study are used to develop general building design recommendations for the different climate regions of Nepal (see following chapter).

Table 2.9: Recommendations for opaque envelope insulation of hotel buildings in Nepal ([9])

Bioclimatic zone	U-Value for Wall			U-Value for Roof			U-Value for Floor		
	Minimum Comfort[a] W/m^2K	Maximum Comfort[a] W/m^2K	Thickness Insulation mm	Minimum Comfort W/m^2K	Maximum Comfort W/m^2K	Thickness Insulation mm	Minimum Comfort W/m^2K	Maximum Comfort W/m^2K	Thickness Insulation mm
Warm (<500m)	0.35	0.35	100	0.70	0.40	50-100	-	0.90	0-25
Moderate warm (501-1000m)	1.60	0.60	50	0.70	0.40	50-100	-	0.90	0-25
Moderate (1001-1500m)	1.60	0.60	50	0.70	0.40	50-100	-	0.90	0-25
Moderate cold (1501-2500m)	0.60	0.35	50-100	0.70	0.40	50-100	0.90	0.50	25-50
Cold (>2500m)	0.25	0.25	150	0.25	0.25	150	0.50	0.25	50-100

[a] Minimum and maximum comfort as defined in [9]

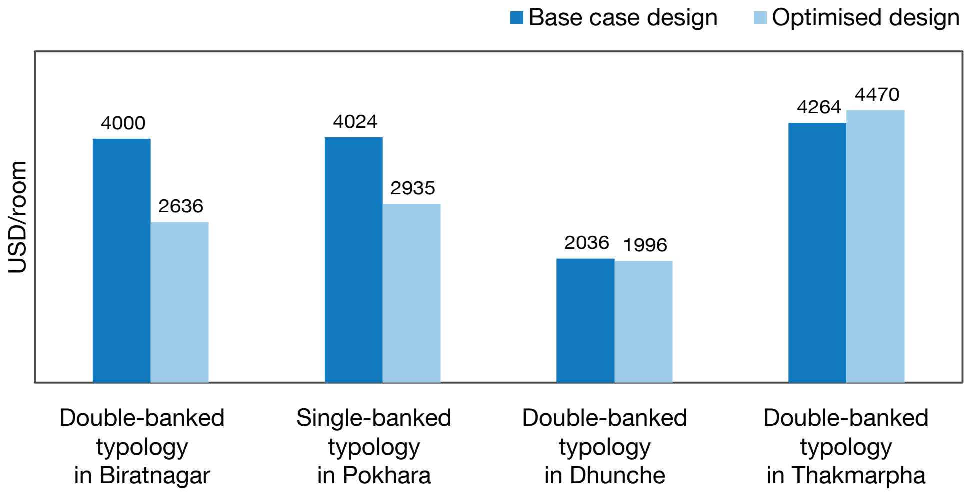


Figure 2.12: Comparison of life cycle costs for base case design and optimised passive design for different typologies and locations (adopted from [9])

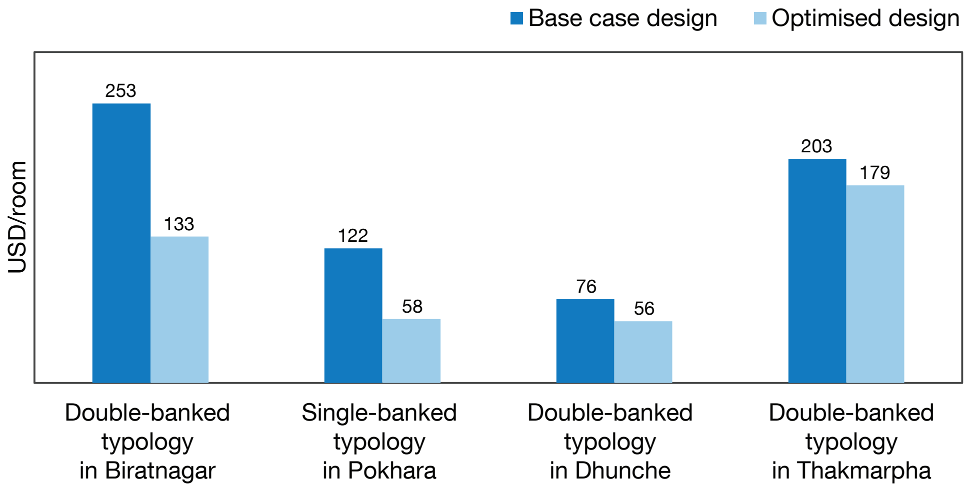


Figure 2.13: Comparison of annual electricity costs for base case design and optimised passive design for different typologies and locations (adopted from [9])

Chapter 3

Design and policy recommendations

3.1 Adaption of bioclimatic zoning for Nepal

Nepal is a small country with high climatic variation mainly due to the large differences in elevation. The climate is of composite character which means neither dry nor humid conditions are dominating. In contrast, the humidity level varies significantly from season to season mainly influenced by the South Asian monsoon. Due to the proximity to the tropics of Cancer, temperature differences between winter and summer period are perceptible but moderate. The variation in temperature and humidity levels leads to four different seasons which can be described as followed: 1. Winter season (December to February), 2. Pre-monsoon (March to May), 3. Summer or monsoon season (June to September), and 4. Post-monsoon (October to November).

In the most populated regions of the country which are located between 60 masl to 1,500 masl, the winter is mild and dry with daily maximum temperatures close to the comfort zone. The hottest and driest period is the pre-monsoon from March to May when maximum temperatures rises above the comfortable level. With the beginning of the monsoon season, temperatures drop few degrees but humidity rises, similar to sticky conditions in hot and humid climates. In the post-monsoon, temperature and humidity fall down to a comfortable level and it rains only occasionally. While the sky is mainly cloudy during the monsoon season, clear sky conditions are dominant in all other season.

In the context of this thesis the first proposal of a bioclimatic zoning for Nepal was developed leading to an elevation based climate classification of four zones (published in [8], see also Appendix *Publication II* on page 101:

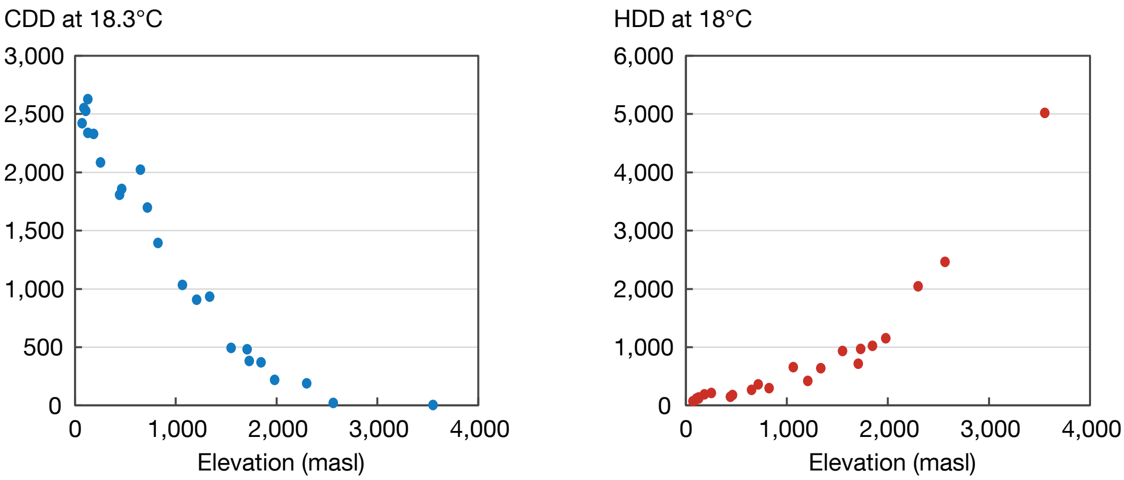
- Warm climate (below 500 masl)
- Temperate climate (from 501 masl to 1,500 masl)
- Cool temperate climate (from 1,501 masl to 2,500 masl)
- Cold climate (above 2,500 masl)

Passive solar design strategies for each bioclimatic zone were identified by using the bioclimatic approach. The further energy simulation based analysis found an inconsistency of priority passive design strategies within the temperate climate. Therefore, a further differentiation of the temperate climate zone is necessary. As a result it is suggested to improve the bioclimatic zoning leading to five elevation-based climate zones (see Figure 3.2):

- Warm climate (below 500 masl)
- Moderate warm climate (from 501 masl to 1,000 masl)
- Moderate climate (from 1,001 masl to 1,500 masl)
- Moderate cold climate (from 1,501 masl to 2,500 masl)
- Cold climate (above 2,500 masl)

Table 3.1 gives an overview about the climatic conditions in each bioclimatic zone by indicating dry bulb temperatures in the different seasons, annual rainfall, cooling and heating degree days as well as humidity conditions. It can be seen that the warm and moderate warm climate zone have a considerable long period of hot and humid conditions.

The analysis of heating and cooling degree days for all assessed locations confirm a clear relationship with regard to elevation (Figure 3.1). That means, the lower the elevation, the higher the cooling degree days. In contrast, the higher the elevation, the higher the heating degree days. Locations below 1,000 masl are dominated by cooling with more than 1100 cooling degree days (CDD18) while they have less than 400 heating degree days (HDD18). Locations between 1,000 and 1,500 masl have a moderate amount of cooling degree days



(a) CDD18 **(b)** HDD18

Figure 3.1: Relationship between elevation and cooling degree day (CDD18)[a]/heating degree day (HDD18)[b]

[a]Calculated at 18.3℃ acording to ASHRAE-method[35]
[b]Calculated at 18℃ acording to EUROSTAT-method[36]

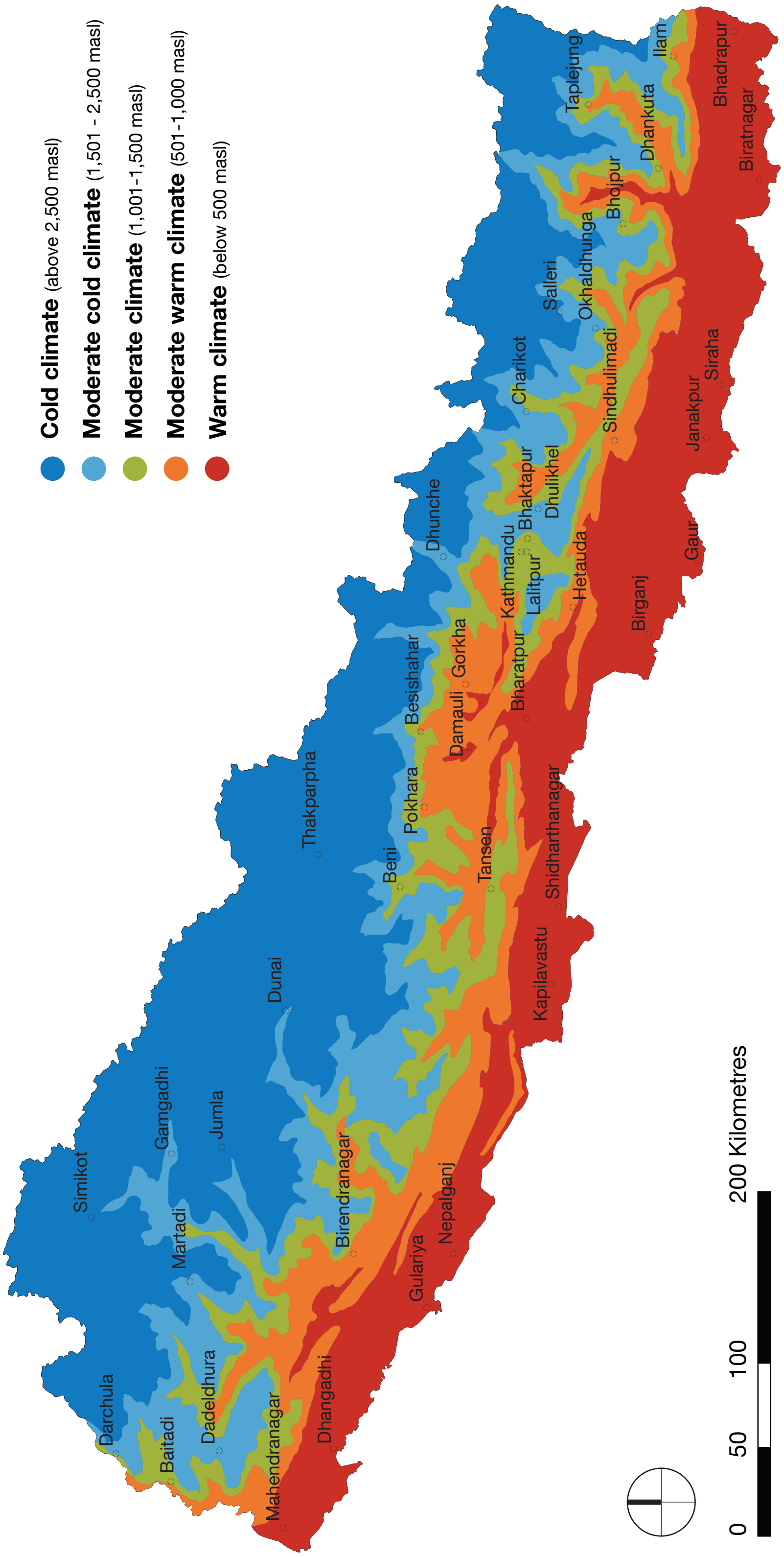


Figure 3.2: Bioclimatic zoning for Nepal with five zones

Table 3.1: Specification of reclassified bioclimatic zoning for Nepal

Bioclimatic zone	**Warm climate**	**Moderate warm climate**	**Moderate climate**	**Moderate cold climate**	**Cold climate**
Elevation (masl)	< 500	501 – 1,000	1,001 – 1,500	1,501 – 2,500	> 2,500
Temperature (°C)					
Summer	23 – 36	21 – 35	18 – 29	14 – 27	6 – 21
Pre/post-monsoon	11 – 37	9 – 36	8 – 30	2 – 27	– 4 – 19
Winter	9 – 25	6 – 23	5 – 22	-2 – 20	-9 – 12
Annual rainfall (mm)	1,400 – 2,200	1,000 – 4,000	900 – 2,000	800 – 2,000	300 – 1,300
CDD18[a]	> 1,800	1,100 – 1,800	500 – 1,100	100 – 500	< 100
HDD18[b]	< 200	200 – 400	400 – 700	700 – 2400	> 2,400
Absolute humidity (g/kg)[c]					
Average	14.7	11.8	10.7	6.5	4.5
Minimum	5.4	3.7	3.0	1.3	0.5
Maximum	27.0	23.1	21.3	15.7	12.4
Hot and humid conditions[d]					
Total hours (h)	3252	1283	645	10	0
Percentage (%)	37.1%	14.6%	7.4%	0.1%	0%

[a] Calculated acording to ASHRAE-method[35].
[b] Calculated acording to EUROSTAT-method[36].
[c] Humidity conditions for one selected location per climate zone, namely: Biratnagar, Pokhara, Kathmandu, Dhunche and Thakmarpha.
[d] Accumulated time when dry bulb temperature >26.7°C and humidity ratio >12 g/kg.

and heating degree days. All locations above 1,500 masl are dominated by heating with more than 700 heating degree days; they have less than 500 cooling degree days.

Aiming to compare all bioclimatic zones, Figure 3.3 indicates the relative importance of passive and active design strategies for each climate zone. It can be seen that natural ventilation for cooling and solar control are the most important climate responsive design strategies in Nepal's warm and moderate warm climate. Passive solar heating has priority in the moderate, moderate cold and cold climate to reduce the energy demand for heating. High thermal mass is important in all climate zone except the warm climate. It can be noticed that insulation of the building envelope is only slightly important in moderate warm and moderate climate due to the moderate temperatures. Regarding the active design, fan-forced ventilation plays an important role in warm, moderate warm and moderate climate. Dehumidification is fairly important in the warm and moderate warm climate zone. While active cooling is very important in the warm climate zone, active heating is very important in Nepal's moderate cold and cold climate. The predominant design strategies for each climate will be described in detail below:

The warm climate zone (below 500 masl) has the hottest temperatures of the country resulting into the highest energy demand for active cooling systems. Additionally, dehumidification is very much required during the monsoon season due to the high humidity levels. In the post-monsoon season more than 20% of the time thermal comfort can be reached by dehumidification only. However, passive design can contribute to considerable cooling energy savings. Natural ventilation strategy can be used as cooling strategy almost one third of the year. Solar control is needed about 30% of the year. The demand for heating is very low and can be reduced to zero if the building is optimised for passive solar heating for the coldest period of the year. Thereby, thermal mass plays a secondary role and should not

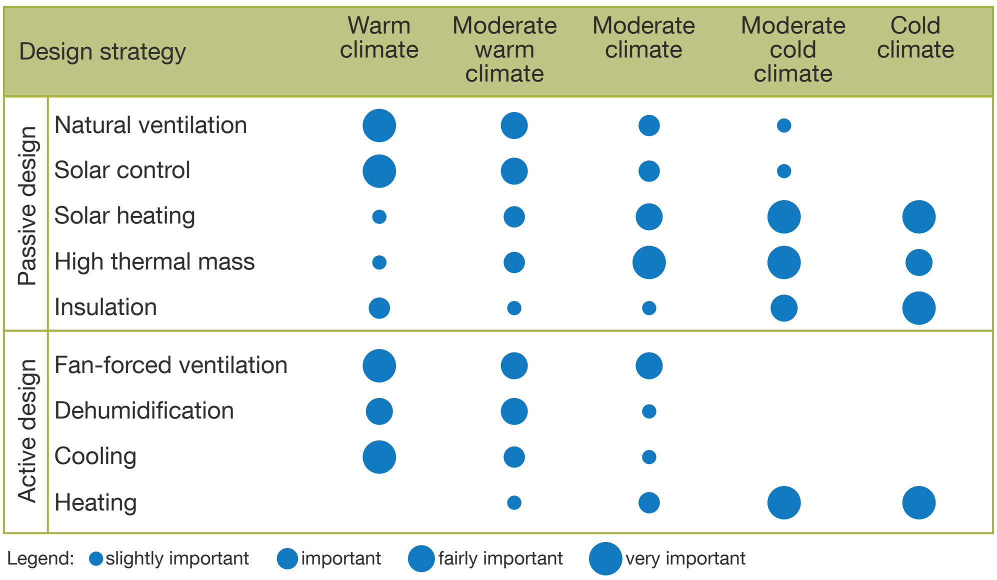


Figure 3.3: Importance of building design strategies by bioclimatic zone

be too high to reduce the risk of overheating in the hot season. An appropriate solution for the contradictory impact of thermal mass could be the application of massive floors, while walls are light weighted and well insulated. Insulation of the building envelope will contribute to reduce the need for cooling.

In the moderate warm climate zone (from 501 masl to 1,000 masl) both summer and winter are mild and the need for heating and cooling is limited. According to the simulation results of this research energy consumption for space conditioning is lowest compared to other climate zones in Nepal. Natural ventilation cooling and solar control in the warm season can reduce the need for active cooling considerably. Dehumidification is the most important active measure for reaching thermal comfort in the warmer period. However, some cooling will be needed during the hottest days of the year. For the cold season, the optimisation of the design for passive solar heating combined with medium to high thermal mass can reduce the need for heating to a minimum. Thermal mass is highly recommended for this climate because it is effective as a heat sink for hot days and a heat storage for cold days. Using thermal mass the high daily temperature can be balanced. According to the simulation results of the hotel typologies, passive design (excluding insulation) can achieve energy savings between 22% and 38%. Cost-optimum insulation levels at 0.35 W/m^2K lead to an energy reduction between 35% to 47% [9]. Similar savings might be achieved in the residential sector due to the fact that dwellings and hotels have a similar use pattern.

Nepal's moderate climate (from 1,001 masl to 1,500 masl) has mild temperatures in summer and winter resulting in the combined need for heating and cooling. However, the need for cooling is much lower and the need for heating is higher than in the moderate warm climate. The heating demand in this climate will be always higher than the cooling demand. If natural ventilation cooling, solar control strategies and high thermal mass are applied in the building design, the cooling demand can be reduced to a minimum. Similarly, insulation of the envelope combined with high thermal mass and the design optimisation for passive solar heating will reduce the demand for heating. Considering passive design features like thermal mass, solar control and building orientation, energy savings of 39% to 50% can be reached. The insulation of the building envelope to a cost-effective level of about 0.40 W/m^2K will lead to energy savings of 37% to 40% [9].

The moderate cold climate zone (from 1,501 masl to 2,500 masl) is dominated by the need for active heating during at least six month of the year (from October to March). In contrast the cooling demand will be almost zero if the building openings are designed to have moderate solar gains in the warmer summer period. Natural ventilation cooling will assure thermal comfort during hot summer days. Passive solar heating and high thermal mass are the most important strategies for the colder period. The simulation-based study of this thesis indicates that passive design (excluding insulation) can lead to energy savings of between 28% and 73% depending on the typology. Envelope insulation reaching a thermal transmittance of 0.35 W/m^2K is cost effective and results into savings of between 41% and 50% [9].

The cold climate zone of Nepal (above 2,500 masl) is a region where winters are harsh and summer temperatures hardly reach the comfort zone level. In this climate there is no need for cooling. In contrast, heating is necessary almost all year. Over 60% of the time active heating is needed. In winter solar gains can cover some heating demand during the day. According to the building energy simulation study conducted in the context of this thesis, energy saving potentials through passive design (excluding insulation) are only between 9% to 23%. Envelope insulation with an U-Value of 0.25 W/m^{2}K can bring savings between 38% and 53% compared to an uninsulated building [9].

Figure 3.4 shows a representation of all bioclimatic zones using the psychrometric chart. The perimeter line for each zone was created as the contour of monthly lines for mean minimum and maximum temperatures and relative humidity of all weather stations which fall into the zone. Consequently, it represents the monthly temperature and humidity levels of the zone. The figure illustrates the climatic diversity within the Nepalese territory which implies the need for specific passive design in each climate zone.

The following sections illustrates the characteristics of the five bioclimatic zones and the recommended design strategies in detail aiming to be a practical guideline for architects, engineers and home-builders in Nepal. According to the existing construction practises it is assumed that the building can be naturally ventilated during the time when outdoor temperatures are comfortable.

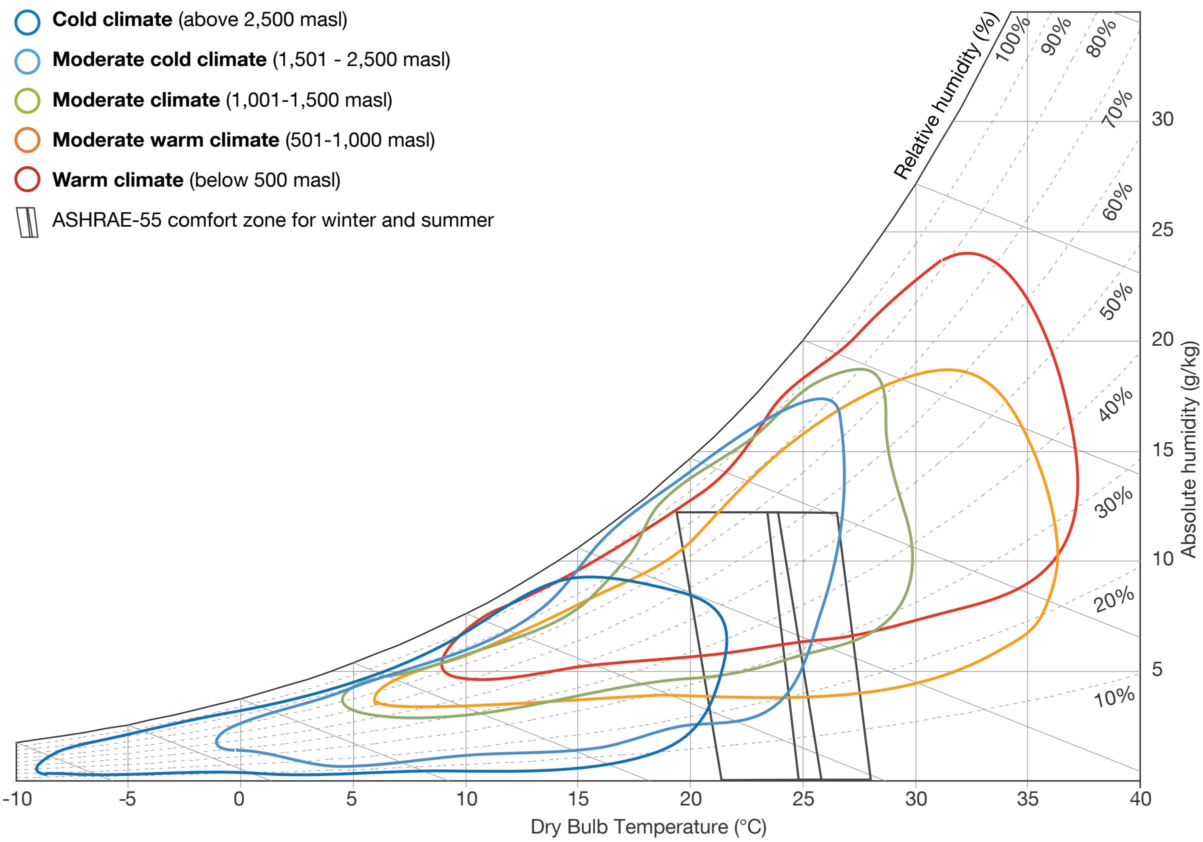


Figure 3.4: Presentation of bioclimatic zones in the psychrometric chart: Perimeter line based on monthly values for mean minimum/maximum temperature and relative humidity of all weather stations in the zone

3.2 Design guidelines for warm climate

3.2.1 Climate and design

With annual mean temperature between 23°C and 25°C, the warm climate of Nepal (below 500 masl) is the hottest climate of the country. However, seasonal changes are still noticeable. The cold and dry season (December to February) is short with mean temperatures slightly below the comfort limits. The sky is mostly clear with occasionally foggy days depending on the micro-climate. The hottest period is from April to June when day temperatures can rise above 35°C. This is also the driest season with an absolute humidity ranging between 5 g/kg and 15 g/kg. With the beginning of the monsoon rain in June, temperature decreases slightly but humidity can rise up to 25 g/kg. Diurnal temperatures ranges between 22°C and 36°C. In the post-monsoon (from October) humidity drops again and diurnal temperatures might drop down 15°C (Figure 3.5).

The physical discomfort in this climate is dominated by heat stress. In the warm-humid monsoon season high humidity reduces the possible heat dissipation from the human body through evaporation. Therefore, this climate will always need an active cooling or dehumidification system. However, about one third of the year natural ventilation cooling can bring thermal comfort without the need for active systems. Additionally, discomfort might occur during the night time in the cold season, if the building is not properly insulated. Depending on the insulation level and orientation some active heating will be required.

The main passive design strategies for this climate are solar control and natural ventilation (Figure 3.6). The building design should prioritise the minimisation of direct and indirect solar gains by reducing the window areas, effective shading and the use of light coloured materials. Cross or stack ventilation strategies as well as the consideration of the local winds for the building layout are an important contribution to reduce the need for active cooling.

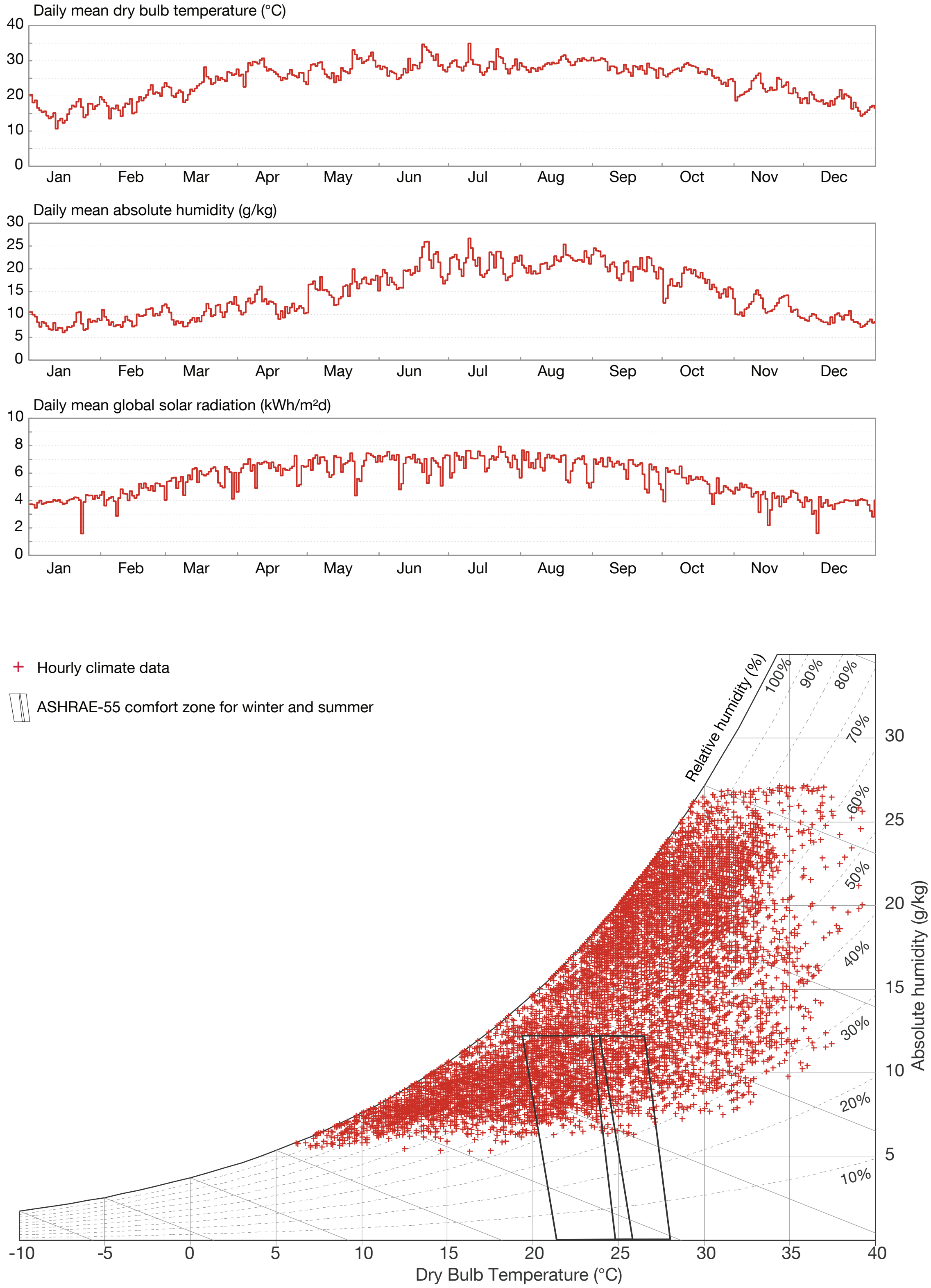


Figure 3.5: Climate conditions of Biratnagar representing warm climate zone

3.2.2 Building form and pattern

The building layout in this climate should reduce solar penetration and enhance natural ventilation. Therefore, rather elongated volumes are recommended with the longer facade facing South and North. The building depth should be low to allow for cross ventilation.

Settlement patterns in this climate shall be rather sparse to allow air movement and natural ventilation for cooling. The orientation of the buildings towards the breeze is desired because one third of the year natural ventilation can increase the thermal comfort within the building. The traditional Tharu settlements in the southern part of Nepal are good examples for such a pattern. Tharu houses were either loosely situated along the road or arranged in clusters of semi-closed compounds. In some settlements houses were placed around a courtyard which has one side opened towards the breezy winds. [7]

Thermal mass does not play such an important role like in the other climate regions of Nepal. In the warm humid season low mass buildings perform slightly better than high mass buildings. However, the performance of low mass buildings is worse in the cold season because the solar heat gains cannot be stored for the colder night times. A solution set to this problem is the application of thermal mass inside the building, for example through massive floors and partition walls. Accordingly, night ventilation can effectively cool down the thermal mass during night time.

3.2.3 Building envelope

The insulation of roof and wall with U-Values between 0.35 to 0.4 W/m^{2}K is cost-effective in this climate. Floor insulation is only recommended at minimum level of 0.90 W/m^{2}K due to the short heating period. In the warmer season the cooler ground might work as a natural heat sink. Building insulation can lead to energy savings of up to 47% [9].

The fenestration area is mainly responsible for the solar heat gains of a building. Minimising solar gains has priority in warm climate. Therefore, windows should be kept small to moderate in size with preferred orientation towards South and North. South facing windows need horizontal shading devices with a projection factor between 0.2 and 0.4. West and east facing windows are not recommended. If necessary, they should be small and effective shading devices like vertical fins are required.

Aiming to reduce solar gains through windows, glazing with a low solar heat gain coefficient (below 0.25) is recommended in the warm climate of Nepal. Although double glazing windows are more than double as expensive as the standard single glazing windows, their installation is cost-effective in this climate and, thus, highly recommended to reach the best performance [9]. Being a new construction technology, double glazing manufactured currently in Nepal reaches a thermal transmittance between 2.5 W/m^{2}K and 3.2 W/m^{2}K. Compared to European standards this U-Value is high due to commonly used aluminium frames and the lack of thermal breaks. It is anticipated that with further dissemination of double glazing, the manufacturing process will be improved and reach international standards.

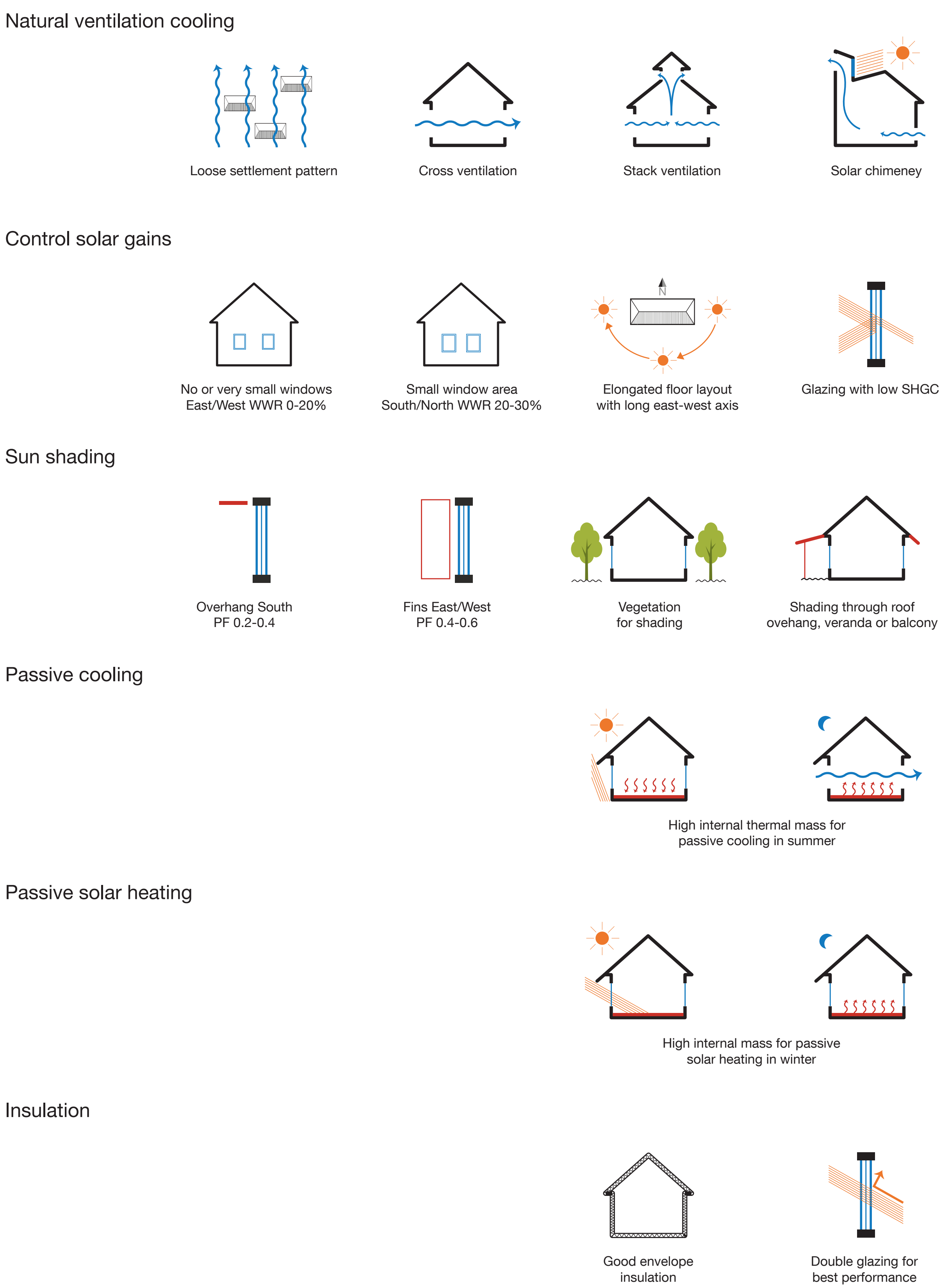


Figure 3.6: Passive design strategies for warm climate of Nepal

3.3 Design guidelines for moderate warm climate

3.3.1 Climate and design

All locations between 501 masl and 1,000 masl are located in the moderate warm climate zone of Nepal. Although the annual mean temperature is with 21°C to 22°C only few degrees Celsius lower than in the warm climate, it is a much more comfortable climate. The cold and dry winter season has mean temperatures clearly below the comfort limit resulting into the need of active heating. May is the hottest month with average maximum day temperatures up to 35°C. In the dry season absolute humidity ranges between 5 g/kg and 15 g/kg. During the wet monsoon season from June to September, temperature decreases slightly but absolute humidity can increase to daily average values above 20 g/kg. Diurnal temperatures ranges between 18°C and 34°C. In the post-monsoon (from October) humidity drops again while diurnal temperatures range between 8°C and 30°C (Figure 3.7).

Although this climate is much more comfortable than the warm climate of Nepal, physical discomfort is dominated by heat stress. From May to August day time temperature rises above the required thermal comfort. Additional high humidity from June to August reduces the possible heat dissipation from the human body through evaporation. In the winter season, particularly during night time, the physical comfort depends upon the prevention of heat loss.

Similar to the warm climate the control of solar gains, sun shading and natural ventilation cooling are the main passive design strategies in this climate. Due to the fact that winter temperatures are a few degrees lower than in the warm climate zone, passive solar heating is also very important. Therefore, medium to high thermal mass is recommended in addition to sufficient window openings facing south (see Figure 3.8).

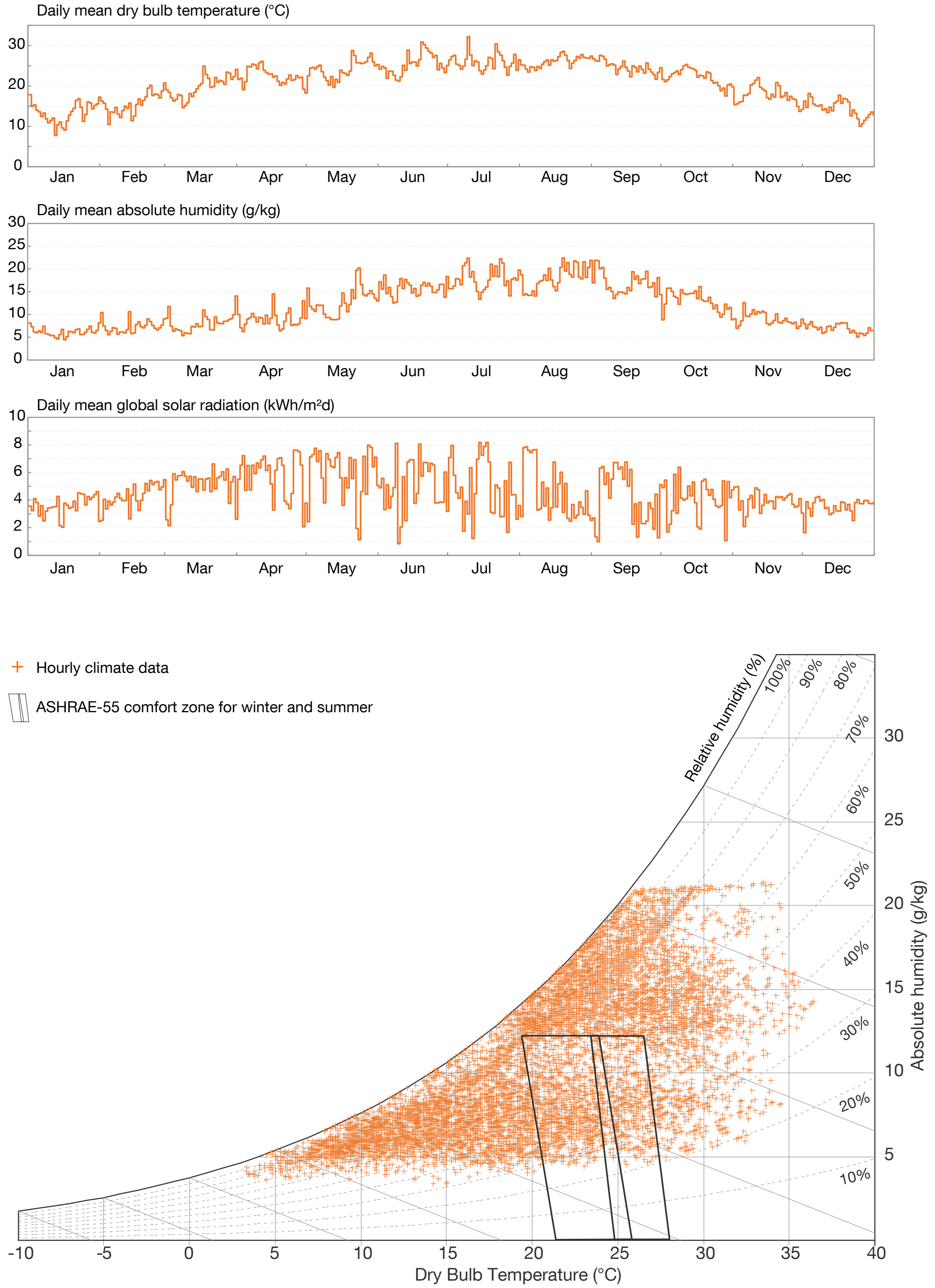


Figure 3.7: Climate conditions of Pokhara representing moderate warm climate zone

3.3.2 Building form and pattern

Loose settlement patterns and elongated floor plans can foster the effect of natural ventilation cooling. Concepts like cross and stack ventilation can bring thermal comfort for about 30% of the time of the year. The longer axis of the building should be aligned from east to west to control solar gains.

Medium to high thermal mass brings clear advantages and energy savings in the moderate warm climate zone. The reason for that is the higher contribution of solar gains for heating the building in winter and, thus, reducing the energy needs for mechanical heating. High thermal mass serves also as thermal sink during the hot and dry pre-monsoon season.

3.3.3 Building envelope

The main fenestration area is recommended to be rather small (20–30%) facing south and north. East and west facing windows are not recommended or should be as small as possible. For southern windows an overhang with a projection factor of 0.2–0.4 is necessary. Flexible shading devices are recommended for all other orientations. Shading is very important to reduce direct solar gains from May to September.

For the purpose of passive heating, solar gains are required in the cooler winter season. A moderate insulation level with U-Values between 0.4–0.6 W/m^2K for roofs and walls is required to assure the effectiveness of passive solar heating and to reduce the heat loss in winter. For hotel building it is estimated that increasing the insulation level can result in energy savings up to 40% compared to an uninsulated building [9].

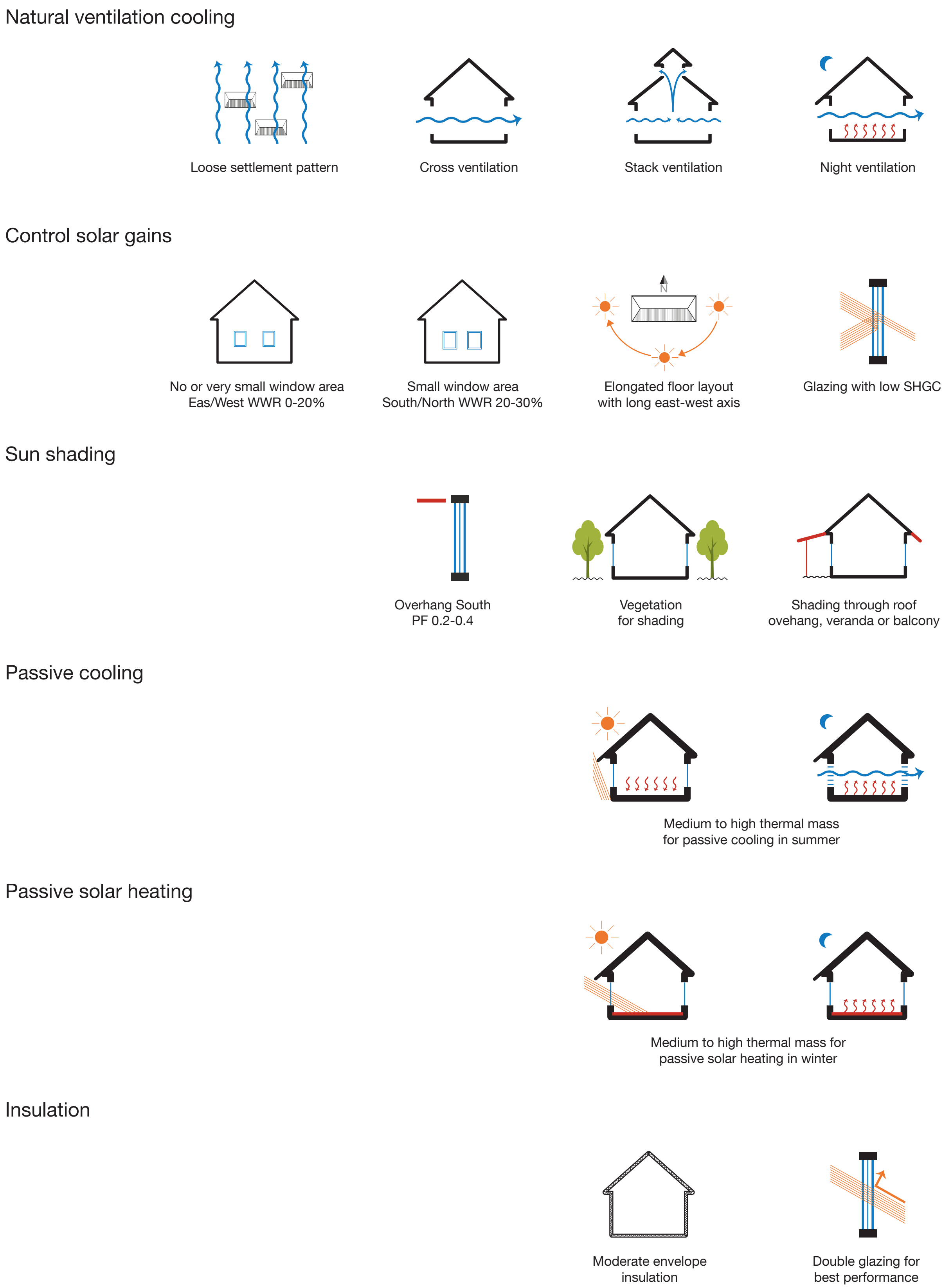


Figure 3.8: Passive design strategies for moderate warm climate of Nepal

3.4 Design guidelines for moderate climate

3.4.1 Climate and design

The moderate climate zone of Nepal includes all locations above 1,000 masl elevation and below 1,500 masl which have an annual mean temperature of about 19°C. In the cold and dry winter season night temperatures can decrease to just above the freezing point resulting into the need of an active heating system. The hottest months are May and June with diurnal temperature rising up to 35°C. While the daily absolute humidity is often still below 10 g/kg in April and May, it can rise up to 15 g/kg after the start of the monsoon rain in June. In monsoon season from June to September diurnal temperatures range between 18°C and 30°C. In the post-monsoon (from October) humidity level drops again down below 10 g/kg and diurnal temperatures range between 5°C and 27°C (Figure 3.9).

The moderate climate zone has one of the most comfortable conditions. However, some physical discomfort may be caused by cold stress in winter and heat stress with high humidity in summer. Depending on the building typology and the use of passive design energy consumption can be reduced by up to 70% [9]. The optimisation of design for natural ventilation cooling can avoid the need for active cooling. Nonetheless, an active heating system might be required.

The challenge in this climate is to control solar gains in the warm season and to foster passive solar heating in the cold season. Sun shading of windows can contribute to reduce overheating. Natural ventilation cooling can minimise the need for active heating systems (see Figure 3.10).

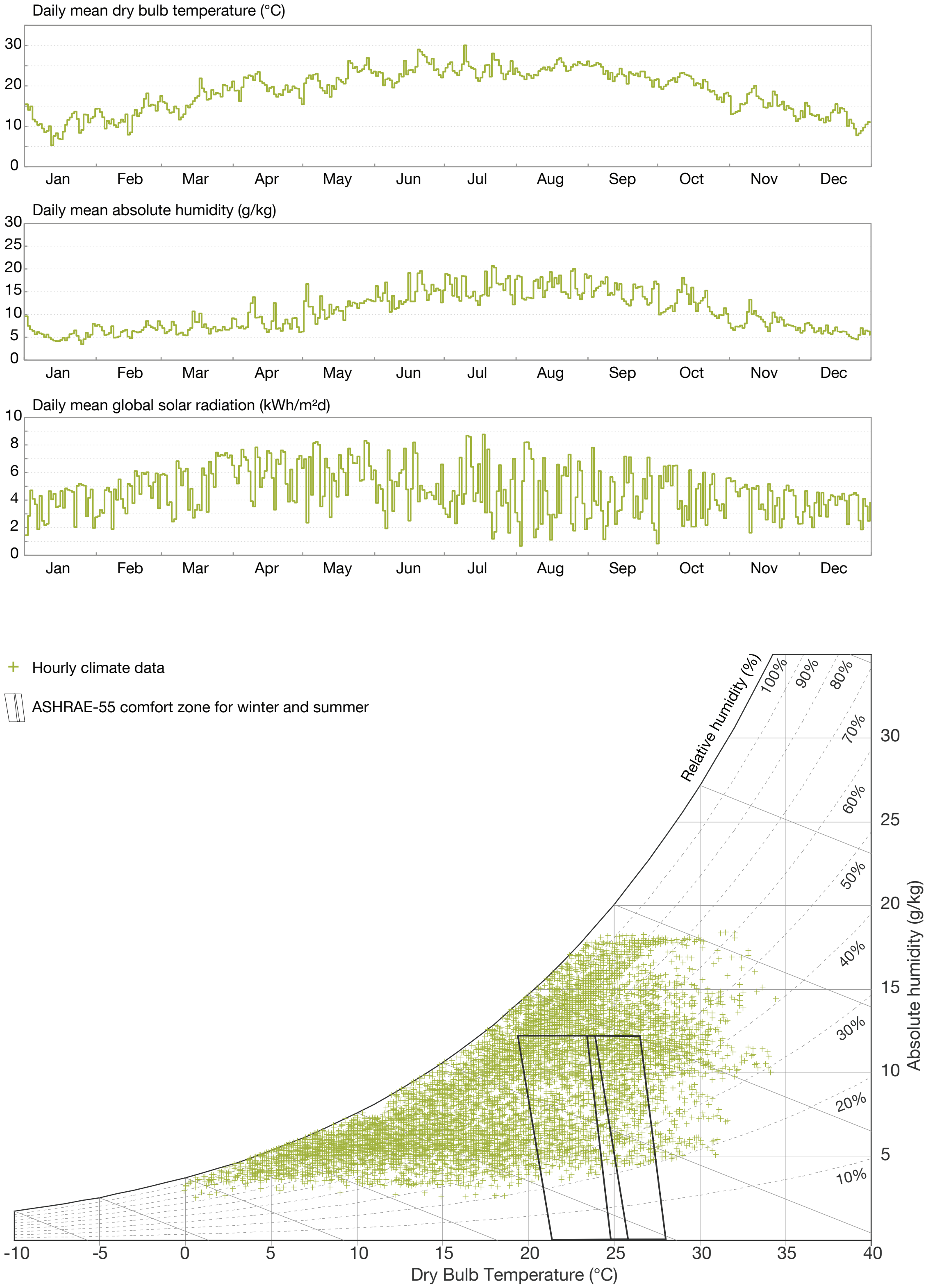


Figure 3.9: Climate conditions of Kathmandu representing moderate climate zone

3.4.2 Building form and pattern

A rather elongated building layout is recommended with the longer facade facing South and North. The building depth should be moderate to allow cross ventilation during the hot and humid season. Other strategies like stack ventilation are also suitable to reduce the need for mechanical cooling.

The settlement pattern of moderate density that does allow solar penetration during winter season is favourable. The typical Newari courtyard typology is a good example for such a spatial structure because it optimises solar gains and shading [7]. Furthermore, the courtyard system allows natural ventilation that is necessary during the warm and humid monsoon season.

High thermal building mass is a priority strategy in this climate and performs better than low mass due to the fact that the thermal mass can be used as a thermal sink during the hot season and as thermal storage in the cold season. High mass is essentially required to optimise the design for passive solar heating.

3.4.3 Building envelope

Large window areas facing south with a WWR between 40% and 60% are most suitable to balance solar control and solar gain. However, an overhang or flexible shading system should be provided to reduce the risk of overheating. Any fenestration areas facing north, east and west should be kept small (WWR 10–20%). [9]

Shading strategies have a moderate impact on energy consumption reduction. An overhang with a projection factor (PF) of 0.2 is recommended to shade south facing windows when the WWR is greater than 40%. Alternatively, a more flexible shading device like external blinds or shutters can be used whenever overheating occurs.

Shading the buildings can also be achieved through vegetation, a wide roof overhang or by integrating a veranda into the design. Typical vernacular houses in the hilly region of Nepal always have a roofed balcony along the longer building facade creating a semi-open space [7].

Moderate insulation of the building envelope has a major influence on energy consumption reduction and is highly recommended. It is estimated that energy savings up to 50% of energy for heating and cooling can be achieved by reducing the thermal transmittance of the building envelope to 0.4 W/m^{2}K [9].

Although double glazing might not bring life cycle cost savings, it can bring other advantages like increased thermal and acoustic comfort. Windows with a high solar heat gain coefficient (above 0.6) are recommended, particularly, for south facing windows that are optimised for passive solar heating. If site constraints lead to a design with windows mainly facing east and west, it has to be evaluated if a lower solar heat gain coefficient is more appropriate to avoid unnecessary overheating.

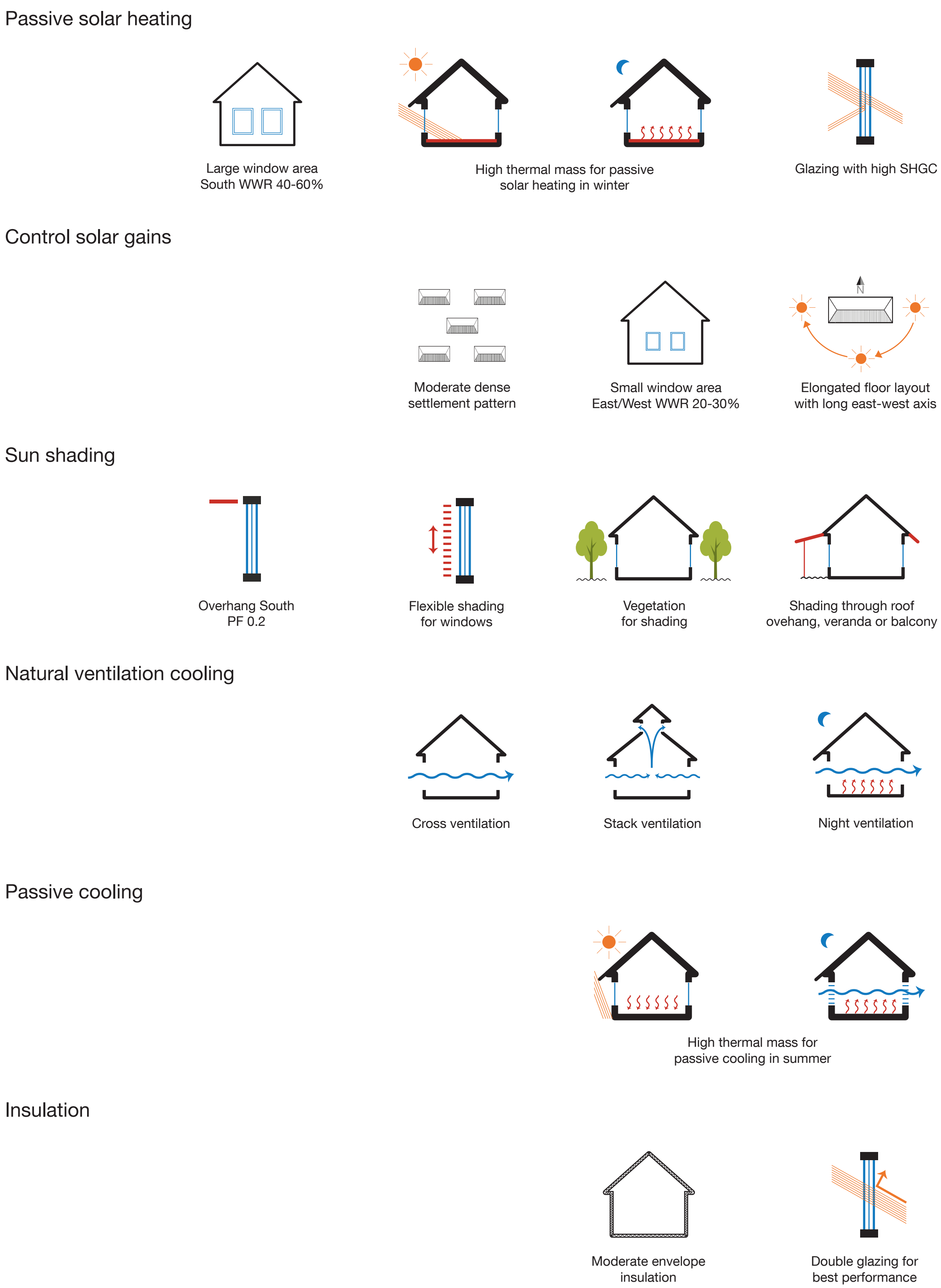


Figure 3.10: Passive design strategies for moderate climate of Nepal

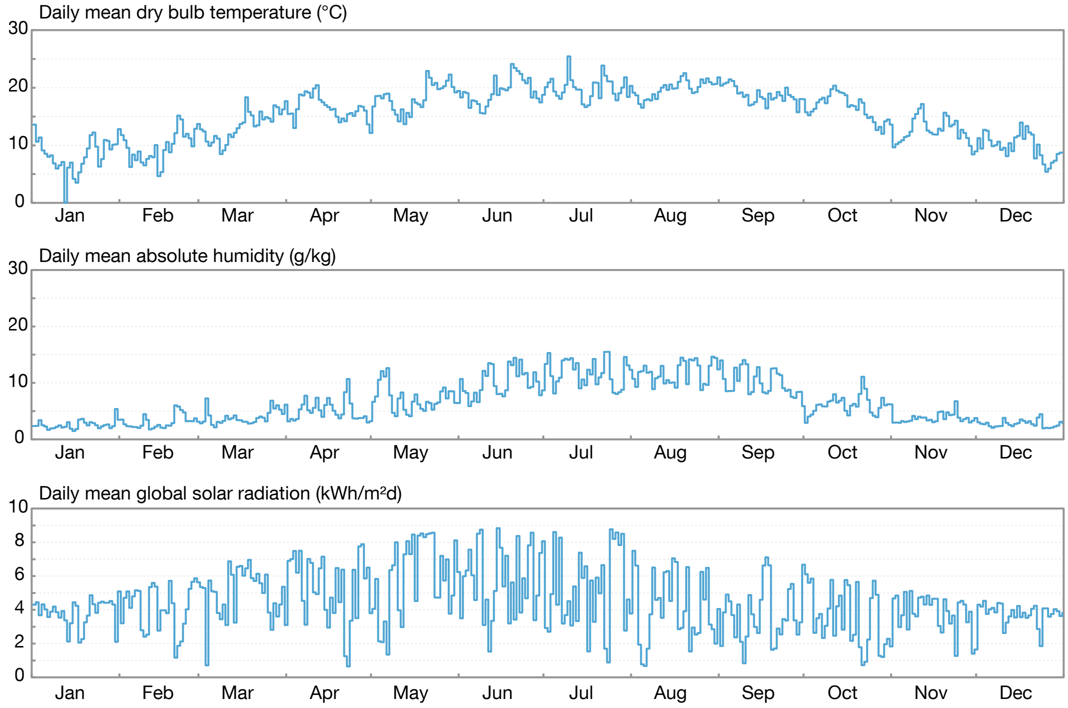
3.5 Design guidelines for moderate cold climate

3.5.1 Climate and design

The moderate cold climate zone is comprised of all locations above 1,500 masl and below 2,500 masl. The annual mean temperature lies between 15°C to 17°C. This climate has a longer cold period from November to March where low outside temperatures create the need for active heating. In winter (from December to February) day temperatures are between 12°C and 22°C while night temperatures can be as low as –4°C. The hottest month is May with diurnal temperature rising up to 30°C. In summer (June to September) diurnal temperatures range between 10°C and 30°C. With the end of the summer diurnal temperatures go down to average values between 12°C and 18°C. The absolute humidity ranges between 3 g/kg and 7 g/kg in the dry season while it increase to daily averages between 7 g/kg and 15 g/kg (Figure 3.11).

The physical discomfort in this climate is dominated by cold stress due to the longer winter period and the low night time temperatures in the pre- and post-monsoon season. However, active heating might be required not more than one third of the year depending on the insulation level and other design factors.

There are three important passive design strategies suggested for the moderate cold climate: 1. Reducing heat losses, 2. Passive solar heating, and 3. Natural ventilation cooling for day time in summer (see Figure 3.12). Reducing heat losses are essential to minimise the need for active heating during the winter season. Passive solar heating can assist the active heating system in winter and keep the indoor temperature at a comfortable level during colder nights in the warmer season of the year. Natural ventilation cooling is needed in summer during daytime when outdoor temperatures and humidity levels are above the comfort zone.



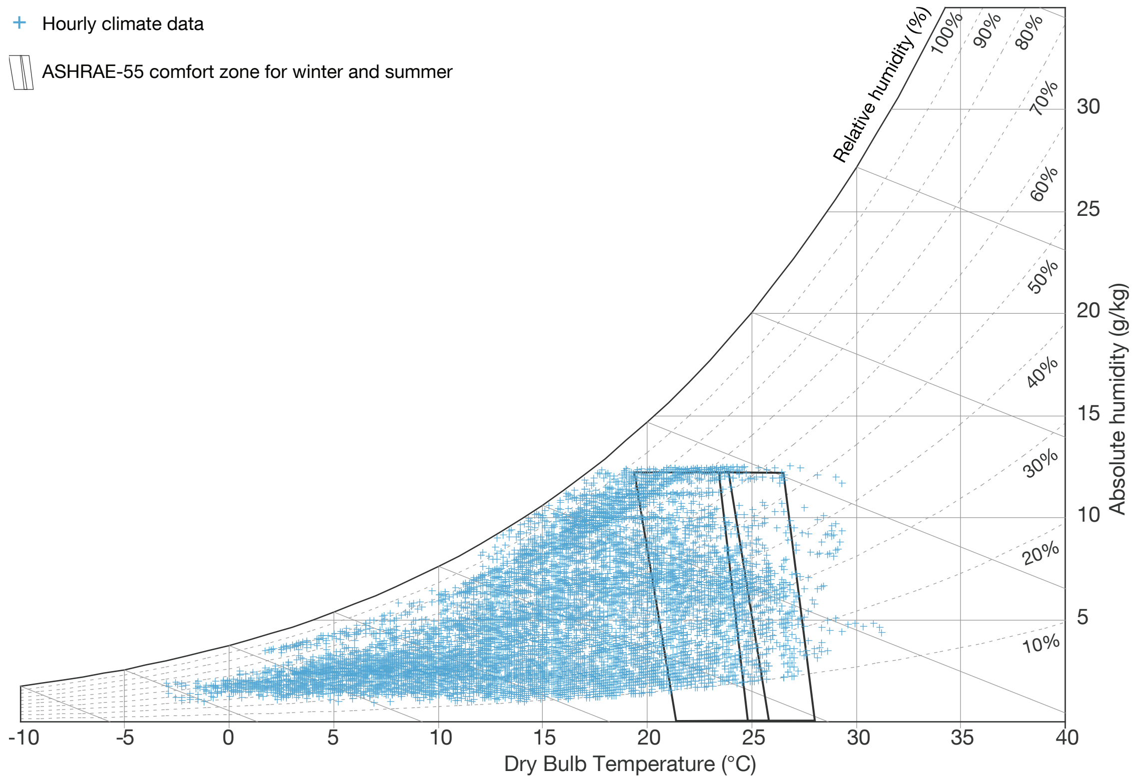


Figure 3.11: Climate conditions of Dhunche representing moderate cold climate zone

3.5.2 Building form and pattern

Moderate compact settlement patterns are recommended for this climate region. Attached houses like in the traditional Tamang villages have less outer envelope surface area than individual houses which lead to the reduction of heat losses [7].

The orientation of the most important building functions towards south will assure effective use of passive heating and, thus, reduce the energy consumption of the buildings. For example, the guest rooms of the hotel design with an elongated building layout should be allocated on the southern side along the corridor.

The application of materials of high thermal mass is highly recommended to reduce heating energy consumption in moderate cold climate. Particularly, in the pre- and post-monsoon where only night temperatures are below the comfort limit, thermal mass can store the solar heat during the day and release it during the night. Thereby, the need for active heating can be reduced to a minimum.

3.5.3 Building envelope

Appropriate envelope insulation can reduce the heat losses of the buildings in winter. Additional provision of large window areas (WWR 40–60%) facing southward can optimise the passive solar heating effect and, thus, reduce energy consumption for heating. Small to moderate windows (WWR 20–30%) are recommended for the east and west facing facade while the northern facade should have no or very small windows (WWR max. 20%).

A good insulation is recommended to reduce heat losses through the building envelope. Reducing thermal transmittance of walls, roof and ground floor to 0.35, 0.4 and 0.5 W/m^2K, respectively, might lead to energy savings up to 50% [9].

According to the simulation results for hotel buildings in Nepal double glazing is cost-effective over the life time of the building (20 years) and is highly recommended for this climate [9]. A good envelope sealing can bring further energy savings due to fact that unintended cold air infiltration is avoided.

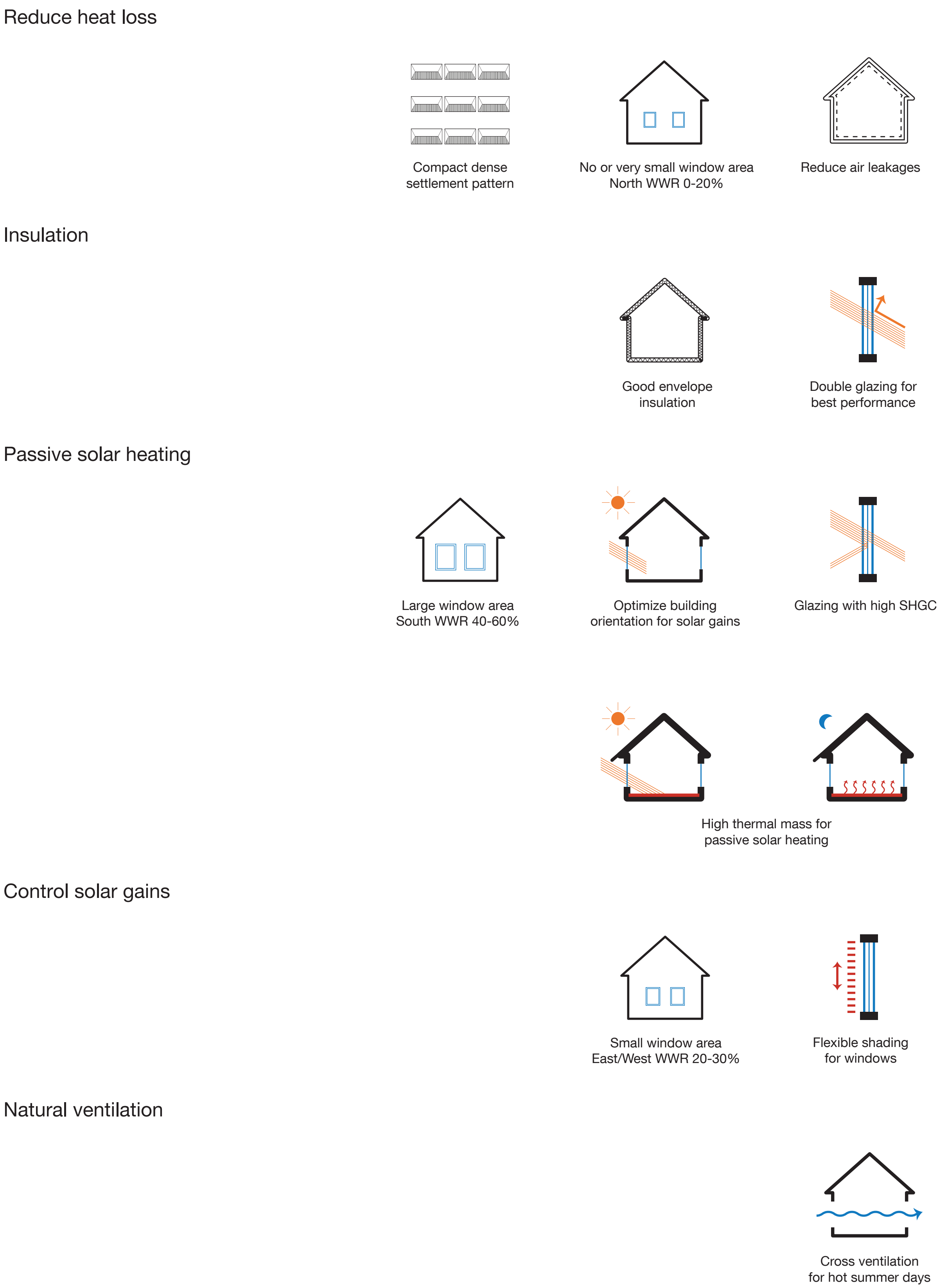


Figure 3.12: Passive design strategies for moderate cold climate of Nepal

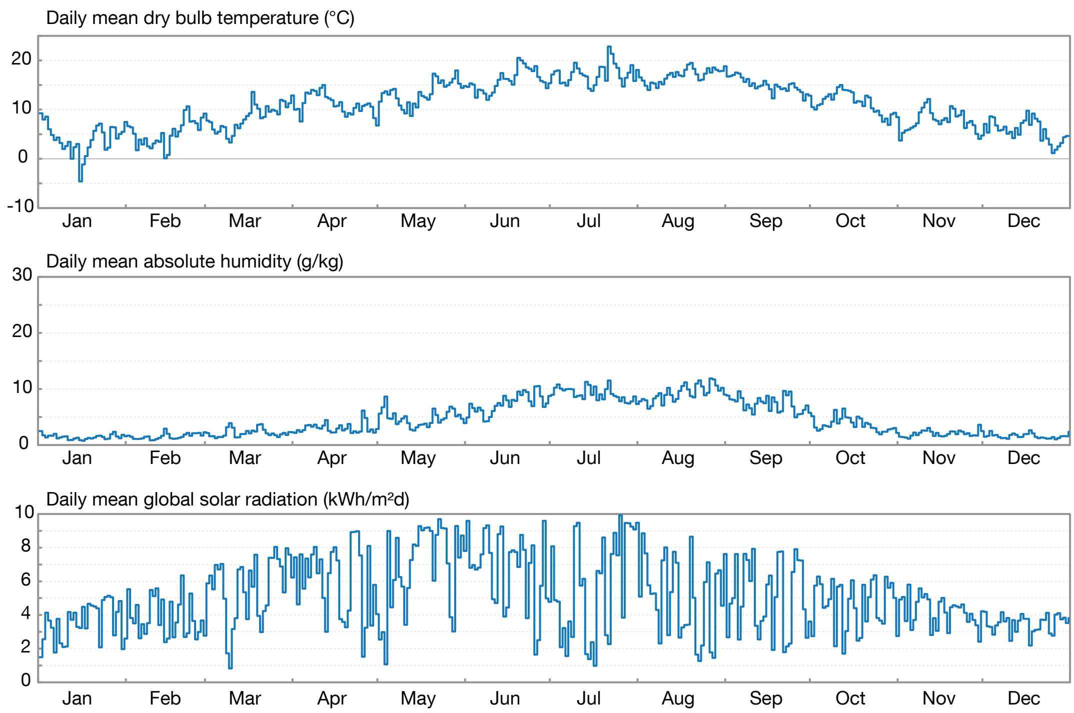
3.6 Design guidelines for cold climate

3.6.1 Climate and design

All locations at elevations above 2,500 masl are part of Nepal's cold climate zone with annual mean temperatures below 11°C. In this climate active heating is needed at least six months of the year to assure thermal comfort within the building. The coldest months are January and February with day temperatures slightly above 10°C and night temperatures of at least 5°C below the freezing point. All locations that are in the rain shadow of the Annapurna mountain range North-East of Pokhara (e.g. Thakmarpha) are not so much influenced by the monsoon rain and have very low humidity levels and almost no precipitation all over the year. In summer (June to September) depending on the elevation, day temperatures can reach up to 25°C. However, night temperatures fall always below the comfort level and might result into the need of active heating. The diurnal temperature range in post-monsoon season is between 0°C and 15°C (Figure 3.13).

The physical discomfort lies in cold stress. Depending upon the elevation an active heating system is always required to assure thermal comfort inside the building and will at least be used about 50% of the year. Although the main heating season is during the long winter period, at locations above 3,500 masl heating might be required all over the year.

The main design strategy in this climate is to reduce the heat loss of the building (see Figure 3.14). High solar radiation all over the year makes the use of passive solar heating very effective but not sufficient. An active heating system might be always required.



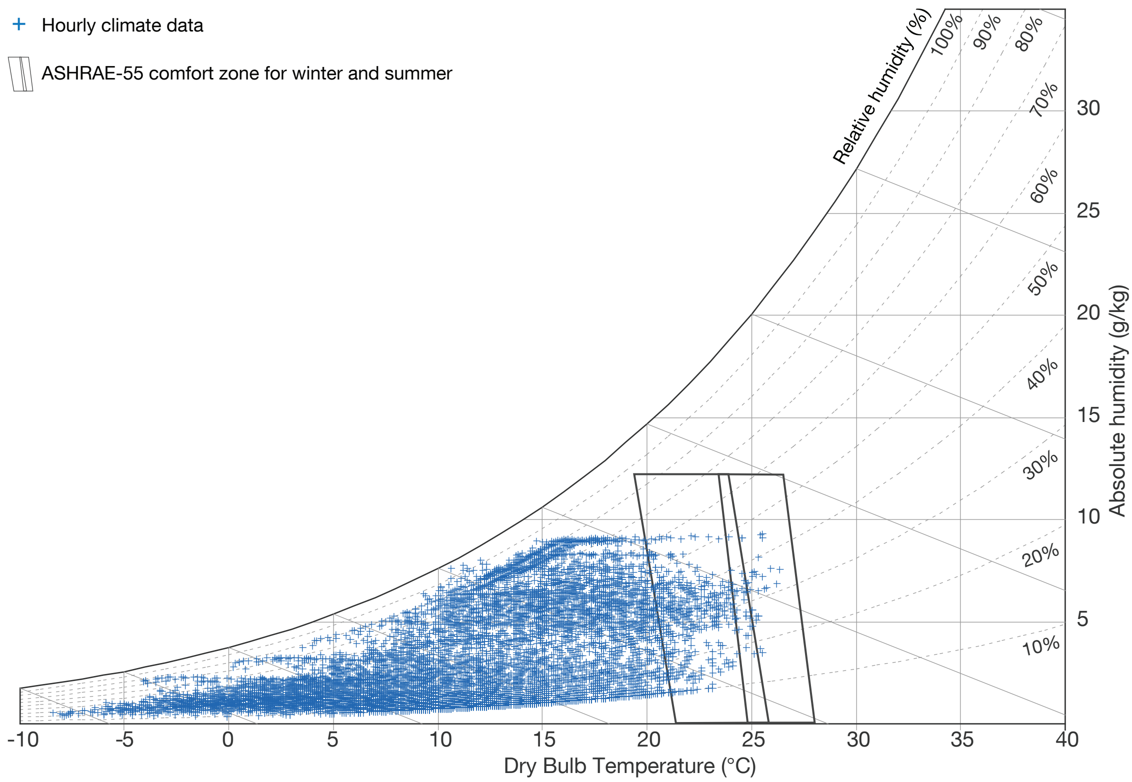


Figure 3.13: Climate conditions of Thakmarpha representing cold climate zone

3.6.2 Building form and pattern

A compact settlement pattern and building layout are important strategies to reduce heat losses of the building in the cold climate zone. The traditional settlement structure of Nepal's mountain tribes are a good example for such a compactness. The vernacular buildings in Mustang, for instance, are often attached to each other, sharing the same wall to reduce the exterior building surface and, thus, the heat losses. Furthermore, vernacular houses in the mountain region have almost square ground floor plan resulting into a low surface-to-volume ratio [7].

The orientation of the mainly occupied building functions towards the sun (South) and the creation of buffer zones between them and the exterior can reduce the need for heating. Traditional houses of Thakali people in Nepal's mountainous regions have two and a half stories where the main living area is located on the second floor [7]. The ground and upper floor contains secondary functions like livestock stables and storage rooms and create a thermal buffer zone to protect the main living spaces from the outside cold.

The simulation results have shown that high thermal mass is a very important strategy to reduce energy consumption in this climate. The thermal mass can store the solar heat gains and support the active heating system to maintain thermal indoor comfort.

3.6.3 Building envelope

The combination of high thermal mass, very good envelope insulation and, a moderate fenestration area towards south and east (WWR 20–40%) are the right strategies to optimize passive solar heating in this cold climate. However, an active heating system will be always required, particularly, during the long and cold winter season. Windows towards north and west should be avoided and fenestration facing east and west is recommended to be as small as possible (WWR max. 20%).

Windows with double glazing and high solar heat gain coefficient (>0.6) are suggested to reduce heat losses and ensure effective passive heating, respectively. According to the simulation results for hotel buildings in Nepal double glazing in this climate is cost-effective over the life time of the building (20 years) [9].

A further issue for heat losses is the leaky envelope due to poor quality of construction. Cracks and gaps in the building envelope should be sealed using caulk, spray foam, weather strips or similar products. The weather stripping around window and door framing is particularly important to reduce heat losses through unintended air infiltration.

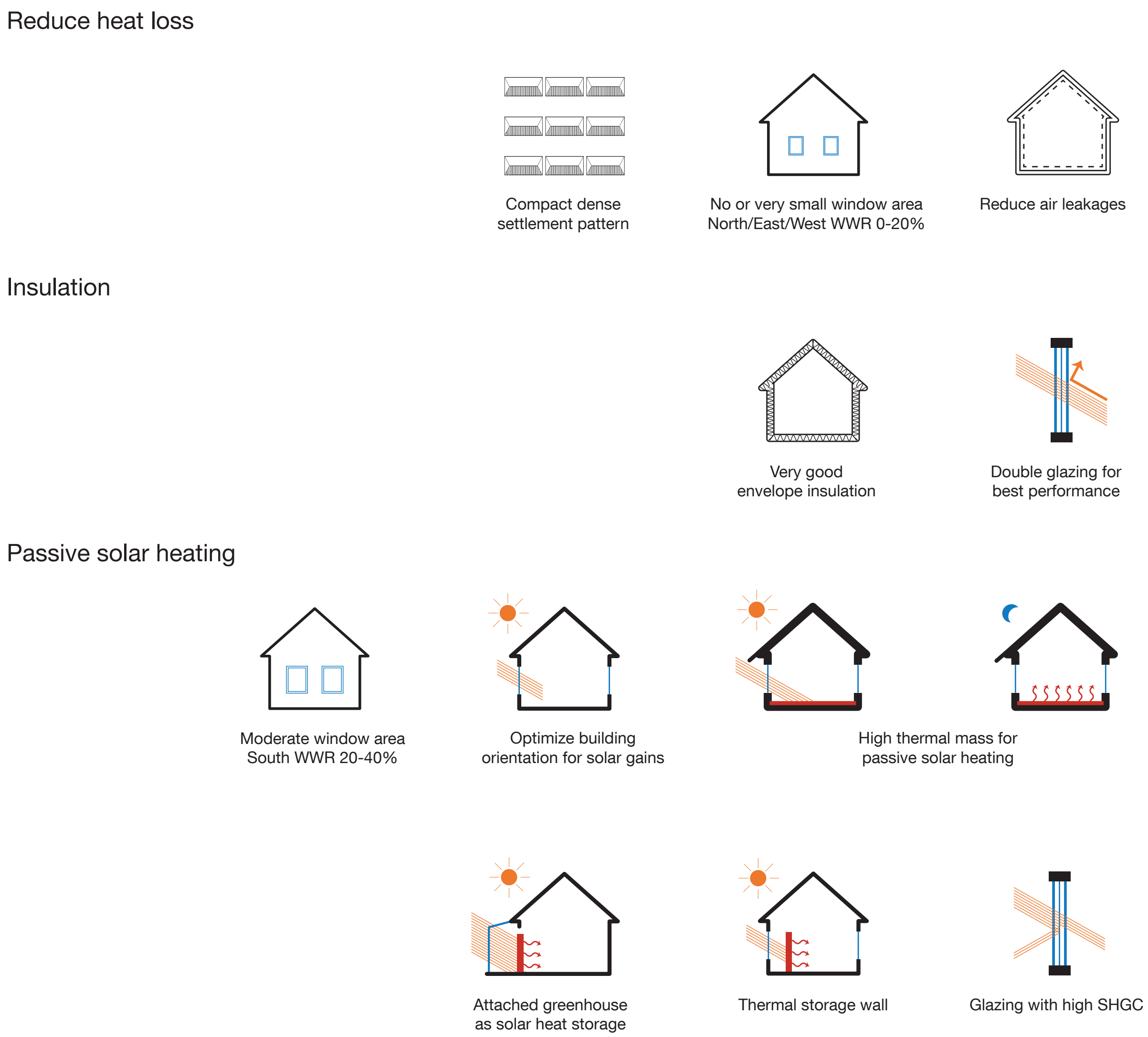


Figure 3.14: Passive design strategies for cold climate of Nepal

3.7 Heating and cooling systems

3.7.1 Current status

The majority of the buildings in Nepal has neither a modern cooling nor heating system. On the one hand thermal comfort requirements are still very low and people are very well adapted to the local climate [37, 38]. On the other hand the country often suffers from supply shortage of electricity and fuel which makes the running of space conditioning system extremely costly and unreliable.

However, in urban centres new commercial buildings and residences of the upper middle class are increasingly equipped with space conditioning systems. Most common are decentral split systems and window air-conditioners for cooling as well as portable electric or gas heaters for heating purposes. Often this space conditioning equipment is added later by the user of the building because the building owner has no interest to invest in costly central space conditioning systems.

Is the building owner and user the same person or organisation, which is often the case for banks, hotels, or office buildings of big companies, the provision of a central HVAC system might be considered. In this case, a conventional air-driven HVAC system is installed leading often to oversizing of equipment due to the lack of know-how. Although the climate in the hilly region of the country, where also the capital Kathmandu is located, require more space heating than cooling, building owners and builders are more concerned about space cooling. A reason for this might be the fact that new buildings are often designed with large unshaded window areas resulting into overheating in the warm season.

The high solar radiation makes the application of solar energy technologies suitable for Nepal. Solar thermal collectors are already a standard technology for water heating in residential buildings in the urban centres. Photovoltaic systems were introduced and are still subsidised for rural electrification in the remote areas of Nepal. Recently, photovoltaic systems have reached commercial viability as electricity backup in the urban centres of the country. Compared to photovoltaic systems, conventional diesel backup generators have higher running costs and supply shortage of petroleum products leads often to unreliability of these systems.

The increasing trend to install active heating and cooling systems in new buildings demands for a catalogue of suitable solutions to assure energy-efficient provision of thermal indoor comfort. In the following section, possible technology solutions are discussed aiming to make suggestions for heating and cooling systems that are energy-efficient on one side and can be easily combined with renewable energy supply systems on the other side.

3.7.2 Natural versus mechanical ventilation

Experiences from the developed countries have shown the negative impact of mechanical ventilation systems such as the Sick Building Syndrome [39]. Naturally ventilated building are often more accepted by the user. Consequently, there is a trend towards more user control. Mechanical ventilation systems are also very energy-intensive and imply higher construction costs. This has led to the development of more energy-efficient hybrid ventilation concepts and the mixed mode operation of mechanical heating and cooling systems [40].

The building stock in Nepal is still very traditional and most buildings are naturally ventilated. It is common practice to open all windows of the house during a cool summer night and close them in the morning when temperature rises. In contrast, international investors like big hotel chains are guided by the idea to built sealed envelopes which are fully air-conditioned hoping to provide the best comfort to their clients.

Looking at the climate conditions in the country, temperature and humidity levels are moderate for more than six months of the year except for the extreme mountain climate in the upper Himalaya. Rather than switching towards energy-intensive sealed buildings with mechanical ventilation systems, natural ventilation can be used to provide thermal comfort at no cost.

However, when comfort requirements rise mechanical ventilation systems might become necessary. Particularly, in the warm climate zone of Nepal mechanical ventilation will be required when using radiant cooling systems due to the need of dehumidification. At noise polluted sites mechanical ventilation is often the only solution to ensure thermal comfort without neglecting the acoustic comfort.

3.7.3 Split system

Efficient split systems are a suitable solution for residential and small to medium scale commercial applications as well as for spaces that are not continuously occupied. They can provide sufficient thermal comfort where cooling and heating loads are moderate. Due to the small size of the system, their efficiency is limited and cannot reach the level of centralised systems. Modern heat pumps can combine space conditioning and hot water provision at a higher efficiency than two separate systems. This is highly recommended for buildings with moderate hot-water demand like residences and small to medium scale hotels.

The installation of split systems is relatively simple and very much suitable for retrofitting. However, exterior space for the compressor unit (on the facade or roof) is required and can affect the facade design as well as leading to noise pollution. The investment cost for split systems is low compared to central heating and cooling systems but running costs are high. An integration of renewable energy systems is not possible. Split systems are suitable for all climate regions except the cold climate zone.

3.7.4 Hot-water convector

Hot-water convectors are used in a conventional hydronic heating systems for cold climates. In contrast to traditional hot-water radiators, convectors are more efficient and operated with lower flow temperatures. It is recommended for heating purpose in Nepal's moderate cold and cold climate. Solar thermal collectors can provide heat at very low cost. If the solar collector area is not sufficient an air-source heat pump or a biomass boiler might be installed, becoming a very suitable space conditioning system for Nepal's heating dominated climate regions. For a solely solar thermal driven system, a large hot water tank might become necessary for buildings that are occupied for 24 hours.

3.7.5 Radiant floor heating and cooling

Radiant floor heating and cooling provides space conditioning through the integration of water-bearing pipe system into the floor. The floor materials must be heat conducting and preferably of high to medium thermal mass. The system can be used for heating and cooling. However, cooling capacity is low because the flow temperature during cooling mode should not be lower than 18°C [41]. Therefore, the radiant floor heating and cooling systems are recommended for climate conditions with moderate heating and low cooling needs. It is recommended for all climate zones except warm climate.

The system can be easily powered by renewable energies like ground-source or water-source heat pump as well as solar thermal collectors. Due to the fact that solar collectors are often already foreseen for hot-water provision, the collector area could be expanded to power the radiant floor heating system at very low cost. If the heating demand is higher an air-source heat pump or biomass boiler can be installed.

3.7.6 Thermally active building systems (TABS)

The thermal activation of massive building components like concrete slabs or walls is one of the most cost-effective solutions for moderate cooling and heating loads [42]. The thermal mass of the building is used as radiant cooling and heating system by integrating a water-flown pipe system into the concrete ceilings. Therefore, concrete slabs must be exposed. Using the thermal lag of the building mass, night cooling can decrease the temperature inside the building and reduce the need for cooling during day. TABS are very much suitable for office buildings but can also reduce cooling energy in buildings that are occupied 24 hours.

In Nepal's moderate warm and moderate climate TABS alone might provide sufficient heating and cooling. However, in warm climate where more cooling is required, the installation of a mechanical ventilation might be necessary to pre-cool and dehumidify the air. The main advantage of TABS is the simple integration of renewable energy systems for heat generation and refrigeration due to the low flow temperature. Ground-source or water-source heat pumps might be used for heating and cooling: Solar thermal collectors can be used for heating only.

3.7.7 Chilled beam system for heating and cooling

The chilled beam technology is a central space conditioning system designed to heat and cool large buildings. The primary advantage compared to conventional central air conditioning systems is the lower energy consumption and, thus, operating costs. A chilled beam is a convection system where the air is cooled or heated by passing through a water driven heat exchanger (chilled beam) which is integrated into the suspended ceiling or suspended in short distance from the ceiling. If the system needs to provide cooling and heating a fan coil convector should be installed to ensure sufficient air circulation during the heating period.

Chilled beam technology might become a technology option for large commercials building with high thermal comfort needs. For buildings with low ventilation requirements and moderate cooling load, the use of chilled beams with natural ventilation is possible [42]. However, the installation of a mechanical ventilation system might be necessary to dehumidify the air during the monsoon season, particularly in Nepal's warm climate zone. In this case, heat recovery is possible and pre-cooling by an earth tunnel or pre-heating by solar air collector could be provided.

3.7.8 Summary

The previous section summarised some energy-efficient technology options for active heating and cooling systems in Nepal. Depending on the heating and cooling demand, not all systems might be suitable for all climate zones. Figure 3.15 and Table 3.2 concludes the applicability of the space conditioning system by bioclimatic zone and building type, respectively. Table 3.3 summarises which renewable energy sources can be used to power the different systems.

The proposed list of technology options does not claim to be exhaustive. Depending on the thermal comfort requirements, site conditions and building configuration other heating and cooling concepts might be applied.

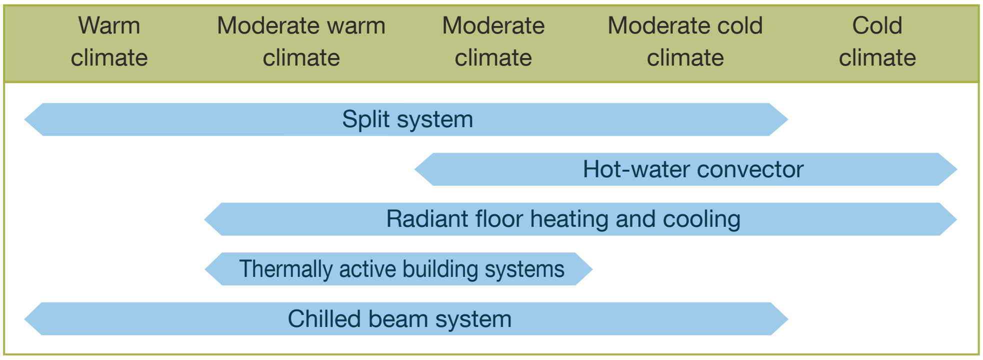


Figure 3.15: Suitability of active heating and cooling systems by climate zone

Table 3.2: Recommended heating and cooling systems by building type (based on [41, 42])

	Split system	Hot-water convector	Radiant floor heating/cooling	TABS	Chilled beams
Residential buildings	✓	✓	✓		
Offices	✓[a]	✓	✓	✓	✓
Hotels	✓[a]	✓	✓	✓	✓
Department stores	✓[a]			✓	✓
Government buildings		✓	✓		✓
Schools		✓	✓	✓	
Conference halls				✓	✓
Hospitals		✓			✓
Industrial buildings			✓	✓	✓

[a] small-to-medium scale.

Table 3.3: Renewable energy integration for heating and cooling systems

	Solar thermal collectors	Geothermal heat pump	Biomass	Solar air collector	Earth tunnel
Split system					
Hot-water convector	✓	✓	✓		
Radiant floor heating/cooling	✓	✓	✓		
TABS	✓	✓	✓		
Chilled beams	✓	✓		✓	✓

3.8 Policy implications

Nepal's energy consumption per capita is still very low in comparison to industrialised countries. Access to reliable and affordable energy sources is fundamental for economic development [3]. However, any new policy with regard to energy utilisation has to consider the environmental impact on the one side and the sustainable economic growth on the other. Policies that foster energy consumption are less likely to speed up economic development in Nepal than to degrade the environment [43]. In contrast, policies strategies for energy conservation and carbon emission reduction would not hamper the long-term economic growth and are, therefore, the most appropriate policy option. Nepal's policy makers should focus on the enhancement of efficient energy use, particularly, under the scenario of the unreliable power supply and the increasing dependency on fossil fuel imports [43].

The issue of energy efficiency has been incorporated into policy strategies like the draft of the National Energy Strategy, the National Climate Change Policy and the National Urban Development Strategy [44–46]. However, energy efficiency in buildings is not yet incorporated into the regulatory framework for building construction. There is no building energy conservation code in place and the national building code is mainly concerned about the structural resistance, particularly, in regard to earthquake safety [26]. The building bye laws set minimum requirements for access, open space, building area and height, daylighting, and ventilation [47].

For this reason, it is highly recommended to develop and introduce a building energy conservation code. International experience has shown that mandatory building energy codes are a highly efficient policy measure to foster energy efficiency in buildings [6]. However, one of the main challenges regarding the implementation of energy-efficient buildings in least developed countries is to cover the incremental cost [48]. Although the life cycle cost study for hotel buildings in Nepal has shown that most energy efficiency measures pay back the initial investment [7], building owners might not be able to afford the additional investment costs. Therefore, it is important to focus on policy measures for the market segment where the economic benefits are greatest, resulting into high probability of enforcement, for example commercial buildings.

Electricity prices in Nepal are still very low. However, the scheduled electricity outages caused by the power crisis has lead to the need of expensive diesel-driven backup systems. Particularly in the commercial building sector and the larger scale residential building developments electricity backup systems are essential to provide proper services. In this market segment, the incremental cost of energy-efficient design can easily be recovered by reduced investment and running costs for expensive backup systems. Properly designed, these buildings might need a less powerful backup system or can provide the same services without any which would, finally, reduce the incremental cost.

In the residential sector policies should concentrate on measures which do not increase the investment costs of the building such as design strategies and optimal orientation, shading, natural ventilation, locally available low-cost construction techniques and insulation materials. This can be done by the adoption of design guidelines for energy efficient homes according to the bioclimatic zones based on this research (see previous sections). The Green Homes Project initiated by UN-Habitat has shown that municipalities are willing to incorporate energy-efficient and sustainable building components in their regulations [49]. In the long run such guidelines should lead to a national mandatory Green Building Code which considers energy efficiency on the one hand but also other sustainability issues like water efficiency, environmental impact of building materials and so on.

The Nepal Energy Efficiency Programme (NEEP), a Nepali-German cooperation programme to promote energy efficiency, started to support the Nepali government in 2010 to promote energy efficiency in various sectors with the technical support of the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ). The building sector, except energy audits in few hotels, was not in the focus of the programme in the beginning. Since 2014, NEEP is promoting the introduction of market based energy efficiency services for the private and public sector. Furthermore, it supports the Nepali government to institutionalise an energy efficiency entity which is envisaged to mainstream energy efficiency in the country and to establish a regulatory framework. [50]

Many studies have identified that the lack of awareness and know-how is one of the major barriers for the implementation of energy efficiency measures [51, 52]. Therefore, the government has to take the lead and initiate pilot projects of energy-efficient public buildings such as government offices, schools or low-cost housing to showcase the feasibility of energy-efficient buildings. In the long term, energy efficiency has to be a key consideration in government buildings. Consequently, the right signal will be given to push the construction sector towards more energy efficiency.

Besides the building design, new regulations need to target energy consuming appliances in buildings which are mostly imported from neighbouring countries. There is an urgent need to adopt an energy labelling for such appliances to reduce the waste of energy through inefficient household applicances. Due to the fact that the neighbouring countries India and China have already such appliance standards in place, the official recognition of these standards might be a fast way to introduce an appliance standard for such a small market place like Nepal.

The introduction of mandatory energy performance audits is recommended to foster energy efficiency in large commercial and public buildings. Therefore, a mechanism for certified energy auditors like in India could assure quality audits not only in industrial but also in the building sector [53].

The state-owned utility Nepal Electricity Authority (NEA) can also play an active role in promoting energy efficiency. Similar to the campaign for energy-efficient light bulbs (CFL), NEA should conduct subsidy programmes for energy-efficient building technologies. In countries like Brazil, utilities have conducted refurbishment programmes in informal settlements resulting into the reduction of electricity theft [54].

To overcome financial barriers the development of specific grant and incentive schemes is necessary. This could be done by the establishment of partnerships with international bodies, for example through climate change adaptation programmes or similar. Furthermore, fiscal instruments like import tax exemption on energy-efficient building technologies and the reduction of building permit fees for energy-efficient designs can contribute to reduce the incremental cost. Fiscal incentives for national industries to develop low-energy building technologies (e.g. lightweight concrete blocks or insulation materials based on rice husk) can strengthen the local economy and reduce the need to import.

Finally, extensive awareness raising and training programs are required to ensure the implementation of energy efficiency policy measures. Thereby, all stakeholder of the building value chain have to be targeted to assure regulation enforcement. In the long term energy efficiency has to be incorporated into all educational institutes that train building professionals. (see Table 3.4)

Table 3.4: Summary of policy recommendations

Short term	Long term
Regulatory instruments	
Introduce mandatory building energy code for large commercial buildings	Introduce mandatory green building code for residential buildings
Introduce climate-responsive design guidelines and bioclimatic zoning	
Initiate pilot projects of energy-efficient public buildings such as government offices, schools, low-cost housing.	Ensure that energy efficiency is a key consideration in government buildings by establishing energy-efficient operation procedures and regular energy audits
Adopt energy efficiency label for electric appliances from India and/or China	Develop own energy efficiency labels for electric appliances including air conditioners
Introduce mechanism for certification of energy auditors	Introduce mandatory energy performance audits for large commercial and public buildings
Economic instruments	
Conduct utility-led subsidy programmes for energy efficiency technologies	
Establish financial partnership with international bodies to develop grant and incentive schemes	Develop own grant and incentive schemes
Fiscal instruments	
Grant import tax exemption on EE building technologies similiar to renewables for rural electrification	
Fiscal incentive for local industries to develop low-energy building technologies	
Information dissemination	
Launch extensive training programmes for building professionals	Incorporate energy-efficient design in the curriculum of educational institutes for building professionals
Public awareness raising campaigns for energy efficiency in buildings	Include energy efficiency into environmental education programmes at schools

Chapter 4

Building energy conservation for low-carbon development

4.1 Energy saving scenarios for the building sector

Energy consumption in developing countries like Nepal will increase with economic development and rising living standards. The pace of growth depends strongly on how fast modern consumption patterns are adopted. The comparison of energy use per capita and human development index from 1990 and 2012 in Figure 4.1 illustrates the different development paths in developing countries. Brazil could reach the same level of development as China with only two third of per capita energy consumption. A major share of consumption growth will be used in buildings for heating and cooling purpose.

In order to give an outlook on the impact of energy conservation in the future, energy savings scenarios for the Nepalese building sector were developed. On the one hand, the hotel building sector is selected for the scenario development representing an important growth sector for economic development. On the other hand, future saving potentials are estimated

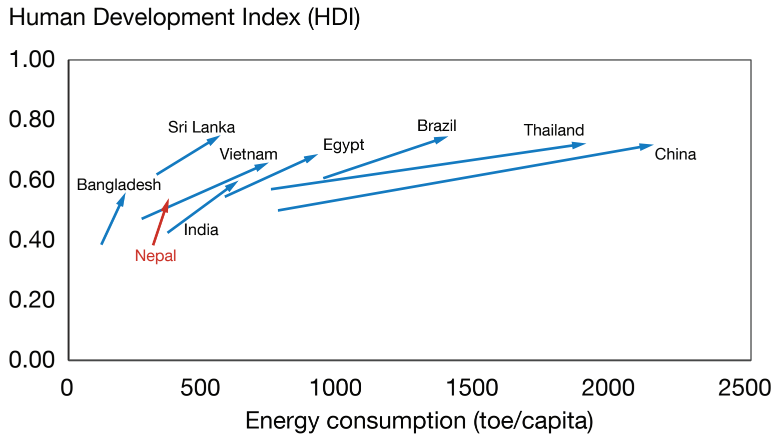
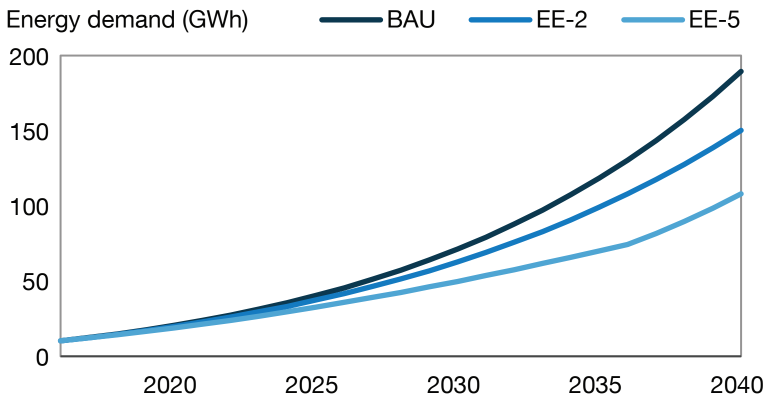


Figure 4.1: Energy use and human development index (HDI) from 1990 to 2012 for selected countries (Data from [55, 56])

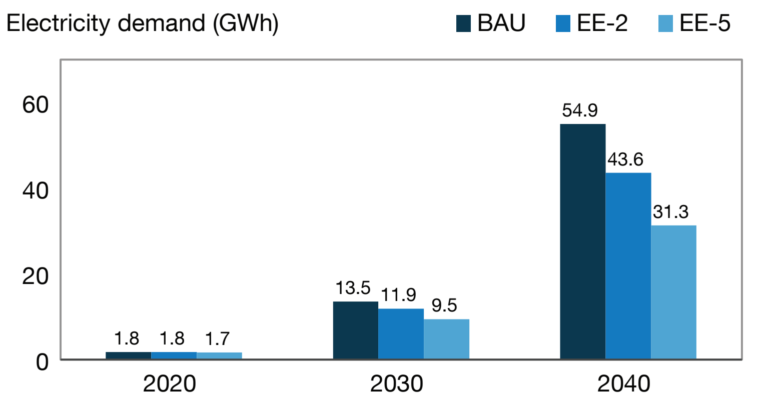
for the residential sector being the major contributor to energy consumption growth.

Projections for Nepal's hotel buildings estimate that the annual energy demand for space conditioning will grow from 10.2 GWh in 2016 to 189.5 GWh in 2040 (Figure 4.2a). Assuming a moderate energy efficiency scenario (EE–2), energy savings of 39.2 GWh or 21% could be achieved in 2040. In the high energy efficiency scenario (EE–5) energy savings of about 81.5 GWh or 43% are obtained. Assuming that the consumption share of electricity is going to increase from 5% in 2016 to 29% in 2040, about 54.9 GWh of electricity will be used for heating and cooling in hotels in 2040 under the Business-as-usual (BAU) scenario. In the moderate (EE–2) and high (EE–5) energy efficiency scenario this amount will be reduced to 43.6 GWh and 31.3 GWh, respectively.

From country perspective the commercial sector including hotels has a share of only 3.4% of total primary energy consumption. The largest amount of energy (80.4%) is consumed in the residential sector corresponding to 84.0 TWh. About 12.1 TWh (14%) of this amount is



(a) Energy demand



(b) Electricity demand

Figure 4.2: Energy demand projection of hotel buildings in Nepal under different scenarios[a] (BAU: Business-as-usual scenario, EE-2: Moderate energy efficiency scenario, EE-5: High energy efficiency scenario)

[a]Assumptions described in appendix *Approach for energy saving scenarios*

used for heating and cooling whereby 98% comes from traditional biomass. Electricity use for space conditioning in residential buildings amounts to 218 GWh which correspond to 1.8% of primary energy. About 28% of this amount is used for heating and 78% for cooling. Concerning the whole power sector of Nepal, about 7% of all electricity is used for space conditioning in residential buildings. [57]

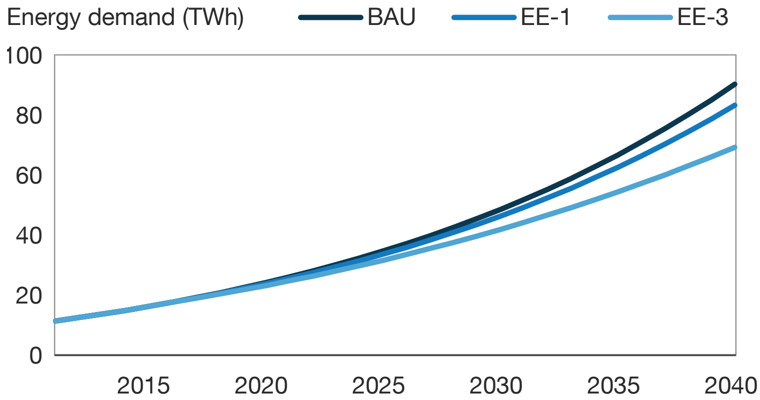
Today traditional biomass for heating purposes is mainly used in the rural areas whereby electricity for heating and cooling is used in the urban centres of the country. In the future, further urbanisation and increasing living standards will lead to a substantial growth of electricity use for space conditioning in Nepalese dwellings.

In a Business-as-usual (BAU) scenario which assumes no further energy efficiency improvements, it is estimated that the residential energy consumption for heating and cooling will rise from 12.1 TWh in 2011 to 90 TWh in 2040. Considering a slow dissemination of energy efficient building design and technologies (Scenario EE–1) consumption would increase to only 83.1 TWh. In the moderate energy efficiency scenario (EE–3) energy consumption is estimated to rise only to 69.2 TWh in 2040. That means energy savings of 23% could be achieved under a moderate energy efficiency scenario (EE–3) in 2040.

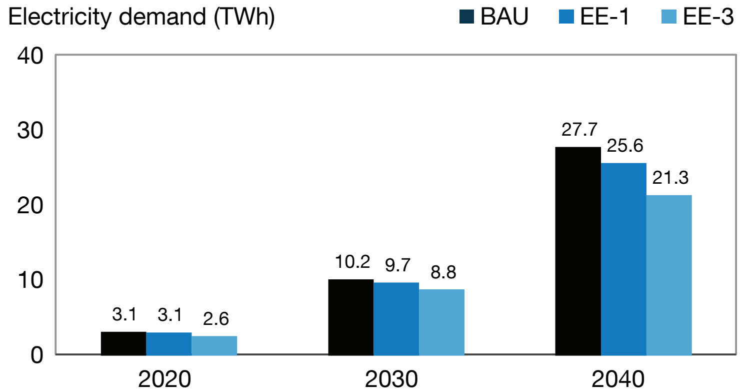
The residential energy scenario assumes that the share of electricity use for heating and cooling rises from 1.8% in 2011 to 30.8% in 2040. Consequently, in the BAU scenario residential buildings will consume annually 27.7 TWh of electricity in 2040. In the slow (EE–1) and moderate (EE–3) energy efficiency scenario electricity demand is predicted to rise to only 25.6 TWh and 21.3 TWh, respectively.

According to the BAU scenario the amount of electricity consumed by building's space conditioning systems in 2040 will rise by a factor of more than hundred. This will increase the need to expand the power supply side drastically. Having experienced the severe impact of the current power crisis which is hampering the economic development in Nepal, demand side management should be on the priority agenda of policy makers. Slowing down consumption growth reduces the need for high investments in the construction of new hydro power plants.

The presented energy scenarios show that energy efficiency in buildings can considerably slow down the growth of the energy consumption. Therefore, government regulations and policy actions are indispensable to ensure a low carbon development path for the country.



(a) Energy demand



(b) Electricity demand

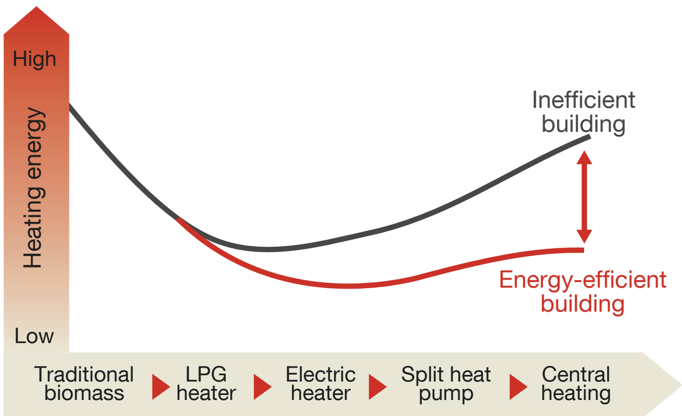
Figure 4.3: Energy demand projection of residential buildings in Nepal under different scenarios[a] (BAU: Business-as-usual scenario, EE-1: Slow energy efficiency scenario, EE-3: Moderate energy efficiency scenario)

[a] Assumptions described in appendix *Approach for energy saving scenarios*

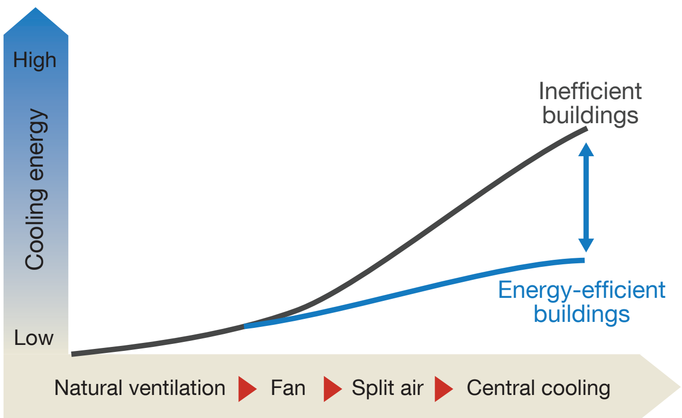
4.2 Critical transition to modern buildings

The modernisation of the Nepalese building sector is going through a critical transition. Economic development, population growth and fast urbanisation will lead to a substantial increase of energy consumption in buildings and the change of technology used for heating and cooling purposes. Figure 4.4a and Figure 4.4b illustrates the implication of switching heating and cooling technologies regarding energy consumption in buildings.

Traditional biomass which is still used for space heating in the rural areas will be soon replaced by modern heating technologies like liquefied petroleum gas (LPG) heaters and electric heaters and later by split heat pumps and central heating systems (see Figure 4.4a). The positive effect of switching to modern fuels is a reduction in energy intensity in the first run. However, more LPG for space heating has to be imported which will widen the trade deficit with India. Inefficient electric heaters will add substantial load to the power grid and worsen the power deficit, if the further expansion of the electricity generation is not sufficient to cover the additional demand. Modern split heat pumps can provide space heating at higher



(a) Heating energy



(b) Cooling energy

Figure 4.4: Technology transition and building energy use for heating and cooling in Nepal

efficiency than electric heaters. Still they imply a growth of the electricity demand growth. At a later stage central heating systems might be disseminated in the market due to higher comfort needs. This transition can also be critical if such systems rely on imported fossils.

Currently, most buildings in Nepal are cooled by natural ventilation because thermal comfort requirements are still very low compared to the developed world. However, there is a trend to install modern cooling technologies like fans and window air conditioners in office buildings. The dissemination of these technologies in the whole building sector will add electricity load to the power grid and, consequently, will be critical for the reliability of the power supply system. In the cooling dominated climate region central air conditioning system might become a standard technology in the future to fulfil higher thermal comfort standards.

The transition to buildings with modern space conditioning technologies that are more energy intensive will consequently lead to an substantial growth of energy consumption. In particular, the use of so called modern fuels like electricity and fossil fuels will increase. The consumption growth can only be slowed down by promoting energy-efficient building design and the use of highly-efficient space conditioning systems. Building design should optimise the use of natural resources for passive heating and cooling as well as natural ventilation. In the heating dominated climate zone building envelope insulation is critical to reduce the energy demand of mechanical heating systems. In the cooling dominated regions solar control is required to avoid overheating and reduce the energy demand of active cooling systems.

Projections for Nepal's energy sector indicate that the transition from traditional and fossil fuels to electricity is imminent [58]. It is predicted that the electricity supply will continue to be based on hydro power which is free of climate-damaging carbon emissions. Hence, the switch to space conditioning systems that rely solely on electricity might become the most environmentally friendly option. However, the current critical situation of the power supply is casting doubts with regard to such a scenario being feasible. Therefore, the integration of decentralised renewable energy systems into modern heating and cooling systems is highly recommended.

4.3 Limitations of the study and future research

This PhD research is the first comprehensive study on climate-responsive design and energy efficiency in buildings conducted in the context of the developing country of Nepal. Recognising the importance of traditional knowledge, a large number of vernacular houses in different climate regions of the country were analysed to identify passive design strategies for each climate.

Furthermore, the first bioclimatic zoning for Nepal was developed analysing a climate data from all of the country. Due to the climatic diversity within the Nepalese territory, the bioclimatic zoning for building design is essential to develop and introduce energy-efficient design guidelines or an energy conservation building code.

Finally, the effectiveness of passive design strategies for each climate zone was evaluated in a quantitative manner for one sub-sector (hotel buildings) and cost-effective insulation levels for the building envelope are proposed. The quantification of energy savings and cost-effectiveness of passive design strategies resulted in design guidelines for energy-efficient hotel buildings in Nepal which can be used to develop an energy conservation building code.

It was not in the scope of this research to cover all aspects and areas of energy efficiency in buildings in Nepal. Few important issues were selected that have been identified as crucial to set the foundation. Thereby, the focus was on the architectural design to reduce the operational energy demand for space heating and cooling. Energy consumption for lighting and appliances was not considered. Similarly, the topic of embodied energy that can amount to a substantial share of the building's life cycle energy demand was not in the scope of this study.

Conducting research in developing countries like Nepal is facing the challenge of the lack of reliable data, especially with regard to the building stock. Monitoring studies on energy performance of buildings were not yet conducted. Climate data in form of a typical meteorological year, which is the main input to conduct thermal energy simulation, is only available for two locations in the whole country. Therefore, this doctoral research had either to collect and generate the needed data or to make reasonable assumptions.

Future research in the field of energy efficiency in buildings in Nepal is needed to consolidate the findings of this research. Surveys and measurement-based studies on the energy use in buildings should be conducted for different building types and in the different climate zone to fully understand the dimension of the growing energy consumption.

Recently, few Nepalese architects and building owners have started to implement energy-efficient design strategies in newly constructed buildings. These pioneer designs should be analysed and monitored to find out which design strategies are effective to provide thermal comfort with minimum energy input.

Further simulation-based studies are needed to investigate which passive design measures are effective in building typologies other than hotels. Consequently, building sub-sectors can be identified where policy intervention is most needed, leading to substantial energy savings. The focus on electricity savings will determine which actions are required to slow down the electricity consumption growth in buildings and, thus, to reduce the demand-supply gap in the power sector.

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Glossary

Absolute humidity: Absolute humidity is the measure of moisture (water vapour) in the air, regardless of temperature, and is expressed as grams of moisture per cubic meter or kilogram of air.

Base case model: In thermal building simulation, the base case model refers to a reference design of a building before starting to optimize the design to improve its thermal performance.

Bioclimatic design: Bioclimatic design considers the local climate conditions during the process of designing a building aiming to provide the best thermal indoor comfort without the need of mechanical means. Basic elements are passive systems which utilise natural sources (for example, sun, air, wind, vegetation, water, soil, sky) for heating, cooling and lighting.

Bioclimatic zoning: Bioclimatic zoning in the context of building design refers to a climate classification which is developed for building design. Many countries whose territory extents over several climate zones have developed such a zoning to establish standards and regulations for energy efficient building design.

Cooling degree day: Cooling degree day (CDD) is a measure of how much (in degrees), and for how long (in days), outside air temperature was higher than a specific base temperature (comfortable indoor temperature). It reflects the amount of energy that is needed to cool a building and is here calculated at a base temperature of 18.3℃ according to ASHRAE-method [35].

Cold stress: Cold stress refers to the condition that occurs when the human body do not feel comfortable. A cold environment forces the body to work harder to maintain its core temperature of 37℃. There are four factors which contribute to cold stress in buildings: low indoor temperatures, increased and cold air movement and dampness. If a person experiences cold stress depends also on personal factors such as clothing, metabolic heat, state of health and acclimatisation.

Climate change: The term climate change is used to describe the phenomena of rising global air temperatures and changing climate patterns which is mainly caused by human activities. Since the start of the industrialisation, human activities have released large amounts of carbon dioxide and other greenhouse gases into the atmosphere. The majority of greenhouse gases come from burning fossil fuels to produce energy, although deforestation, industrial processes, and some agricultural practices also emit gases into the atmosphere.

Climate-responsive design: Climate-responsive design is used as synonym for bioclimatic design (see above) and refers to the design practice that considers the local climate conditions at site to provide a comfortable indoor environment to the user and to reduce the energy demand of the building.

Cost effectiveness: Cost effectiveness is an economic measures to describe the relationship between monetary input and desired output. In the context of energy-efficient buildings a design measure is cost-effective when the additional investment cost is lower than energy cost savings over the building's life cycle (see also life cycle cost).

Energy saving scenario: Energy saving of energy efficiency scenarios provide a framework for exploring future energy demand in buildings, under different conditions. The starting point of the analysis is the business-as-usual (BAU) scenario which assumes that the level of energy efficiency in buildings does not improve in the future. An energy savings scenario explores how far the energy demand for buildings can be reduced if specific energy efficiency measures are implemented.

Energy efficiency: Energy efficiency refers to the effort to reduce the energy demand of buildings to provide thermal and visual comfort to its users. In short, energy efficiency means using less energy to provide the same level of comfort. The energy use intensity in kilowatt-hours per square meter is generally used to compare the levels of energy efficiency between different buildings.

Heat stress: Heat stress is a form of overheating that the occupants of a building may experience when the measures their body uses to regulate internal temperature begin to fail. It is dependent on a range of environmental factors like air temperature, air velocity, radiant temperature, relative humidity and the uniformity of conditions as well as personal factors such as clothing, metabolic heat, state of health and acclimatisation.

Heating degree day: Heating degree day (HDD) is a measurement which was developed to estimate the energy demand for heating a building. The heating requirements for a given building in a specific climate are directly proportional to the number of HDD in this climate. Heating degree days in this study are defined relative to the base temperature of 18℃ according to EUROSTAT-method [36].

Insulation: The term insulation refers to thermal building insulation which is one of the most important measures to reduce the energy consumption of buildings. Insulation reduces heat loss or heat gain through the building envelope and is a key factor to achieve thermal comfort for its occupants.

Life cycle cost: The life cycle cost of a building includes all recurring and non-recurring costs over the whole life span of the building. It includes acquisition and construction costs, operating and maintenance costs as well as residual values. The life cycle cost analysis

(LCCA) is a method for assessing the cost-effectiveness of energy efficiency measures. For example, with the help of LCCA it can be determined whether the incorporation of a high-performance HVAC or glazing system, which may increase initial cost but result in reduced operating and maintenance costs, is cost-effective or not.

Natural ventilation cooling: Natural ventilation cooling describes all design strategies that enhances the air movement into and within the building to cool down the indoor environment and increase the thermal comfort of the building user.

Passive cooling: Passive cooling includes all passive design strategies that reduce the need for mechanical cooling while maintaining thermal comfort. The most important measures are natural ventilation, thermal mass and orientation for cooling.

Passive design: Passive design concept uses natural resources instead of electricity or fuel to provide the best indoor comfort for building users. These strategies include daylighting, natural ventilation, and solar energy.

Passive solar heating: Passive solar heating includes all passive design strategies that reduce the need for mechanical heating while maintaining thermal comfort. The building's design is optimised to increase the solar heat gains during the cold period of the year.

Projection factor: The projection factor (PF) is the ratio of the horizontal depth of the external shading device (often overhang or fins) divided by the height of the fenestration.

Relative humidity: Relative humidity measures the moisture (water vapour) in the air relative to the temperature of the air. It is expressed as the amount of moisture in the air as a percentage of the total amount that could be held at its current temperature.

Solar heat gain coefficient: The solar heat gain coefficient (SHGC) refers to the solar energy transmittance of a whole window system considering the glazing and frame material as well as deviders and screens (if present).

Solar control: Solar control describes the process to design a building in such a way to minimize solar heat gains and, thus, reduces the need for active cooling. This can be achieved by measures like reducing the window area, optimising the building orientation or through the shading of windows.

Solar gain: Solar gain, also called solar heat gain, refers to the heat energy from the sun (solar radiation) which is collected by the building through windows, wall and roof raising the building's indoor temperature. The amount of solar gain increases with the ability of any intervening material to transmit or resist the radiation.

Thermal building simulation: Thermal building simulation is a computational dynamic method to analyse the thermal performance of a building design. The objective is to optimise the design with regard to energy demand while providing the best thermal and visual comfort for the users. Building simulation is also used for selecting and sizing of mechanical equipment or to predict the annual energy consumption of the building.

Thermal comfort: Thermal comfort is defined as "that condition of mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation." [59]. It depends on the air temperature, humidity, radiant temperature, air velocity, metabolic rates, clothing levels and acclimatisation. However, thermal comfort is highly subjective and difficult to measure because it is highly subjective. Thermal mass is particularly beneficial in climates with large diurnal temperature differences.

Thermal conductivity: Thermal conductivity describes the property of a material to conduct heat. It is measured in watts per meter and kelvin (W/mK). It is an important input parameter for thermal building simulation.

Thermal mass: Thermal mass is the ability of a material to absorb and store thermal energy. Building materials like concrete, bricks require a lot of thermal energy to change the temperature because of the high density. They are therefore said to have high thermal mass. Lightweight materials such as timber have low thermal mass. Depending on the climate, the appropriate application of thermal mass in buildings can be used to reduce the energy demand for heating and cooling. For example, thermal mass can store solar energy during the day and re-radiate it at night (see passive solar heating).

Thermal transmittance: Thermal transmittance, also known as U-value, describes the quantity of heat that passes through of a building structure divided by the difference in temperature across that structure. It takes heat loss due to conduction, convection and radiation into account. The units of measurement are W/m^2K. The better-insulated a structure is, the lower the thermal transmittance will be.

Traditional biomass: Traditional biomass includes firewood, charcoal, manure and crop residues which plays still a vital role in meeting the energy needs of mostly rural people in developing countries. In buildings, it is used for cooking and heating. Apart from being energetically inefficient and time consuming, the use of traditional biomass is connected to several severe health and environmental problems.

U-Value: The term U-Value, or thermal transmittance (see above), is the rate of heat transferred through a building structure, divided by the difference in temperature across that structure. U-values are measured in Watts per square metre per degree Kelvin (W/m^2K). The lower the U-value of a building component, the better it insulates. While a solid brick wall has an U-value of about 2.0 W/m^2K, a cavity wall without insulation of 1.5 W/m^2K and a very good insulated wall of 0.18 W/m^2K.

Appendices

Appendix A

Publication I

The following publication is part of this PhD research:

S. Bodach, W. Lang, and J. Hamhaber. “Climate responsive building design strategies of vernacular architecture in Nepal”. In: *Energy and Buildings* 81 (2014), pp. 227–242

Contribution:

I was a major contributor to this study. In close cooperation with the co-authors, I developed the research design, collected the data and conducted several field visits. The analysis and interpretation of the data was done mainly by me. All authors were involved into the critical revision of the manuscript and the final approval of the version to be published.

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Climate responsive building design strategies of vernacular architecture in Nepal

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ABSTRACT

Vernacular architecture is the result of hundreds of years of optimization to provide a comfortable shelter in a local climate using available materials and known construction technologies. Due to the absence of mechanical means, traditional buildings use solar passive measures to achieve thermal comfort conditions. In most developing countries it can be observed that with the modernization of the building sector this traditional knowledge of smart and climate responsive design is being lost. Instead the modern building design is dominated by universal architecture that neglects local climate conditions and traditional construction techniques and materials. This paper reviews examples of vernacular architecture and its building elements in Nepal and analyses in a qualitative manner which bioclimatic design strategies were applied.

1. Introduction

Worldwide around 40% of energy is consumed in buildings [1]. Due to population growth, increased urbanization and improvements of living standards most of energy consuming buildings will be located in the urban centers of the developing world. The depletion of energy resources and the risk of climate change are demanding for a sustainable development path based on renewable energies and energy efficiency [2]. Climate responsive or solar passive building design can play a significant role in reducing the energy demand of buildings without compromising modern living standards.

The most important function of buildings is to provide shelter with appropriate thermal and visual indoor comfort for its occupants. The comfort level in a building depends upon the designs in combination with the outdoor climate. Design irrespective to climatic conditions means either to create uncomfortable indoor environments or to increase the need for maintaining thermal comfort through artificial means. As our ancestors had fewer technologies available for heating and cooling, vernacular houses are mainly designed to optimize the use of natural resources like the sun and wind [3–7]. Several studies have proven that better thermal performance can be achieved by passive measures in vernacular architecture [6–9]. The developing world's construction practices until recently were basically grounded onto this knowledge of traditional building techniques. However, modernization together with the need of effective and fast provision of shelters for the increasing population has flooded the market with new building designs, technologies and materials. These are rapidly accepted by users who demand for such designs and express increased thermal comfort expectations. The group of new building professionals does often apply new designs without considering local climate conditions.

Consequently, traditional houses are disappearing and the knowledge about its construction practices is slowly forgotten. Therefore, the need to document this knowledge of traditional constructions practices is evident. Few studies [10–12] have analyzed vernacular architecture from specific locations of Nepal in regard to climate responsiveness. This research is the first comprehensive study on solar passive design features of a large number of vernacular houses from all over the country. Following the principle "Learning from the past" [13], it might be the groundwork to develop new and more sustainable design strategies for the fast growing building sector that consider the local climatic conditions while aiming at the reduction of energy-intensive and expensive artificial means to provide comfort.

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2. Methodology and structure

Besides the climatic variations in Nepal, diversity of culture has led to a large range of different architectural expressions that are mostly documented by anthropologists, ethnologists and architects [14–21]. This research is based on a literature review and field research in Nepal.

In a first step, the paper gives an overview of the research country Nepal focusing on aspects that are most relevant for the development of vernacular architecture such as cultural and geographical diversity, local materials and climate.

Secondly, the climate conditions in Nepal are investigated, based on climate data from four weather stations that are representing the most important climatic zones of the country. The study identifies the dominating bioclimatic design strategies for the four predominating climates using three tools: Olgyay's bioclimatic chart [3], Givoni's psychrometric chart [4] and Mahoney Table [5]. Olgyay's bioclimatic chart is based on the outdoor climate factors considering humidity versus temperature [3]. Monthly data of minimum and maximum relative humidity and temperature are plotted onto the chart for each month. If the plotted line falls within the comfort zone, conditions are comfortable in the shade and in still air. If the line falls partly or totally outside of the comfort zone, corrective measures are necessary such as the use of solar radiation, air movement or evaporative cooling [3]. Givoni uses the psychrometric chart for the bioclimatic analysis [4]. A psychrometric chart is a graph of the thermodynamic parameters of moist air at a constant pressure. Givoni's chart predicts the comfort conditions within the building based on outside climate factor. As in Olgyay's chart the combination of monthly temperature and relative humidity indicates the recommended passive design strategy for each month. The chart contains the comfort zone, marked by a solid line and several zones for passive design strategies, namely passive solar heating, humidification, evaporative cooling, natural ventilation, and high thermal mass [4]. The Mahoney Table methodology is a set of reference tables that use monthly climate data of temperature, relative humidity and precipitation to calculate indicators for heat and cold stress as well as humid and arid conditions for each month. The combination of these indicators results into simple design recommendation, e.g. "reduce sun exposure", "compact building layout' or "medium sized openings" [5].

In the third step, this research analyses a variety of vernacular houses in Nepal, located in different climatic zones, in respect to their design and construction in order to determine the applied climate-responsive design strategies. For the analysis of traditional housing the approach of [22,23] was adapted. Both studies use a set of building features to analyze the design and construction techniques of the vernacular buildings in regard to climate-responsiveness. This research has selected the following features to assess the vernacular houses of Nepal in a qualitative manner: settlement pattern, building form and orientation, building stories and internal space arrangement, design and construction materials of walls, roof, foundation, floors, ceilings and openings.

Concluding, the study compares the design strategies identified in the second step based on bioclimatic approach with the actually applied strategies in the vernacular houses aiming to prove the hypothesis that traditional houses are very much adapted to the local climate conditions.

3. Research region

3.1. Geographical diversity

Nepal's territory expands about 800 km east–west and 200 km north–south and displays a highly varying topography (Fig. 1).

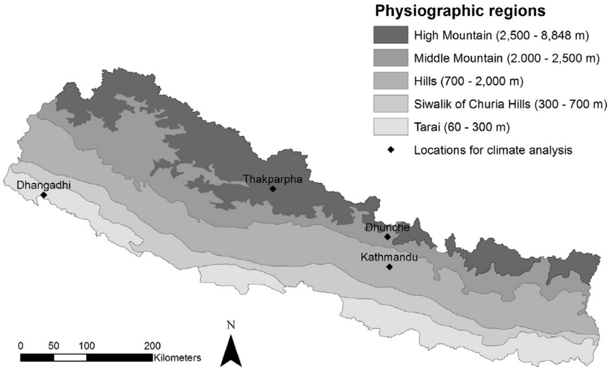

Fig. 1. Physiographic regions of Nepal Adapted from [38].

Altitude reaches from 65 m.a.s.l. (meters above sea level) to 8848 m.a.s.l. at the Mount Everest, the highest summit of the world. This is leading to a variety of climatic and vegetation zones. Climate has also strongly influenced the traditional architectures. Furthermore, Nepal's population is composed of a large number of different ethnic groups as a result of successive migration of Tibeto-Burman people from the north-east and Indo-Aryans from the south-west [24]. Each ethnic group has its own culture, religious beliefs as well as traditions, and in most cases, also language. Geographical diversity has resulted in diverse socio-economic and cultural patterns and, thus, in a variety of different architectural expressions. Typical houses of a number of ethnic groups (Tharu, Limbu, Newar, Sherpa, Tamang, Thakali, etc.) are analyzed within this study.

3.2. Traditional building materials

The local availability of certain building materials, in particular mineral based materials, depends on the geology of the location. Due to the geodynamic process in the Himalayan region Nepal's geology has a high complexity of many thrusting, faulting, folding and metamorphic effects. Nepal is divided into five distinct morpho-geotectonic zones from south to north: the Tarai Tectonic Zone, the Churia Zone (also called: Siwalik), the Lesser Himalayan Zone, the Higher Himalayan Zone and the Tibetan Tethyan Zone [25]. These five zones compromise a total number of eight geomorphic units which lead to different kind of available materials for building construction (Table 1). On the other hand climatic conditions determine the typical vegetation in a region and, thus, the availability of organic building materials like wood.

The Tarai Region's geology is mainly characterized by coarse, gravel, and finer sediments. Rich fertile alluvial soil is the basis for fertile agricultural land and dense Sal forest. Therefore, traditionally abundant reserves of wood, thatch, and further biogenic material as well as mud and sand are locally available for house construction.

In the Hilly Region of Nepal more stones (schist, phyllite, gneiss, granite, limestone and slate) are available and used as construction material. In larger valleys like Kathmandu lacustrine soil deposits are used for brick making. Sand and gravel is available from the riverbeds. Dense vegetation in the form of Sal or hill forests lead to the wide availability of timber. Fertile land and favorable climate conditions allow for the production of other vegetation based building materials like thatch.

The Himalayan Mountain Region provides abundant resources of stones, rocks and mud. Due to the small availability of fertile land

Table 1
Availability of traditional building materials.

Region	Geomorphic unit	Width (km)	Altitudes (m)	Main rock type	Soil type	Typical vegetation	Available traditional building materials
Tarai Region	Northern edge of Gangetic Plain	20–50	60–200	Alluvium: coarse, gravel in the north becoming finer southwards	Rich fertile alluvial soil, gravelly and sandy soil	Fertile agricultural land, dense Sal forest	Abundant: wood, thatch, daub, other biogenic materials, mud, sand, gravel Scarce: stones, rocks
Hilly Region	Churia Hills or Siwalik	10–50	200–1000	Sandstone, mudstone, shale, conglomerate	Gravelly and sandy soil	Sal forest	Abundant: stones, slate, timber, thatch, clay for brick making, sand, gravel
	Dun Valleys	5–30	200–300	Alluvium: coarse to fine sediments	Rich fertile alluvial soil	Sal forest	
	Mahabharat Range	10–35	1000–2500	Schist, phyllite, gneiss, quartzite, granite, limestone, slate	Fertile residual soil	Along middle slope: hill forest,	
	Middle Mountain	40–60	200–2000	Schist, phyllite, gneiss, quartzite, granite, limestone, in valleys: also finer alluvial sediments	Fertile residual soil, in valleys: Lacustrine soil (fertile and clay for brick making)	Mixed evergreen forest, open grazing and woodlands	
Himalayan Region (Mountain)	Fore Himalaya	20–70	2000–5000	Gneisses, schists and marbles	Low fertile glacial soil	Evergreen coniferous forest up to 4000 m, alpine grassland up to 4500 m	Abundant: stones, rocks, mud Scarce: timber and other biogenic materials
	Higher Himalaya	10–60	>5000	Gneisses, schists and marbles	Low fertile glacial soil	No vegetation	
	Inner and Trans Himalayan Valleys	5–50	2500–4000	Gneisses, schists and marbles; in Trans Himalayan Valley: also finer sediments from limestone, shale, sandstone	Low fertile glacial soil	Scarce vegetation	

Adapted from ([1,16–18]9).

and the harsh climatic condition timber and other organic materials for building purposes are rather scarce.

3.3. Climate analysis

Nepal has large climatic variations from hot sub-tropical climate to cold tundra climate. Several geographical factors influence the climate of the country, like latitude, altitude, slope orientation, prevailing as well local winds, and vegetation [24]. Two climate classifications are presented in the following. However, this study uses the more detailed country specific classification from Shrestha [24].

According to the global Koeppen-Geiger Climate classification [26] Nepal has four climate zones: warm climate with dry winters and hot summers (Cwa), warm climate with dry winters and warm summers (Cwb), snow climate with dry and cold winter and cool summer (Dwc) and tundra climate (ET).

Shrestha [24] divides Nepal into five climatic regions, namely, sub-tropical, warm temperate, cool temperate, alpine and tundra climate (Table 2). Nepal's climate has two main seasons: winter that lasts roughly from October to March and summer from April to September. Due to the fact that Nepal's climate is strongly influenced by the Monsoon the summer season can be subdivided into a hot and dry period (from April till mid-June) and a warm and rainy period (from mid-June till September) [24]. To evaluate the bioclimatic or climate-responsive building design strategies for Nepal, local climate data from four typical locations of Nepal were collected and analyzed. Tundra climate is not considered in the analysis due to the fact that there are very few settlements above 5000 m.a.s.l. Fig. 2 illustrated the climate conditions of four location (see Fig. 1), namely Dhanghadi, Kathmandu, Dhunche, and Thakmarpha based on monthly data series of 36, 35, 22, and 34 years, respectively.

Dhanghadi (28°48′ N, 80°33′ E) is situated in the Far western Tarai of Nepal has sub-tropical climate dominated by the monsoon (Koeppen: Cwa). During winter months the mean temperature is about 15 °C. Summers in Dhanghadi are very hot exceeding temperatures well above 30 °C. During winter and the dry summer season the monthly average precipitation is between 4 mm and 72 mm. When monsoon starts in June the rainfall increases up to 550 mm per month.

Kathmandu (27°42′ N, 85°22′ E) is representing the warm temperate climate of Nepal that is mainly dominant in the Hilly Region (Koeppen: Cwb). During summer outdoor conditions are comfortable with average temperatures between 20 and 24 °C. In winter the mean temperature drops down to 10 °C. In January minimum temperatures of 2 °C can be reached during night time. The dry season has monthly precipitation between 9 mm and 106 mm while during rainy season 365 mm are expected in average.

Dhunche (28°48′ N, 85°18′ E) situated in the Himalayan Mountains of Nepal at an elevation of almost 2000 m is selected to represent the cool temperate climate (Koeppen: Dwc). Summers are significantly cooler than in Kathmandu while average temperature during winters are only little colder. However, Dhunche is considerably more humid with an annual rainfall of almost 2000 mm. The lowest precipitation occurs in November and December. Most rain falls in July and August.

Thakmarpha (28°45′ N, 83°42′ E) is located in the rain shadow of Annapurna range having a dry and cold alpine climate (Koeppen: Dwc). In contrast to the three other selected locations Thakmarpha has a very low annual precipitation. During winter, temperature drops below 0 °C. In summer season the mean maximum temperatures rises up to 21 °C. Monthly monsoon precipitation is only about one tenth (44–67 mm) compared to the sub-tropical Tarai.

Table 2
Nepal's climatic zone (after [24]).

Climatic zone	Altitude	Mean temperature		Annual average precipitation	Selected locations
		Winter	Summer		
Sub-tropical	0–1200 m	15 °C	>30 °C	100–200 mm	Dhanghadi
Warm temperate	1200–2100 m	10 °C	24–30 °C	100–200 mm	Kathmandu
Cool temperate	2100–3300 m	<5 °C	20 °C	150 mm	Dhunche
Alpine	3300–5000 m	<0 °C	10–15 °C	25–50 mm in snow	Thakmarpha
Tundra	Above 5000 m	Below 0 °C		Snowfall	

4. Climate-responsive design strategies for Nepal

For the four representative locations the following design recommendations were identified by using Olgyay's bioclimatic chart [3], Givoni's psychrometric chart [4] and Mahoney Table [5] as described in the methodology above. Exemplarily, Givoni charts for four climates are shown in Fig. 3.

4.1. Sub-tropical climate

The enhancement of air movement is essential for the sub-tropical climate of Nepal. It is recommended to allocate rooms single-banked and provide permanent provision for air movement, e.g. through cross or stack ventilation. According to the Mahoney Table (Table 3) houses should be oriented north and south (long axis east–west) to reduce solar heat gains, particularly during the hot season. Openings should be of medium size (20–40% of outer wall area) and exclude direct sunlight during summer months through shading devices. High thermal mass with night ventilation might provide thermal comfort, particularly during the hot and dry summer period. However, light building materials are recommended for the hot and humid monsoon season. Light, well insulated roofs are recommendable for this climate. Olgyay's chart and Givoni's chart indicates that solar radiation in form of solar passive heating can be sufficient to provide thermal comfort during the short winter period. The protection of the building from heavy monsoon rain is necessary according to the Mahoney Table (Table 3).

4.2. Warm temperate climate

Temperature in Nepal's warm temperate climate does not drop down drastically during winter. Therefore, solar radiation combined with thermal mass of the building can keep the indoor temperature at a comfortable level. Buildings should be oriented with the longer façade toward south and have medium sized openings; by this way solar penetration of the south façade could provide solar heat gains in winter (when the sun angle is low) and reduce overheating in summer. Shading devices for windows are needed for the summer period. From December to January active solar or conventional heating might be partly needed. The Mahoney Table recommends heavy external and internal walls and light but well insulated roofs. However, according to Givoni's chart thermal mass is only favorable during April and May to balance the internal temperature swing (Fig. 3). In humid summer months air movement is the essential bioclimatic design strategy for Nepal's warm temperate climate. Therefore, single-banked room arrangement or other means of natural ventilation are recommended (Table 3). Heavy rains during monsoon season claim for protection and adequate rainwater drainage.

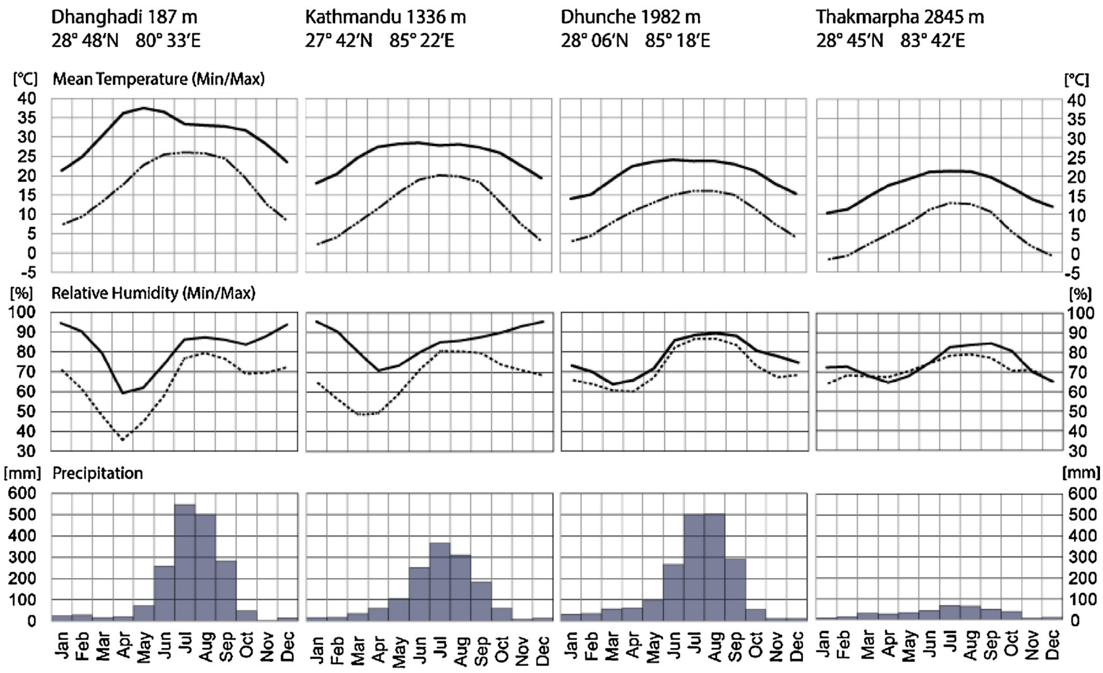

Fig. 2. Climate diagrams of four selected locations in Nepal (after [39]).

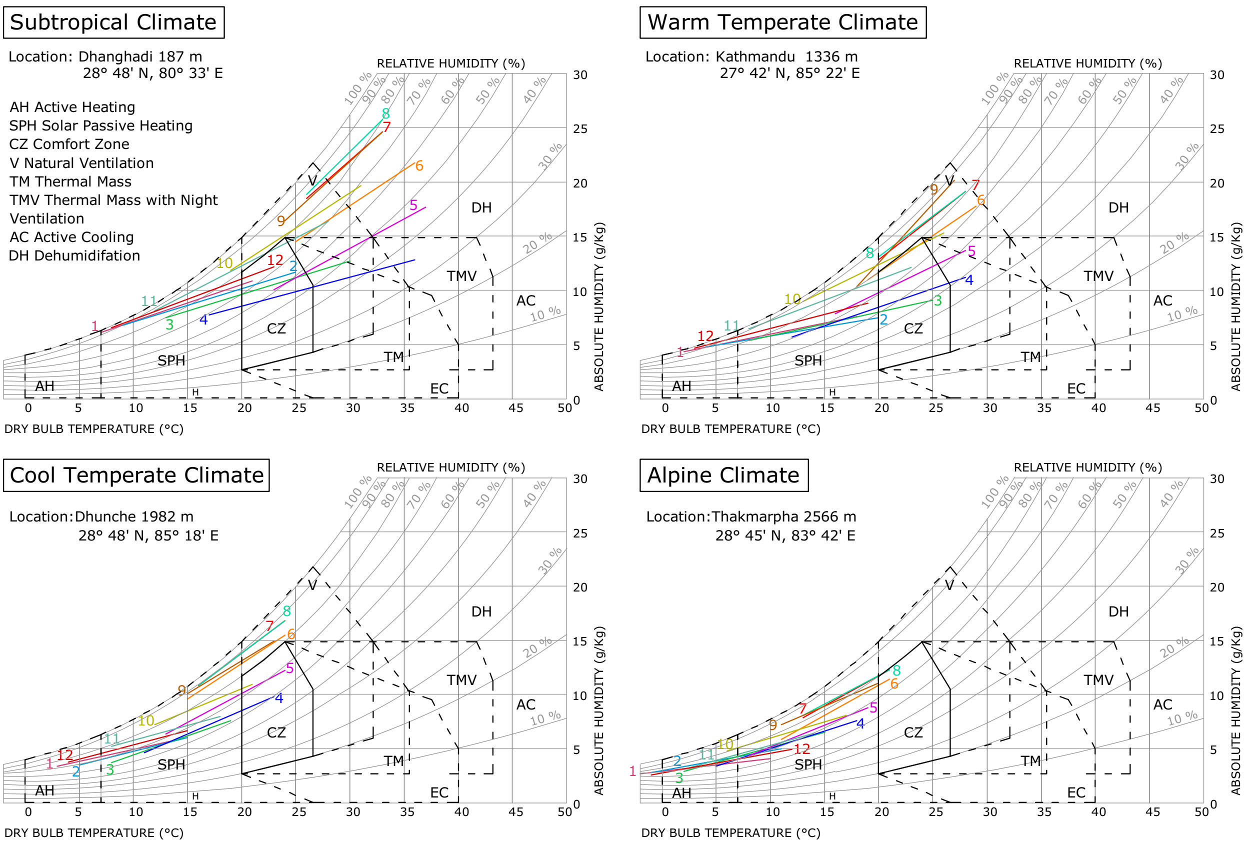

Fig. 3. Givoni's bioclimatic chart for four representative climate zones of Nepal.

4.3. *Cool temperate climate*

In cool temperate climate the use of solar radiation for passive heating is an effective design strategy during the longer winter period from October to March. In contrast to warm temperate climate a compact building layout is recommended by the Mahoney Table. During half of the year active solar or conventional heating is needed, particularly during night time. However, due to high solar radiation in winter solar passive heating combined with thermal mass (heavy walls and floors with thermal time-lag of more than 8 h) can reduce the need for conventional heating considerably. The rest of the year passive solar heating solely can provide comfort during cool nights. From June to September natural ventilation of the building is needed to avoid over-heating during the day (Table 3). According to Mahoney Table openings should be medium sized and protection from heavy rains as well as adequate rainwater drainage is necessary.

4.4. *Alpine climate*

In contrast to the conditions within the cool temperate climate zone, Nepal's alpine climate is far colder and dryer. Protection from the cold is necessary from October to April (Table 3). Therefore, compact building layout and small openings (15–25% of outer wall area) are recommended. According to the Mahoney Table room arrangement should be double-banked with temporary provision for air movement during summer days. Heavy external and internal walls are dominant climate-responsive design strategies to enhance solar passive heating effect for large temperature swing between day and night. In contrast to Nepal's temperate climates heavy roofs with thermal lag of more than eight hours are desired. Active solar or artificial heating is required during long winter periods. In summer nights comfort can be achieved if the building's thermal mass can store enough heat that is gained from solar radiation during the day. Low precipitation amounts

Table 3
Recommended design strategies for each month in different climate zones of Nepal according to Mahoney Table.

Design strategy	Subtropical climate											
	J	F	M	A	M	J	J	A	S	O	N	D
H1: Air movement essential							■	■	■	■		
H2: Air movement desirable		■										
H3: Rain protection necessary						■	■	■	■			
A1: Thermal capacity			■	■	■	■						
A2: Outdoor sleeping				■								
A3: Protection from cold	■											

Design strategy	Warm temperate climate											
	J	F	M	A	M	J	J	A	S	O	N	D
H1: Air movement essential						■	■	■	■	■		
H2: Air movement desirable		■	■	■	■	■	■	■	■	■	■	
H3: Rain protection necessary						■	■	■				
A1: Thermal capacity			■	■	■							
A2: Outdoor sleeping												
A3: Protection from cold	■											■

Design strategy	Cool temperate climate											
	J	F	M	A	M	J	J	A	S	O	N	D
H1: Air movement essential						■						
H2: Air movement desirable						■	■	■	■	■		
H3: Rain protection necessary						■	■	■	■			
A1: Thermal capacity	■	■	■	■	■							
A2: Outdoor sleeping												
A3: Protection from cold	■	■	■								■	■

Design strategy	Alpine climate											
	J	F	M	A	M	J	J	A	S	O	N	D
H1: Air movement essential												
H2: Air movement desirable						■	■	■	■			
H3: Rain protection necessary												
A1: Thermal capacity	■	■	■								■	■
A2: Outdoor sleeping												
A3: Protection from cold	■	■	■	■						■	■	■

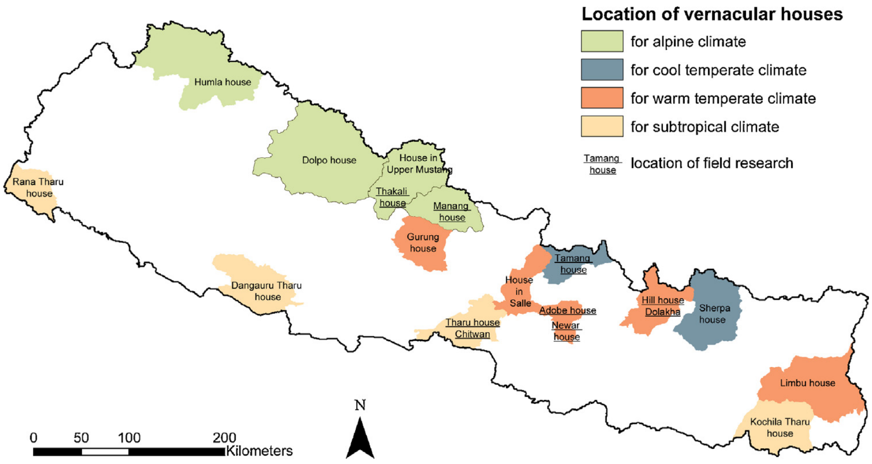

Fig. 4. Nepal map with location of analyzed vernacular houses.

eliminate the need to protect the building from heavy rains or high humidity.

5. Climate-responsive design in vernacular houses of different climate regions

A total number of 19 vernacular house are analyzed in the following according to the climate classification. The locations of the houses are shown on the map in Fig. 4.

5.1. Sub-tropical climate

The analysis of vernacular architecture in Nepal's subtropical climate refers to the following houses: Tharu houses in Chitwan (field research), Traditional Tarai houses [12,27], Rana Tharu house in Kanchanpur district of Far-western region [15], Dangaura Tharu house in Dang district of Mid-western Region [15,16] and Eastern Kochila Tharu in Morang and Sunsari of Eastern Nepal [15].

Due to the dominating tropical monsoon climate houses have to protect from heat and heavy rainfall [27]. Local materials mainly used are cane, timber and thatch [12]. They lead to the design of a comfortable 'breathing' house that means the building envelope is rather permeable and enhance natural ventilation [15].

5.1.1. Settlement pattern

The traditional settlement pattern in sub-tropical climate of Nepal is rather loose than dense. Tharu houses are either loosely situated along the road or they create clusters of semi-closed compounds [15,16]. Rana Tharu houses are arranged around a courtyard that is open to at least one side so that breezy winds can flow through the settlement. In the Dangaura Tharu village the long houses are arranged in one single row along the road with a wide open yard in front of each house [12]. This facilitates easy penetration of air through the houses.

5.1.2. Building form and orientation

The buildings have rectangular floor plans that are enclosed with low walls, sometimes no higher than 75 cm [12]. Dangaura and Eastern Kochila Tharu houses are found to be typical Longhouses while Rana Tharu houses have a more compact floor plan. The longer axis of Dangaura Tharu houses is more than twice of the shorter axis. The longer facade is typically oriented north–south which reduces the exposure to the sun.

5.1.3. Building stories and internal space arrangement

Most vernacular houses in Tarai have only one single floor or, like Rana Tharu houses, a ground floor with a mezzanine that is used as storage [15]. They have high ceilings for enhancing permanent ventilation that is strongly needed in this hot and humid climate. However, due to increasing urbanization and higher settlement density one of the Tharu studied houses in the Eastern Nepal was found to be of two-story.

The spaces in the studied houses are organized more in a horizontal manner. The internal space is almost undivided and, thus, enhances a continuous natural circulation of cool air coming from the shaded area below the eaves [12]. The studied Longhouses have only one division that does not reach the roof so that air can freely circulate (Fig. 5). In Rana Tharu houses big vessels, which store grain, are used for dividing the space. In all Tharu houses semi-open spaces in form of a veranda are occupying a large part of the floor plan. The verandas are shaded by the roof overhang and provide an additional comfortable space for daily activities (Fig. 6). Having two story houses, the Eastern Kochila Tharus use the second floor mainly as sleeping rooms and storage. One-third of the second floor plan consists of a veranda that provides a breezy semi-open sleeping space for hot and humid summer months [15].

5.1.4. Walls

The walls of traditional Tarai houses are rather light and mostly made of wattle and daub [27]. The upper portion of the exterior wall is observed to be of bamboo strips that are loosely woven into an open mesh which provide day lighting and permanent ventilation. Unplastered walls of wood or reed have random gaps. External walls might also be made of thin woven cane mats tied onto a timber frame, rendered with mud plaster and white washed [12].

5.1.5. Roof

Most traditional roofs in Nepal's subtropical climate are made of thatch in the form of a pitched roof [12,15,16]. The triangular opening at either end and the low windows ensures the permanent inflow of air from the shaded area below the eaves that leads to inside temperatures that are usually much lower than outside temperatures [12] (Fig. 7). Dangaura and Kochila Tharu houses have also light, well insulating thatch roofs. The wide roof overhang protects walls from direct sun radiation. Verandas are formed by extending the roofs and provide a comfortable place to work and even sleep at night [27].

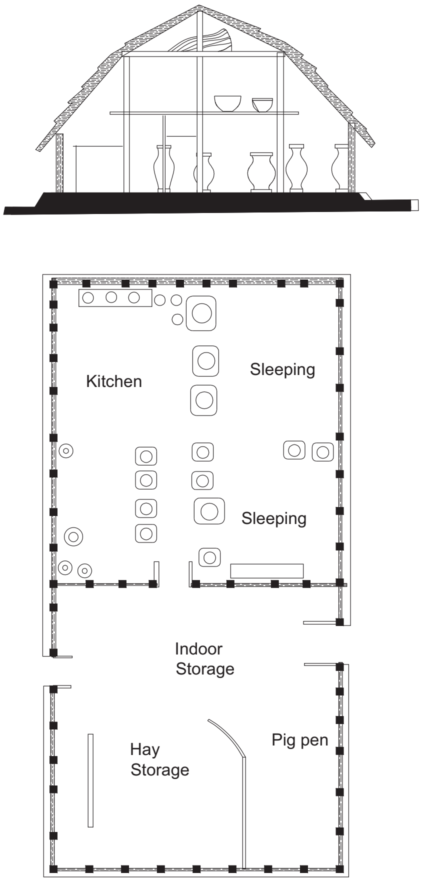

Fig. 5. Floor plan and section of Dangaura Tharu House (after [15]).

5.1.6. Foundation, floor and ceiling

Typically Tharu houses are found on a plinth made of stone or earth to protect the interior from flooding during raining season [12]. Some houses are built on wooden piling from 90 to 300 cm for the same reason [27]. The elevation from the ground by piling as well as high ceilings enhances air circulation within the building. Floors are made of compacted earth, clay tiles or locally available stones that are possibly covered by cement plaster.

Fig. 6. Tharu house with wide roof overhang and shaded veranda in Chitwan.

Fig. 7. Gable opening for air circulation in Tharu House, Chitwan.

5.1.7. Openings

Buildings have very few and low windows that together with an opening in the roof enhance the air circulation to provide comfort during hot and humid summer months [12]. Shading of the windows is provided through roof overhangs and the planting of trees around the buildings [27].

5.1.8. Results

It was observed that settlements are arranged by a loose pattern that allows air penetration – a typical design strategy for hot and humid climates. Rectangular building form and horizontal space arrangement in one story is dominant. Wall and roofing materials are rather light than heavy and are often permeable to air. The high and almost undivided interior space together with the openings in wall and roof enhances the natural ventilation within the building. In some houses openings are located in such a way to foster stack ventilation. Wide roof overhangs including the provision of shaded veranda space reduces the direct solar gain through walls and openings. For comparison characteristics of all analyzed houses in subtropical climate are listed in Table 4.

Concluding, the traditional house design in subtropical climate of Nepal is very climate responsive. Main strategies like enhancing air movement within the building and protecting from the strong solar radiating are considered.

5.2. Warm temperate climate

Representing the traditional architecture in the warm temperate climate of Nepal, house typologies from different ethnic groups and locations in the Hilly Region were studied, including Hill houses in Dolakha district (field research), Houses in Salle in Dhading district [28], Newar houses in Kathmandu valley ([14,20,21], field research), the Indo-Nepalese house in central Nepal [16], an Adobe house in Kathmandu Valley (field research), the Gurung houses in Thak Village of Kaski district [12,29] and the Limbu house in Eastern Nepal [16,30,31].

5.2.1. Settlement pattern

Settlements in Nepal's warm temperate hill climate are rather of scattered and dispersed character. Houses are placed on the hill terraces along the slope surrounded by each family's fields. The villages and towns built by the tribe of Newars only, have a denser settlement pattern with its characteristic courtyards [21].

5.2.2. Building form and orientation

There are several types of building forms strongly depending on settlement density and ethnicity. Newar houses being part of compact settlement with high density are arranged to create interconnected courtyards [14,20]. The courtyards are designed in such a way to allow solar penetration of buildings and provide a warmer outside space for all kind of household activities during sunny winter days. In contrast to Newar settlements, other traditional houses in hilly Nepal are rather dispersed [16]. Most of the houses have a rectangular shape except Gurung houses that have a round floor plan [12]. Often the elongated plan is situated on the sunny slope of the hills with the longer facade facing toward the south, south-east or south-west (Fig. 11). Larger windows are placed in the longer facade, i.e. facing the sun. Around the open courtyard, which is situated in front of the main building, one or two annex buildings for cattle or storage can be placed. The studied Limbu house was found to have a more compact floor plan. And in contrast to other dispersed houses the shorter facade is faced southwards. Due to religious beliefs Limbu houses are always located parallel to a river bed [30].

5.2.3. Building stories and internal space arrangement

It was observed that traditional houses in non-Newar settlements have not more than two stories. Gurung and Limbu houses have only one and a half stories; the ground floor is the main living area [12,29]. Newar houses have typically three or three and a half stories [11,20,21]. Until the early 16th century residential houses were not allowed to exceed height of the temples in Newar settlements [20]. The low room height being between 1.6 and 1.9 m makes it easier to heat the building during winter season.

Depending on the number of stories, building space is arranged either horizontally or vertically. Having only one a half floor, the space in Limbu and Gurung houses is organized more horizontally. The interior of the Gurung house is an almost open space with only few divisions having a fodder under the roof [29].

In Indo-Nepalese houses the ground floor is also a big open space designated for activities like cooking, dining, meeting and worshipping which are sometimes visually divided by lower walls [16]. The first floor is primarily used as granary and storage for family's valuables and, possibly, as bedroom if the space in ground floor is not sufficient for all family members.

Similarly, in Hill Houses of Dolakha the kitchen and main living area are located on the ground floor while sleeping and storage functions are on the first floor. The space under the roof creates another half story and is used as storage; it is ventilated through small windows at each gable end. The access to the second floor is either provided by a wooden leader inside the building or outside, if the house has a balcony (Fig. 11). A very important part of the house is the veranda which is a semi-open space in front of longer facade normally covered by the roof or the balcony. Verandas and balconies often have closed sides to provide protection from cold wind.

Spaces in Newar houses are vertically planned (Fig. 8). The ground floor is only used for entering the house or sometimes as storage and creates a buffer to the cold and humid ground. The bedrooms are located in the first floor while the main living area is in the second floor. Both receive enough solar radiation through the windows to heat up the room during the day. The space under the roof (attic space) is used as kitchen with an open fireplace [11]. Due to the location of the kitchen on the top of the building, living and bed rooms are protected from overheating in summer. Rooms are found to be double-banked [11]. The courtyard of the Newar houses is an important semi-open space for work. It is designed in such a way to be sunny in winter and shaded in summer.

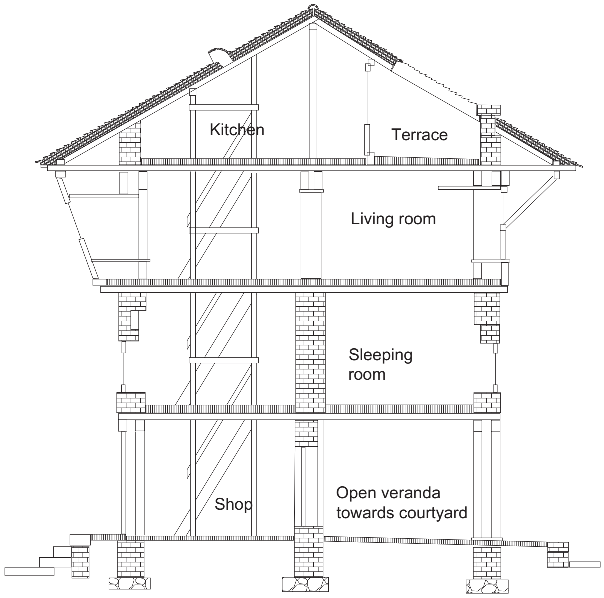

Fig. 8. Section of Newar house with vertical space arrangement (after [21]).

5.2.4. Walls

The walls of houses in Hilly Nepal are mostly made of locally available stones in structural bearing random rubble masonry. Clay and earth are used as mortar. The exterior walls can be up to half meter thick which leads to a high thermal mass of the building. Walls are mostly plastered inside and outside using white, ocher or red mud. The final plaster inside is a thin layer of fin red mud and cow dung is used [16]. Only Gurung houses are made of mud, timber cane and thatch [29]. The walls consist of timber planks and lathe covering both sides with a mixture of mud and cow dung [31]. Newar architecture being the most developed in the region is using sundried or burnt clay-bricks as main walling material (Fig. 9). The walls have a thickness between 28 cm and 70 cm, resulting in a high thermal mass of the building. The outer wall is made of burnt bricks while on the inner side sun-dried inside bricks are used [14,20]. The application of only sundried brick walls (adobe) is also common.

Fig. 9. Hill house in Dolakha with shaded terrace and balcony.

Table 4
Characteristics of vernacular houses in subtropical climate of Nepal.

	Tharu house in Chitwan	Traditional Tarai houses	Rana Tharu house	Dangaura Tharu house	Kochila Tharu house
Settlement pattern	Scattered clusters	Loose clusters of semi-enclosed compounds	Loose pattern around open courtyard	Loose, along the road side	Loose building clusters along road
Building form	Rectangular	Rectangular floor plan	Compact layout	Elongated	Elongated
Building orientation	n.s.	n.s.	Longer façade north–south wards	Longer side east–west oriented	Long facades east–west
Building stories	1	1	1.5	1	2
Internal space arrangement	Horizontal, few divisions	Horizontal manner, almost undivided open space	Horizontal, mezzanine used as storage	Horizontal, few division	Mainly horizontal, 2nd floor includes open veranda
Semi-open spaces	Veranda	Veranda	Open courtyard, veranda	Veranda	Open courtyard, veranda in second floor
Wall material	Wattle and daub, straw and mud, timber, bamboo	Mud plastered woven cane mat tied on timber frame	Mud plastered timber/bamboo walls	Low walls of wood and bamboo covered by mud layer	Lumber on timber structure
Wall thickness	Very thin	Thin, permeable to air	Thin	Thin	Thin, permeable to air
Roof material	Thatch	Thatch or tiles	Tiles	Bamboo lathes with thatch covering	Thatch
Roof type	Pitched roof	Hipped roofs	Pitched roof	Hipped roof	Pitched roof
Roof overhang	Wide	Wide	Wide	Large	Large
Foundation	Plinth of stone and mud	Stone plinth or wooden piling	Earth/stone plinth	Slightly raised platform	Earth/stone plinth
Floor	Compacted earth with fine mud layer	Compacted earth or clay tiles	n.s.	Covered by mud layer made	n.s.
Ceiling	High	High ceilings	High ceiling	High ceiling	n.s.
Openings	Very small	Upper part of exterior wall is made of loose bamboo strips	n.s.	Few and small openings	Few and very small, doors are largest openings

5.2.5. Roof

The typical roof type applied in vernacular architecture in the warm temperate climate of Nepal is the pitched roof supported by a timber structure and covered by locally available hatch, stone slates or tiles. A large roof overhang of minimum 50 cm protects the walls from the heavy monsoon rain and avoids solar penetration of the facade during summer [14,16]. In Central Nepal the roofs were typically covered by thatch that lasts properly maintained up to eight years [16]. In Dolakha's Hill houses slate on timber structure is the main roofing material. The pitched roofs of Limbu and Gurung houses are very steep and use thatch, straw or grass as roofing. Newar architecture has developed a water inclusive roof design of burnt clay tiles which are placed upon a mud layer of 4–10 cm [14,32].

5.2.6. Foundation, floors and ceiling

Most houses in warm temperate climate of Nepal have a stone foundation that protects from flooding during the monsoon season. The foundation of Newar houses is made of a 60–80 cm deep stone plinth [14,20]. In Indo-Nepalese houses and those studied in Dolakha a 30–50 cm thick stone platform serves as foundation of the building. This platform is often extended about 1.50 m at either one or more sides of the exterior walls to create a veranda which is used as semi open working space. The ceilings are very low (not more 1.80 m) to reduce the air volume that needs to be heated during the cold season. In all studied houses a wooden framework of pillars and beams is used to support the ceilings. It is covered by lathwork and rough casting of 20 cm mud layer and a final layer of a mixture of clay and cow dung [16]. In other houses clay or earth is used for flooring [32]. Wood was widely available in the hilly area and is, therefore, used as structural as well as covering material. The additional use of clay and earth increases the thermal mass of the floor and contribute to balance the diurnal temperature changes.

5.2.7. Openings

The openings in houses of Hilly Nepal are rather small, but larger than those in the mountain houses. The windows are mainly located in the longer facade that faces downhill and is mostly oriented southwards. The side and the back wall have often no openings except a small hole from the kitchen which is used as smoke outlet. In Newar houses the main living room has a big window with decorative wood carvings that allows solar radiation of lower angle to heat the room in winter [20] (Fig. 9). Many houses have grilled windows to protect from solar penetration in summer [12]. Remarkable, in Limbu houses the main entry door and larger windows are placed on the shorter facade of the building that is faced southwards [16]. Although most authors describe hilly houses have small windows, compared with mountain houses they are of medium size. The windows are almost always oriented southwards aiming to enhance solar heat gains during winter. The openings are often equipped with shutters that can be closed during cold nights in summer and the cold season. In this way the envelope tightness is increased and the heat losses are reduced.

All studied houses of Hilly Nepal use a large roof overhang to shade south facade and windows. In Indo-Nepalese houses the veranda that is located in front of the longer facade has a thatch covered timber roof structure to provide shading [16]. In the Limbu houses an overhanging timber structure is used to form a veranda surrounding the house in the first floor [16]. The Gurung houses have deep overhanging eaves restrained by brackets [12]. The roof overhang of Newar architecture is widely known because of his decorative character, particularly, in temples and palaces where fine wood carvings can be seen. Moreover, the roof overhang protects the walls from the heavy monsoon rain.

5.2.8. Results

It was observed that many building features of the different houses in warm temperate climate of Nepal are largely similar (Table 5). Most vernacular houses have a rectangular floor plan. The longer facade with the openings is often oriented southwards to enhance solar gains during winter. Due to the wide roof overhang the building facades and windows are shaded in summer. In the dense Newar settlements the smart arrangement of courtyards assures solar passive heating in winter and shading in summer. Generally, houses in this climate are of high thermal mass using locally available materials. Particularly, during sunny winter days

Table 5
Characteristics of vernacular houses in warm temperate climate of Nepal.

	Hill house in Dolakha	House in Salle	Newar house	Indo-Nepalese house	Adobe house	Gurung house	Limbu house
Settlement pattern	Scattered	Scattered	High	n.s.	High	Medium	Scattered
Building form	Rectangular floor plan	Rectangular elongated	Rectangular plan with interconnecting courtyards	Rectangular plan along terrace	Rectangular plan	Round shaped	Rectangular form
Building orientation	Longer side southwards	Longer side oriented downhill	n.s.	South, south-east or south-west	Main long façade south-west wards	n.s.	Parallel to river
Stories	2–2.5	2	3–3.5	2	2.5	1.5	1.5–2.5
Internal space arrangement	Ground floor: kitchen and living; 1st floor: sleeping, storage	Ground floor: veranda, kitchen bed and prayer room, 1st floor: bed rooms, storage, balcony	Vertically use of space: ground floor: storage; 1st floor: bedrooms; 2nd floor: living room; 3rd floor: kitchen	Dominant horizontally, 1st floor used as storage, provision of semi-open space	Vertically, ground floor: shop, storage, 1st floor living and bed room, 2nd floor: kitchen	Internally almost open space, few divisions, mezzanine as fodder	More horizontally, ground floor is main living area
Semi-open spaces	Shaded veranda and balcony	Closed veranda and balcony	Courtyard	Open courtyard	No	Veranda	Veranda and balcony
Wall material	Stone, plastered and painted	Stone and mud	Burnt brick (outside), sun dried brick with mortar (inside)	Stone-mud with mud plaster	Adobe wall (sun dried clay bricks)	Wooden lathe covered with mud	Stone and mud, white or ocher mud plaster
Wall thickness	40–50 cm	50 cm	28–70 cm	35–50 cm	50–60 cm	Thin	Thick
Roof material	Stone slates on timber structure	Thatch and stone slate	Burnt clay tiles on mud layer and timber structure	Thatch or slates on wooden roof structure	Burnt tiles on mud layer above timber structure	Thatch on timber structure	Thatch on timber structure
Roof type	Saddleback roof	Pitched roof	Gable roof	Pitched roof	Pitched roof	Steep	Steep pitched roof
Roof overhang	Wide	Yes	Wide	Yes	Wide	Wide	Wide
Foundation	Stone plinth covered by mud/earth	n.s.	60–80 cm deep stone plinth	30–50 cm stonework platform	Foundation of stones	Low plinth	Stone plinth
Floor	Mud layer	Mud/earth covered	n.s.	n.s.	Mud layer	Mud and cow dung	n.s.
Ceiling	Very low, wooden beams and lathwork	Wooden structure with lathwork and mud covering	Wooden beam	Wooden structure with lathwork and mud layer	Structure of timber and bamboo	n.s.	n.s.
Openings	Medium sized	Medium sized openings toward valley side	Small windows, only for living room large window	Small wooden windows on southwards facades	Rather small,	Very small, grilled windows	Medium sized windows

the thermal mass is favorable to store solar heat gains of the day for cooler nights. The low ceiling height reduces the air volume to be heated in the winter season. The vertical internal space arrangement of Newar houses is optimized for the cold winter because it creates buffer zones in the ground and the upper floor in order to keep the main living and sleeping spaces comfortable.

In summary, it can be said that the vernacular houses in Nepal's warm temperate climate are very well adapted to the local climate condition. They consider the most important climate-responsive design strategies like enhancing solar heat gains during winter and protecting from the strong solar radiation in summer.

5.3. Cool temperate climate

Representing vernacular architecture of Nepal's cool temperate mountain climate the houses and settlements of the following tribes and locations were studied and analyzed: Tamang tribe in Langtang region (field research) and Sherpa tribe in Khumbu village [17]. Khumbu village is located in Solukhumbu district in the North of Eastern development region while Langtang is part of Rasuwa district in central region north-west of Kathmandu valley.

5.3.1. Settlement pattern

Settlements in cool temperate climate are denser than those in warm temperate hills. Sherpa villages are mostly built on the beds of old lakes in broader valleys or on sizeable ledges between the mountainside and river gorges [17]. The settlements of the Tamang tribe are compactly built. Several houses are typically attached to each other reducing the exterior wall surface exposed to the coldness (Fig. 11). The streets of Tamang villages are usually paved with stones.

5.3.2. Building form and orientation

Traditional houses in this climate zone have a more elongated form than those in colder alpine climate [17]. Also L-shape can be found. Tamang houses in Langtang region have a compact rectangular shape. Being attached to each other they create a more elongated building volume. If possible the longer façade is oriented toward the sun to enhance solar gains.

The houses of the Sherpa tribe in Khumbu village (Everest region) stand in small groups together on the slopes of a natural amphitheater [17]. Their elongated building volume is generally standing parallel to the slope. Ground floors are partly built into the slope of the hill of mountain behind it (Fig. 10).

Fig. 10. Façade of Newar house with big wood carved window and large roof overhang.

5.3.3. Building stories and internal space arrangement

It was observed that Sherpa as well as Tamang houses have two stories [17]. In Sherpa houses the ground floor is used for storage and livestock, the main living area is situated in the first floor. Tamangs use the upper story for storage of grain and other household possessions, while the elevated ground floor is used as a kitchen, dining place, and bedroom. In Sherpa houses wooden stairs located inside the building lead to the upper floor; stairs in Tamang house are located outside on the main entry facade of the house. Sherpas use the roof partly as terrace with a small shed for lavatory [17]. Tamang houses have usually a balcony on the first floor and a veranda beneath it in front of the main entrance. In all houses the open hearth, normally located in the center of the kitchen, plays an important role because it is not only used for cooking. It is also the only comfortably warm place where the family members can sit during colder nights and in the winter season. The internal vertical space arrangement of these houses leads to thermal buffer zones which have an insulating effect to keep the main living room as warm as possible.

Semi-open spaces play also an important role in Nepal's traditional architectures in cool temperate climate. In front of Sherpa houses an open space or yard is foreseen where newly harvested crops are spread out for drying, are sorted and graded prior to storage and firewood is piled up for winter month [17]. The porch located at the entry to a Tamang house also serves as a protected

Fig. 11. Floor plan and elevation of Sherpa house (after [17]).

Table 6
Characteristics of vernacular houses in cool temperate climate of Nepal.

	Tamang houses	Sherpa houses
Location	Central mountain, Langtang region	Eastern mountain region
Settlement pattern	Attached houses, rather compact	Houses in small groups along the slope
Building form	Compact rectangular floor plan, attached houses	Elongated rectangular or L-shape
Building orientation	Main façade south-west wards	The longer side toward the slope
Stories	2	2
Internal space arrangement	Vertically, elevated ground floor is main leaving area with kitchen and sleeping, 1st floor storage	Vertically, ground floor as thermal buffer space
Semi-open spaces	Veranda and balcony	Veranda
Wall material	Unplastered stonework	Stonework dry or with mud mortar, mud plaster
Wall thickness	40–60 cm	up to 1 m
Roof material	Wood slat weighted with stones, stone slate (if available)	Wooden pillar and beam structure with heavy stone slabs
Roof type	Pitched roof	Pitched roof
Roof overhang	Yes	Yes
Foundation	Elevated ground floor adapting to the slope	Ground floor partly built into the slope
Floor	Wooden lathwork	Wooden floor with carpet
Ceiling	Low ceilings	Double wooden ceiling
Openings	Small wooden windows only in entry facade	Small openings, only one large living room window faced southwards

semi-open space. These semi-open spaces provide another comfortable place, e.g. in winter when the sun is shining.

5.3.4. Walls

Walls are made of locally available stones with a thickness of up to 1 m [17]. Stonework is made either dry or bound together with rudimentary mortar made of soft clayed earth. In Sherpa houses mostly inner and especially outer walls are plastered with clayed earth and then painted because the plaster is also an excellent weatherproofing material. In Tamang houses the outer walls are made of dry stonework while the entry façade of the first floor is made of timber. Inner walls of main living spaces are often planked with timber lathes.

5.3.5. Roof

Due to the heavy rains pitched roofs are more frequently used in the traditional architecture of the cool temperate mountain climate [17]. Either in Sherpa and Tamang houses the roof rest on a wooden pillar and beam structure. Wood or slate (if available) is often used as roofing material in the form of square or rectangular roofing tiles. Heavy stones are placed on top to prevent them from being blown off by heavy monsoon winds.

5.3.6. Foundation, floor and ceiling

The Sherpa houses in Khumbu village are built on a platform which is made of locally available stones. The double wooden ceilings of these houses are supported by a framework of timber pillars and beams. Carpets are often laid above the wooden floor in the main living areas [17].

Tamang houses are slightly elevated attached to each other forming a terrace structure. The interior structure including floors and ceiling are completely made of timber. Often the main entry façade is also timber cladded.

5.3.7. Openings

In Khumbu village doors and windows of the Sherpa houses are faced to south-east direction for an effective exposure to the winter Sun [17]. Also houses in Langtang village are observed to face south-east. No openings are placed in the back side of the houses which are not sun-faced. In Sherpa houses wooden windows with finely carved decoration and colorful paintings. In the main entry façade of Tamang house one decorated small window is placed as opening. The actual opening of those windows is rather small. Often shutters are used to close the openings completely during night and the cold winter season.

5.3.8. Results

The previous analysis shows that traditional settlements in cool temperate climate tend to be more compact than in the warmer climate zones (Table 6).

Locally available stones, which are used for walls and timber, are also the dominating material for floor, ceilings, interior cladding of wall and roofing. Like in warm temperate climate the high thermal mass of the building is favorable to store solar thermal gains during sunny winter days for the cooler nights. Due to the heavy precipitation during monsoon season roofs are pitched and mostly covered by wood slate and stones. Openings tend to be smaller than in warm temperate climate that leads to the reduction of heat losses. Internal spaces are arranged vertically creating a thermal buffer on the upper and lower level for the main living area.

In conclusion, the mountain houses in the cool temperate climate of Nepal are very well adapted to the local climate conditions. They fulfill the most important design strategy – compact building layout and orientation toward the Sun.

5.4. Alpine climate

Representing vernacular architecture of alpine climate, houses and settlements from the following areas in far-western, mid-western, and western development region of Nepal were analyzed: Humla [12,33], Dolpo [16], Upper and Lower Mustang ([11,34], field visit 2010), Thak Khola villages in Mustang district [16] and Manang [12,16]. All these locations are part of the Himalayan mountain range located on the northern stretch of Nepal between 2500 and 4600 m.a.s.l. (Humla – 3500 m.a.s.l., Dolpo – above 4000 m.a.s.l., Upper Mustang – 2800–4600 m.a.s.l.; Lower Mustang – 2500–3800 m.a.s.l., Manang – 3500 m.a.s.l.). In contrast to cool temperate climate, temperatures are lower and the amount of precipitation is very low throughout the whole year.

5.4.1. Settlement pattern

The villages in such a harsh and cold climate are very compact (Fig. 12). The buildings are often attached to each other creating small alleys that are protected from the cold wind and snow storms. In Braga (Manang district) the houses are grouped closely together sharing one or more exterior walls. In Dolpo the houses are also attached to one other but each house has its own outer wall [12]. Thakali villages are observed to be very compact although adjacent walls are not common.

Fig. 12. Typical attached Tamang house with elevated ground floor.

5.4.2. *Building form and orientation*

Compact building volumes with rectangular building shapes are dominant in Nepal's Alpine climate region [12,16,34]. Many houses in Manang have an almost square ground floor plan [16]. The compact building form reduces the surface-to-volume ratio and, thus, heat losses in this cold climate (Fig. 13). Houses are situated on the southern slope of hills or flat valleys to enhance solar heat gains [16,34]. In this way the high thermal mass of the building can be heated by the strong solar radiation during the day. In Manang closed courtyards are widely used to protect from the cold and strong winds. In Mustang narrow streets and high walls around the buildings marking the pathways have the same function. Other semi enclosed areas like terraces or rooftops are sometimes covered by overhangs or porches to give shade for the strong summer sun [33].

5.4.3. *Building stories and internal space arrangement*

Mountain houses in Nepal have at least two stories [27]. The analyzed buildings in Humla and Manang as well as typical Thakali houses have three levels [12,16]. The Dolpo houses were found to have two and a half stories [16]. In Upper Mustang two-story courtyard houses are dominant [11]. Multiple stories make the total building volume more compact which reduces the heat losses.

The space arrangement within these houses is mainly organized vertically. The ground and top floor are assigned to secondary use and have the effect of thermal buffer to keep the main living area in the first floor as warm as possible (Fig. 14). Animals are housed in the ground floor leading to increase indoor temperature due to their body heat. The main living area in the second floor is horizontally also surrounded by rooms of secondary use like storage, family treasure, etc. that are creating horizontal thermal buffer zones. In some houses the upper floor contains also a prayer room or a sleeping room for summer [11,12,16].

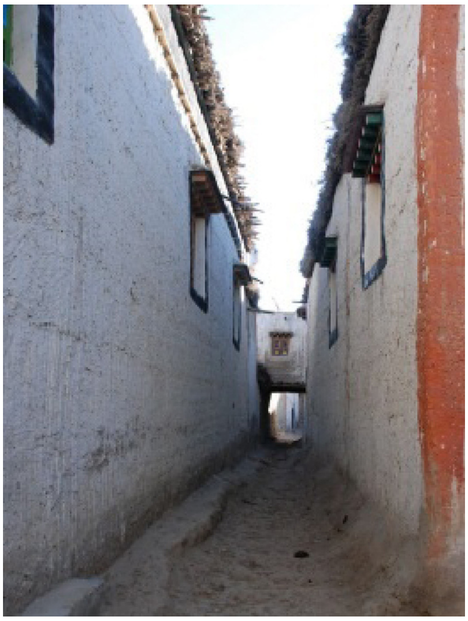

Fig. 13. Narrow lane of compact settlement structure in Upper Mustang.

The flat roofs are forming terraces that are used as open space for any kind of activities during sunny days. The studied shelters of Thakali people in Mustang and in Manang have a small courtyard [16] (see Fig. 14). Being located in a very dense settlement structure the courtyard allows the penetration of day light into almost all inner rooms of the houses.

Semi-open areas play an important role in providing a proper space for working outside of the house during day time. In Humla houses, semi-enclosed areas are built with loose-fitting timber structure in front of each room on the top and middle level [33]. This construction offers some protection from the cold southerly wind. These semi-enclosed areas measure about 6 m^2. Slight overhangs projecting from roofs might also form a semi-enclosed veranda in front of the house.

5.4.4. *Walls*

The walls are traditionally built of natural stone if locally available. In some areas also sun-dried mud bricks or rammed earth is used [27]. In Humla the studied house has an 45 cm massive wall that consist of thick stones and mud-mortar and is restrained by paired timber beams [12,33]. In Dolpo the ground floor walls

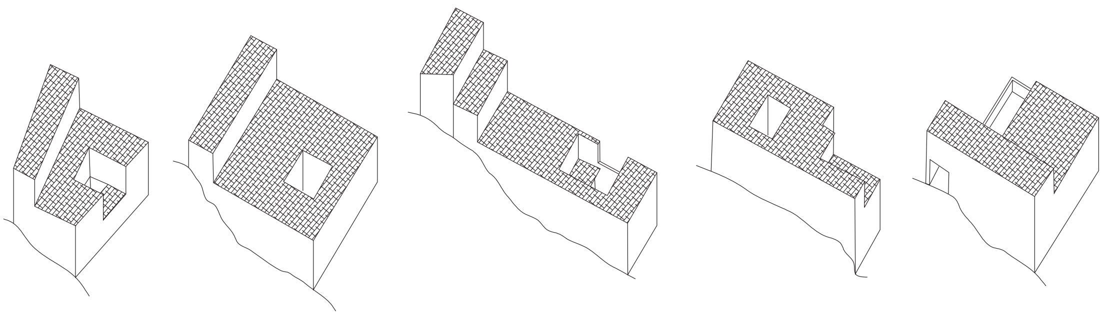

Fig. 14. Compact building typologies of Thakali houses in Marpha, Lower Mustang (after [16]).

are made of stone and mortar with an average thickness of 40 cm while the upper walls are made of lighter sundried bricks [16]. The settlements in Upper Mustang are characterized by mud and mud brick walls [34,35]. Vernacular houses of Thakali people are made of 50 cm thick flat stone masonry that is coated with white and red mud [16]. In summary, all houses are constructed using the most insulating material locally available and have walls of high thermal mass to balance the diurnal temperature range.

5.4.5. Roof

Due to the scarcity or even total absence of rainfall roofs of vernacular houses in alpine climate are generally flat [12,16,27,34]. Using locally available material, the roofs are typically made of stone and mud laid on a timber post and beam structure. Vernacular architecture of this region has developed different techniques to make the roof waterproof. For example, in Humla roofs consist of dried juniper branches laid over roughly cut timber boards with an added layer of black mud and a final waterproof layer of fine white mud [12]. This technique protects from the wet snow that typically falls in the early winter months. Thakali and Manang people have also developed a roof finishing system that uses a fine mud layer to ensure waterproofing. Furthermore, wood is piled on the border of roofs that provides protection from the strong wind [16]. In some mountain houses a slight roof overhang can be seen for protecting semi-closed spaces in front of the house [33].

5.4.6. Foundation, floor and ceiling

All investigated traditional houses are built above the ground using a foundation made of locally available stones [16]. The structure of ceilings is made of timber posts and beams. The room height is generally very low in order to reduce the need for heating. The traditional houses of Humla have a ceiling height between 1.8 and 2 m; rooms in Dolpo houses are only 1.75 m high [16,33]. Floors are covered by a mud layers over the roughly cut wooden boards [12].

5.4.7. Openings

The studied vernacular houses have very small doors and windows made of wood [16,27,34]. Windows are often the most expressive element of the house and have nice carvings with Buddhist symbols [12]. In Upper Mustang villages look like fortified towns due to the reduced window area of the outer walls (Fig. 15). Generally, shutters are used to reduce infiltration of cold air, particularly, during night time. The protection from heat losses is the main bioclimatic strategy to maintain comfortable indoor climate under very cold conditions (Fig. 16).

5.4.8. Results

Vernacular houses in Alpine climate have several more features to protect from the coldness than houses in the other climates of Nepal. Settlements and building volumes are compacter and denser than in temperate climates. The houses have far smaller and less openings in order to reduce heat losses. The internal space arrangement is optimized to create thermal buffer zones. The use of window shutters has the effect to increase the tightness of the building.

Roofs are flat as far less rain is falling than in cool temperate climate. The buildings have a high thermal mass that help to balance large diurnal temperature range between the season and in summer. Semi-open spaces like the sunny flat roof top, wind protected veranda and courtyards play an important role to provide comfortable areas for all kind of household activities during the day.

Concluding, the vernacular house design is very much adapted to the local climate conditions. The main objective is to reduce heat losses during long and cold winter season (Table 7).

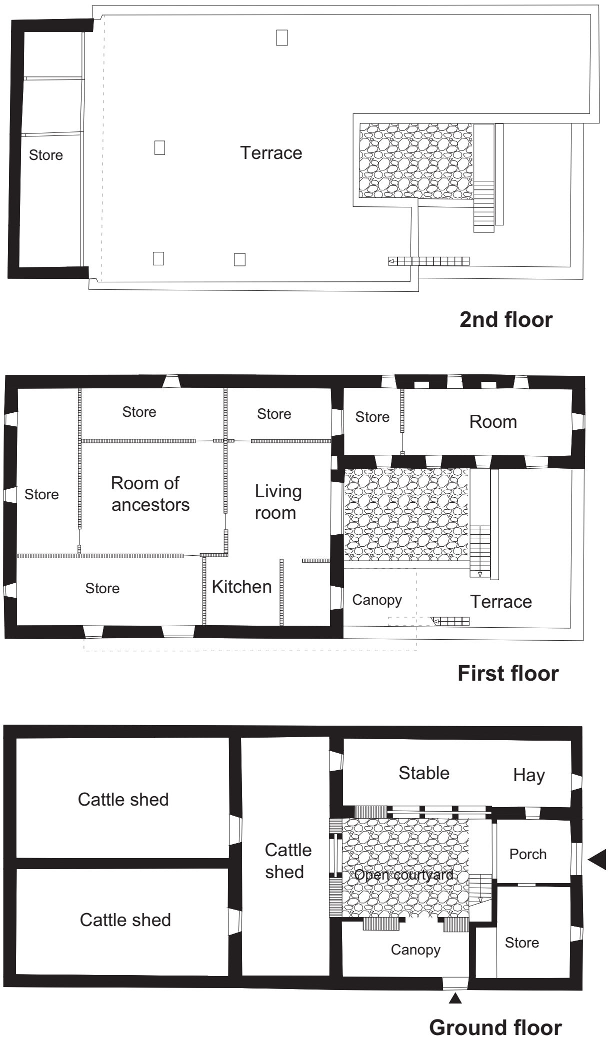

Fig. 15. Floor plan of Thakali house in Taglung (after [16]).

Fig. 16. Typical small windows in building façade in Upper Mustang.

Table 7
Characteristics of vernacular houses in Alpine climate of Nepal.

	Humla house	Dolpo house	House in Upper Mustang	Thakali house	Manang house
Location	Far-western mountain region	Mid-western mountain region	Western mountain region	Western mountain region	Western mountain region
Settlement pattern	Densely scattered, partly attached houses	Houses attached to one other	Dense housing cluster	Compact settlements	Dense, attached houses
Building form	Almost square floor plan	Rectangular	Rectangular toward square	Terraced houses	Almost square surface
Building orientation	South	n.s.	toward sunny side of valley	Southwards facing	Facing south
Stories	3	2.5	2	3	3
Internal space arrangement	Vertically and horizontally use of buffer zones	Vertical space use creates thermal buffer zones	Vertical space arrangement with thermal buffer zones	Centrally and vertically with use of buffer zones	Vertical space arrangement by uses buffer zones
Semi-open space	Roof top	Courtyard, roof terrace	Courtyard, roof terrace	Courtyard, roof terrace	Courtyard, roof terrace
Wall material	Stone and mud mortar	Lower wall: stones and mortar, upper walls: sundried bricks	Sun-dried bricks	Flat natural stone masonry coated with white and red mud	Stone assembled with earth
Wall thickness	45 cm	40 cm	45 cm	50 cm	Thick
Roof material	Mud	n.s.	Mud filling over wooden structure	Severe mud layers	10 cm mud layer on wooden latter
Roof type	Flat	Flat	Flat	Flat	Flat
Roof overhang	50 cm	n.s.	n.s.	Yes	Slight overhang
Foundation	n.s.	n.s.	n.s.	n.s.	Stone, 30 cm deep, 60 cm wide
Floor	n.s.	n.s.	Mud covered	n.s.	n.s.
Ceiling	Low ceilings	Low ceilings	Wooden beam and pillar structure	Wooden structure	Wooden beam and pillar structure
Openings	Small	Very few and small	Small openings in South, West or East facade	Small windows with shutters	Very small wooden windows

Table 8
Climate-responsive design strategies in vernacular architecture of different climatic zones in Nepal.

Climate-responsive design strategy	Climate zones			
	Subtropical	Warm temperate	Cool temperate	Alpine
Solar passive heating	–	+	±	–
Protection from the cold		±	+	+
High thermal mass of walls and floors		+	+	+
High thermal mass with night ventilation	–			
Building orientation north–south	±	±		
Compact settlement and building layout			+	+
Low thermal mass of walls and floors	+			
Light well insulated roof	+	±	±	
Heavy roof				+
Reduction of direct solar heat gain in summer	+	+		
Enhancement of air movement in summer	+	+	±	
Protection from heavy rain	+	+	+	
Outdoor sleeping space for summer	+			
Small openings to reduce heat losses				+
Medium sized openings	±	+	+	
Shading of openings in summer	+	+		

+: applied; –: not applied; ±: partly applied.

6. Conclusion

This study identified many climate-responsive or solar passive design strategies that are applied in vernacular houses of Nepal (Table 8).

Main strategies for subtropical climate of Nepal are solar passive heating in winter, low thermal mass, reduce direct solar gains though building orientation and shading, enhancement of air movement and rain protection. The use of light (low thermal mass) and air-permeable materials for the building envelope and proper placement of openings are enhancing natural ventilation that is essential during warm and humid season. Some but not all houses are orientated north and south as recommended for the reduction of direct solar gains through the façade. All analyzed vernacular houses have adequate shading, semi-opened outdoor spaces for any kind of activities and are protected from heavy rains by a wide roof overhang. Roofs are mostly made of thatch which is a light and well insulating material. Solar passive heating is the only identified bioclimatic design strategies that could not be found in vernacular architecture of subtropical climate.

For the warm temperate climate bioclimatic analysis brought out the following design strategies: solar passive heating for winter, protection from the cold and rain, high thermal mass, enhanced air movement and medium sized windows with shading in summer. These strategies are fully or at least partly applied in the studied vernacular houses. The building orientation toward south as well as the arrangement of courtyards in the more compact Newar settlement enhances solar gains during cold winter and, thus, solar passive heating. However, large roof overhang and shutters keep the steep summer sun away from the building façade to avoid overheating. Recommended high thermal mass of walls and floor as well as light well insulated roof was also found in most studied vernacular houses of warm temperate climate. The courtyard system combined with openings in opposite façades ensures enough natural ventilation in the compacter Newar settlement. While the vertical room setup creates thermal buffer zones to protect from the cold in winter. Shaded semi-open spaces like verandas, balconies and courtyards provide a cooler spaces in summer.

In the cool temperate climate, the building design should be optimized for solar passive heating, protection from the cold in winter, compact settlement pattern and building layout, high thermal mass of walls and floors but light well insulated roof and medium sized. Most of these identified design strategies are applied in the vernacular houses. Heavy very thick stones walls protect the inhabitants from the cold and harsh climate in winter. The arrangement of additional functions like livestock and storage above and below the main living space provides thermal buffer zones. Partly, studied buildings are oriented toward south to benefit from solar heat gains during the day that is stored in high thermal mass of the envelope for cooler night.

Houses in Alpine climate of Nepal need mainly protection from the cold and should enhance solar passive heating. Besides high thermal mass of the walls, floor and roof, a dense and compact settlement structure and building layout is recommended. It was further elaborated that only small openings are suitable. The studied examples of vernacular houses in this climate show few features that would enhance solar passive heating. Priority is given to the protection from the cold through thick heavy walls, very small windows and a very dense settlement structure. Furthermore, the vertical internal space arrangement keeps the main living area with the open fire in the center of the building warm through thermal buffer rooms all around. The flat roof top terrace provides a sunny and warm place for doing any kind of household activity during the day.

The results of this study show that traditional architecture in Nepal is very well adapted to the local climate conditions. The vernacular houses are designed in such a way to provide the most comfortable shelter with the building materials and technologies that were available at that time. The architectural design is optimized to use natural resources like solar radiation and wind efficiently. However, traditional building design and techniques cannot always meet modern living style. Nevertheless, traditional buildings constitute a rich knowledge base that should not be abandoned and totally replaced by modern universal energy-intensive building practices. Instead vernacular design has to be translated and adapted to modern living and comfort requirements. For example, the vertical space arrangement of Newar houses might be inappropriate for modern lifestyle. However, the Newar courtyard settlement structure that is optimized for solar penetration in winter and reduces solar heat gains in summer, can be used to create dense and resource efficient residential areas of modern living.

This study laid the groundwork in identifying the design strategies used by vernacular architecture in Nepal. Further research is needed to translate these traditional strategies into the modern context and come up with appropriate building techniques for the fast developing constructions sector of the country.

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Appendix B

Publication II

The following publication is part of this PhD research:

S. Bodach. “Developing Bioclimatic Zones and Passive Solar Design Strategies for Nepal”. In: *The 30th PLEA Conference - Sustainable habitat for developing societies*. Ahmedabad, 2014

Developing Bioclimatic Zones and Passive Solar Design Strategies for Nepal

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ABSTRACT

Nepal displays a highly varying topography which is leading to a variety of climatic conditions. With the introduction of modern construction technologies in the country, the building sector has adopted uniform design and building techniques that often neglects local climate and rely on energy-intensive mechanical means to provide thermal indoor comfort. The definition of a climate classifications for building design can be an important decision making tool towards climate-responsive and energy-efficient architecture. This paper represents the groundwork for developing bioclimatic zones for building design in Nepal. Based on climatic maps areas of similar climatic conditions were identified. Climate data of various locations within these zone were collected and analysed. A bioclimatic approach was adopted using the psychrometric chart in order to identify passive design strategies for each locations. Finally, an overview of appropriated design strategies for summer and winter for each zones is developed.

INTRODUCTION

Climate-responsive design is considered to be one of the major requirements to drive the building sector towards sustainable development (Szokolay, 2008). However, architects and building planners are still guided by universal design style that is rather focusing on form language and neglecting the local climate conditions (Liedl, Hausladen, & Saldanha, 2012). Climate classification for sustainable building design can fill the gap and guide building professionals which design strategies are suitable in a certain climate context. Many countries that have a variety of climates within their territory have developed a climatic classification for building design - also called bioclimatic zoning. Climate maps for Nepal have been developed based on physiological features and vegetation. However, no building design specific climate zoning is available for the country. Few authors identified the climate-responsive design strategies for specific locations in the country (Upadhyay, Yoshida, & Rijal, 2006). This research is the first comprehensive study aiming to provide the groundwork for developing a bioclimatic zoning and the appropriate design strategies for the whole territory of Nepal.

There are several approaches to define a climate classification for building design. Givoni (1969) distinguishes between four main climate classes, namely hot, warm-temperate, cool-temperate and cold climates; using sub classification he elaborated a total number of eleven climate types for the whole planet. Koenigsberger (1974) developed six climate zones for building design in the tropics based on the two climate factors, temperature and humidity; these factors dominantly influences thermal comfort. Many countries with high climatic variations have developed their own climate zones for building design

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which is often used for defining thermal performance standards for buildings. There is no universal approach for the definition of such a zoning. Most classifications use climate variables (such as temperature, humidity, precipitation, solar radiation, wind conditions) as main criteria (Table 1). Building design factors, e.g. heating and cooling degree day, effective temperature, temperature swing or passive design strategies, are often used as secondary criteria or in combination with climate variables. There are two countries (Argentina, Brazil) that have used only passive design criteria to define the bioclimatic zoning. In some classifications topographical criteria like latitude, longitude, altitude and distance to the coast are added to differentiate bioclimatic zones. Most classifications use the bio-climate chart to identify passive solar design strategies for the different zones.

The way of defining climate classification is from country to country different and few interesting examples are described in detail in the following. USA's climate zones are developed based on the need for heating and cooling using the amount of heating degree days (HDD) and cooling degree days (CDD) (ASHRAE, 2007). China uses the mean temperature in the hottest and coldest month as main criteria. Complementary criteria is the number of days that average temperature is below 5 °C or above 25 °C (Lam, Yang, & Liu, 2006). For the development of the Indian zoning monthly climate data of mean temperature, relative humidity, precipitation and number of clear days were analysed from 233 meteorological stations of the country (Bansal & Minke, 1988). Defined climate conditions must prevail for more than six month; otherwise the location is classified as composite climate. Brazil, being the fifth largest country on the globe with a range in latitude of about 40°, has developed bioclimatic zones adopting the bioclimatic chart from Givoni for hot developing countries. Climate data from 330 locations was plotted on the chart to identify passive design strategies for each location. According to the predominant design recommendations these locations were grouped into different climate classes resulting into eight bioclimatic zones (ABNT, 2003). Argentine has used three indicators to define the zoning: 1. Heating degree days (HDD); 2. Effective temperature (ET) on a typical summer day; 3. Average daily thermal swing for the relevance of thermal mass. The HDD is a key indicator for the heating demand in winter dividing the country in the six main zones. The temperature swing being an indicator for the incorporation of thermal mass is used to classify the four warmer zones into 12 sub-zones. The two colder zones are sub-classified indicating the potential for passive solar heating

Table 1. Climate Classifications for Building Design and Used Criteria

Target region	Used criteria			Source
	Climate	Passive design	Topography	
World	X			(Givoni, 1969)
Egypt	X			(Mahmoud, 2011)
India	X			(Bansal & Minke, 1988)
USA	X	X		(ASHRAE, 2007)
China	X	X		(Lam et al., 2006)
California	X	X		(The Pacific Energy Centre, 2006)
Tropics	X		X	(Koenigsberger, 1974)
North-east India	X		X	(Kumar, Mahapatra, & Atreya, 2007)
Chile	X		X	(INN, 1977)
World	X	X	X	(Liedl, 2011)
Peru	X	X	X	(Chang Escobedo, 2008)
Venezuela	X	X	X	(Rosales, 2007)
Brazil		X		(ABNT, 2003)
Argentine		X		(IRAM, 1996)

METHODS

Research region

Nepal expands from the Gangetric plain at an elevation of 60 m up to the high Himalaya Mountains with the highest peak in the world the Mt. Everest at an elevation of 8,848 m. The highly diversified geography leads to large variation in climate. The climatic diversity has been also reflected in the traditional architectures. While traditional houses in the upper Himalayan have a compact building typology and are attached to each other aiming to reduce heat loss, houses in the subtropical plain have a more elongated floor plan and are distributes in loose settlement pattern allowing air penetration (Bodach, Lang, & Hamhaber, 2014).

With the modernisation of the constructions sector in Nepal, traditional building techniques are replaced by universal design, modern construction technologies and materials. New buildings in urban centres of Nepal are built using column-beam structure of reinforced concrete combined with brick filling walls and flat roofing. Facades with large unshaded glazing area and aluminium panel cladding are typical design options for commercial buildings. Due to centralisation and issues of prestige, modern building practises from the capital Kathmandu are spreading out in other parts of the country where the climatic conditions are very different. Architects and engineers are trained in the capital or in India bringing design ideas and construction techniques from these places that are often inappropriate in the climate of the place.

In contrast to other Asian countries, Nepal has not developed any standards or regulation for a more sustainable building design. The national building code is concerned about structural safety and does not contain any standards on energy efficiency. Currently, the Department of Urban Development and Building Construction (DUDBC) which is the government organisation responsible for drafting building regulation, has started the process to develop green building technology guidelines. However, the lack of a proper bioclimatic zoning makes it difficult to define standards for climate-responsive building design or envelope insulation. A climate classification for building design will be a useful tool for regulators as well as building professionals to enhance climate-adapted design practices and the step forwards towards a more sustainable development of the Nepalese building sector.

Bioclimatic approach and thermal comfort

The bioclimatic approach explores the opportunities to design according to the local climate conditions. Olgyay (1963) developed the first bioclimatic chart based on outdoor climate conditions aiming to identify mitigation measures like solar radiation, air movement or shading to achieve a comfortable indoor climate. Givoni (1963) developed a bioclimatic chart based on indoor conditions using the standard psychrometric chart. His chart has been widely used to identify passive design strategies for different bioclimatic zones (Lam et al., 2006; Rakoto-Joseph, Garde, David, Adelard, & Randriamanantany, 2009; Singh, Mahapatra, & Atreya, 2007). Some countries have used solely his chart to define the climate classification for building design (ABNT, 2003).

The main challenge for developing a bioclimatic chart is the definition of the thermal comfort zone. Thermal comfort is defined as a subjective response of a person in regard to satisfaction with the thermal environment (ASHRAE, 2010). It is influenced by environmental factors, such as air temperature, air movement, humidity, radiation, and personal factors like metabolic rate, clothing, state of health and acclimatization (Szokolay, 2008). For naturally ventilated buildings ASHRAE Standard 55 proposes the adaptive thermal comfort approach and defines a range of acceptable indoor temperature of 2.5 K above and below optimum comfort temperature. Thereby, the comfort temperature is calculated by the outdoor temperature using the equation (1).

$T_c = 0.31T_{out} + 17.8$ (1) (de Dear & Brager, 2002) where T_c is the optimum comfort temperature and T_{out} is the mean outdoor temperature

However, some studies question the applicability of the adaptive model, particularly, in warm and humid climates (Harimi, Ming, & Kumaresan, 2012). Two studies on thermal comfort in Nepal have found that people feel comfortable at temperatures far below and above international comfort standards (Rijal, Yoshida, & Umemiya, 2010). Comparing the optimum comfort temperature using equation (1) and the actual comfort temperature found in the field, temperature differences between 0.2 and 9 K are recorded depending on the region (Table 2). That means the adaptive thermal comfort model of ASHRAE 55 might be not applicable to Nepal.

Table 2. Comparison of predicted comfort temperature and actual found in the field

Location	Altitude	Summer			Winter		
		$T_{mean\ out}$	$T_{c\ pred}$	$T_{c\ field}$	$T_{mean\ out}$	$T_{c\ pred}$	$T_{c\ field}$
Banke	150 m	31.4	27.5	30.0	15.2	22.5	16.2
Bhaktapur	1,350 m	22.2	24.7	25.6	10.6	21.1	15.2
Dhading	1,500 m	25.4	25.7	29.1	13.3	21.9	24.2
Kaski	1,700 m	18.8	23.6	23.4	8.9	20.6	18.0
Solukhumbu	2,600 m	13.1	21.9	21.1	4.0	19.0	13.4
Mustang	3,705 m	n.s.	n.s.	n.s.	6.0	19.7	10.7

$T_{mean\ out}$ **Mean outdoor temperature** (Rijal et al., 2010)
$T_{c\ pred}$ **Predited comfort indoor temperature** (de Dear & Brager, 2002)
$T_{c\ field}$ **Comfort temperature according to field study** (Rijal et al., 2010)

Updating his original research work, Givoni proposed an extended comfort zone for hot developing countries that considers the acclimatization resulting from living in naturally ventilated buildings (Givoni, 1992). It defines temperatures between 18°C and 29°C and humidity levels from 4g/kg up to 17g/kg as comfortable. Givoni's extended comfort zones is used in this study because it is evaluated the most appropriate approach for the Nepalese context. Givoni did not define zones for passive design strategies in his updated chart for hot developing countries. Therefore, this study uses the boundaries defined by Gonzalez et al (1986) for warm and humid climates in developing countries. The upper limit for ventilation is set to absolute humidity of 20.5 g/kg. The ventilation zone was extended to 100% of relative humidity taking reference to several studies conducted in hot and humid climates that found out that local people can cope with higher humidity by increasing ventilation (Gonzalez et al., 1986; Shastry, Mani, & Tenorio, 2012). Solar passive heating zone is defined between 10.5°C and 20.0°C (outside comfort zone). Mechanical heating is needed up to a temperature of 10.5°C. The upper boundary for evaporative cooling is set at the wet bulb temperature line of 24°C. Humidification is needed below wet bulb temperature of 10.6°C.

Nepal’s climatic diversity is mainly caused by the high variation in altitude. Therefore, elevation was chosen as the main criteria for developing bioclimatic zones. Meteorological data (temperature, precipitation) from 26 weather stations were collected either directly from Department of Hydrology and Meteorology or derived from United Nation's Food and Agriculture Organisation (FAO) climate database (FAO, 2014). The station data was used to generate a typical meteorological year (TMY) for each location using the recognized software tool METEONORM (Meteotest, 2014). The TMY was then analysed using the bioclimatic approach.

RESULTS

The plotting of the climate data of 26 locations on the psychrometric chart shows clearly that Nepal has a composite climate that is strongly influenced by the monsoon. Composite means there is no dominating climate for six following months. Instead there are four different seasons that are leading to different design strategies: 1. Winter season (December to February); 2. Pre-Monsoon (March to May); 3. Monsoon or summer season (June to September); 4. Post-monsoon (October to November).

The analysis of the bioclimatic chart of 26 locations led to four different bioclimatic zones (Figure 1): 1.Warm Temperate (below 500 m); 2. Temperate (500-1500 m); 3. Cool temperate (1501-2500 m); 4. Cold (above 2500 m). Table 4 gives an overview about the climatic conditions in each zone. The climate and design strategies for each zone are discussed in the following.

In the warm temperate climate daily temperature rises in pre-monsoon and monsoon season well above the comfort zone reaching up to 35°C. While relative humidity is below 60 % in the pre-monsoon, it increases up to 90 % in monsoon season. The winter month are warm with average temperatures above 10°C. Figure 2 shows that the main design strategies for warm temperate climate zone is natural ventilation in summer and passive solar heating in winter. For the pre-monsoon time thermal mass is recommendable.

Table 4. Characteristics of different bioclimatic zones of Nepal

Bioclimatic zones	Warm temperate	Temperate	Cool Temperate	Cold
Summer temperature				
Mean maximum	29 – 35°C	25–35°C	22 – 26°C	16 – 22°C
Mean minimum	22 – 26°C	18–25°C	14 – 18°C	7 – 12°C
Winter temperature				
Mean maximum	21 – 26°C	17 – 25°C	11 – 20°C	below 10°C
Mean minimum	9 – 15°C	5 – 10°C	-2 – 5°C	below -2°C
Relative Humidity	25 – 90%	20 – 90%	30 – 90%	10 – 90%

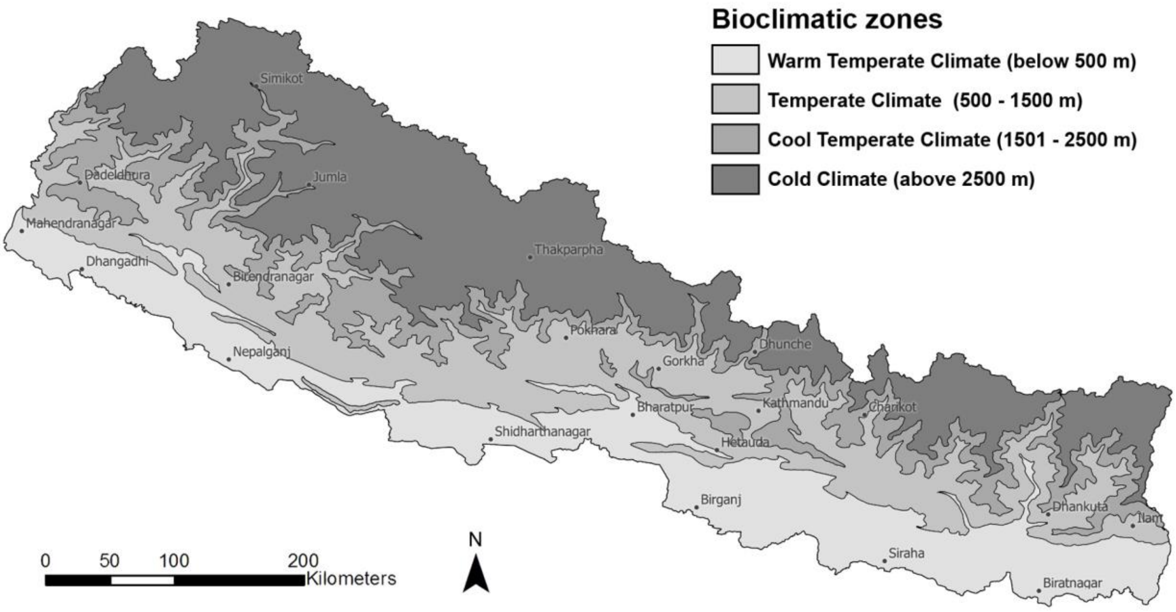

Figure 1 *Bioclimatic zoning for Nepal*

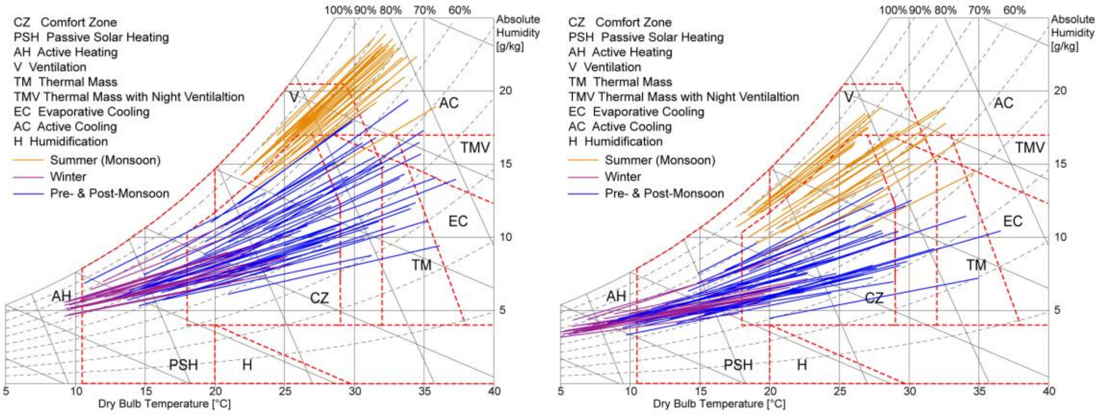

Figure 2 *Bioclimatic chart for warm temperate (left) and temperate climate zone (right)*

In the temperate climate zone average summer temperatures are more moderate, hardly exceeding the comfort zone. During pre-monsoon mean temperatures and humidity is very much comfortable. However, in some places day temperature can rise up to 35°C. In the monsoon season relative humidity might increase above 80% in few locations. In winter temperatures fall below the lower comfort limit;

night temperature can drop down to 5°C. However, day temperature might fall within the comfort zone around 20°C. The most important design strategy for the temperate climate zone is passive solar heating combined with thermal mass (Figure 2). This strategy can balance the high temperature swing during the colder months of the year. Few mechanical heating might be necessary in winter. During monsoon season ventilation is required. Thermal mass can bring relieve and absorb excessive heat in pre-monsoon season.

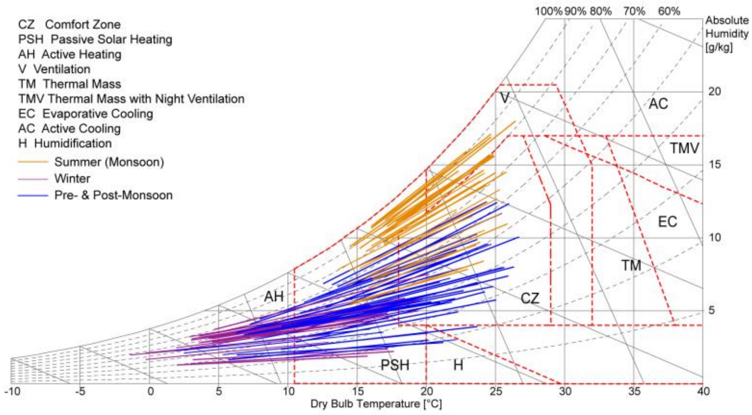

Figure 3 *Bio-climatic chart for cool temperate climate zone*

In the cool temperate climate day temperature in pre-monsoon and monsoon season are within the comfort zone. During monsoon time temperatures are between 15-20°C and relative humidity rarely rises above 80%. In winter average temperatures are clearly below comfort. Night temperatures can down up to the freezing point. Passive solar heating is the most essential strategy used all over the year (Figure 3). In summer thermal mass that store solar heat gain during the day might compensate night temperatures that are often below the lower comfort limit. In winter solar heat gains might contribute to reduce the heating demand by mechanical means. However, mechanical heating is necessary from October to March.

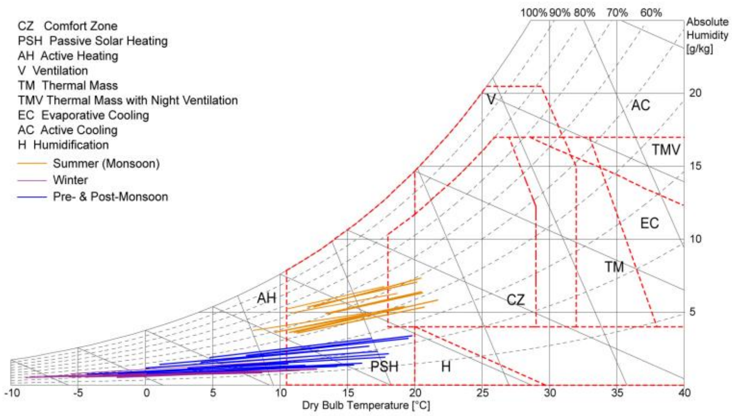

Figure 4 *Bio-climatic chart for cold climate zone*

In the cold climate temperature hardly reach the comfort zone (Figure 4). During summer, day time temperature rarely rises above 18°C. During winter average temperature are around the freezing point. In the cold climate of Nepal passive solar heating is the only design strategy that can be applied. It will reduce the heating demand during the summer month. However, mechanical heating is required all over the year.

DISCUSSION

The bioclimatic chart for the warm temperate climate indicates passive solar heating as main climate-responsive design strategy in winter. By capturing the solar radiation during the day and storing the heat in the thermal mass of the building, lower night temperature can be compensated. By this way mechanical heating is not required. Thermal mass is also desirable during the pre-monsoon for cooling purpose. In contrast the warm and humid summer claims for light building materials like applied in the traditional architecture of the region. The solution to this conflicting design strategies might be the application of high thermal mass in the interior of the building, e.g. for interior walls, floors and ceilings. A suitable construction technique for the exterior walls could be the reverse brick veneer wall. High thermal mass of the northern outside wall without solar exposure is also possible. In any case shading of the openings and the construction elements of high thermal mass has to be provided in summer to avoid overheating. Furthermore, building design should enhance air movements within the building through cross or stack ventilation.

The temperate climate zone is the most comfortable bioclimatic zone of Nepal. Passive solar heating combined with the minimisation of air filtration and good insulation of the building envelope can fulfil most of the heating demand in winter. High thermal building mass is desirable for passive heating as well as passive cooling due to the high daily temperature swing. Enhancing natural air movement through cross or stack ventilation is required during the warm and humid monsoon season.

In cool temperate climate of Nepal passive solar heating strategies is required all over the year. Building layout should be compact and of high thermal mass. Optimising the design for passive solar heating can reduce the amount of mechanical heating. High solar radiation available in winter can also be used for active solar heating by using solar thermal collectors of solar air heating.

The only bioclimatic design strategy in cold climate of Nepal is passive solar heating. However, active heating is needed all over the year. Compact building layout, reduction of air infiltration and good insulation of roof, walls and windows are the imperative to protect from the cold in this harsh mountain climate. The application of active solar heating to support a conventional heating system is recommended.

CONCLUSION

This study developed the first bioclimatic zoning for Nepal. The main passive solar design strategies for the four different bioclimatic zones were identified using the bioclimatic chart. This new climate classification can help planners and architects to make general decisions at early design stage to develop more climate-responsive and energy-efficient buildings. Furthermore, it might be useful for the development of appropriate building energy regulations.

However, the qualitative approach of the bioclimatic chart has its limitations due to the fact that it only considers two climate factors: temperature and humidity. The micro-climatic conditions can vary and a detailed analysis of the site might be necessary to come up with site-specific solutions.

Due to the fact that the climate in Nepal is of composite character design strategies might conflicting each other. Therefore, further research is needed to quantify the effectiveness of the passive design strategies in each climate zones.

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Appendix C

Publication III

The following publication is part of this PhD research:

S. Bodach, W. Lang, and T. Auer. "Design guidelines for energy-efficient hotels in Nepal". In: *International Journal of Sustainable Built Environment* (2016)

Contribution:

My contribution to this simulation study included concept development, acquisition of data, several field visits and data analysis. The concept design was supported by the co-authors. The modelling and simulation was conducted by me in close consultation with the co-authors. The validation of the simulation results was mainly done by the co-authors. The article was drafted by me and critically revised by the co-authors.

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Original Article/Research

Design guidelines for energy-efficient hotels in Nepal

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Abstract

It is predicted that the major increase in energy consumption and, thus, carbon emissions, will happen in the developing world. However, in most developing countries the knowledge about energy efficiency, particularly in the building sector, is quite low. Strategies developed for industrialised countries might not be suitable or must be adapted for the very different context of developing countries. This research aims to find energy-efficient and cost-effective building design options for the case of Nepal. Energy-efficient building design is a non-trivial issue involving a number of interdependent design criteria. Particularly, in composite climates, passive design strategies might conflict each other leading to an inefficient building design. This paper explores the energy conservation potential in hotel design for all bioclimatic zones of Nepal using building energy simulation with parametric analysis. Based on extensive field studies, reference models for typical hotel buildings ranging from small-scale resort hotels to large-scale multi-storey hotels were developed. These reference designs were optimised by varying design parameters such as window-to-wall ratio, glazing material, shading devices, glazing type and insulation levels. During the design optimisation, energy demand as well as cost effectiveness were evaluated. Finally, recommendations for energy-efficient and cost-effective hotel design solutions were suggested. In addition, the bioclimatic zoning for Nepal was consolidated leading to five elevation-based zones that can be used to introduce building energy regulations in the future.

Keywords: Energy efficiency; Hotel buildings; Passive design; Building energy simulation; Parametric study

1. Introduction

The hospitality industry is one of the most important sectors for economic development in Nepal because of tourism. The number of tourists has almost grown by 400 percent in the last decade reaching over 800,000 visitors in 2012 (GoN, 2014). In 2013, the travel and tourism industry contributed 1.5 billion US-Dollars[1] to Nepal's Gross Domestic Product (GDP) which corresponds to 8.2 percent of total GDP. Moreover, the sector is estimated to grow by 5 percent every year in the next decade (WTTC, 2014). The hotel and restaurant business experienced an annual growth rate of over 6 percent per year from 2009 to 2013 (CBS, 2013). The growing numbers of tourists and the boom in the tourism sector have led to more hotels being built by investors.

Many newly constructed hotel buildings are equipped with modern HVAC systems that provide comfortable

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[1] 1 US-Dollar = 100 Nepalese Rupees.

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lodging for their guests. Therefore, the energy consumption in the sector has increased considerably. Due to an increasing gap between electricity demand and supply, Nepal is experiencing a power crisis of unprecedented severity for more than seven years (WECS, 2010). Scheduled power outages of up to 10 h a day in dry season have forced many hotels to instal huge and expensive diesel generator backup systems to ensure the operation of air-conditioning equipment.

New hotel designs often do not consider climate-responsive design strategies or apply any energy efficiency technologies. There are a number of reasons for that. Firstly, the government has not placed any energy conservation regulations. Secondly, architects, engineers and contractors are not familiar with the application of insulation materials for walls, roofs and flooring. Hotel investors are also not aware about potential energy and cost savings that can result from having a hotel with energy-efficient design or increased insulation. Finally, energy-efficient building technology like thermal insulation or double glazing windows are new and expensive leading to high initial investment cost. Business developers do not have the know-how to estimate energy cost savings in monetary terms which is necessary to justify increased investment cost.

Another challenge for energy-efficient building design in Nepal is the diversity of climatic conditions which is the result of a geography ranging from an elevation of 60 metres to the highest mountain of the world at 8848 m. Nepal can be divided into four bioclimatic zones (Bodach, 2014): 1. Warm temperate, 2. Temperate, 3. Cool temperate and 4. Cold climate (see Table 1). The climate in most regions is of composite character with a wide daily temperature swing. This means that passive design strategies, which are effective in reducing heating, might increase cooling demand. The only way to evaluate the effectiveness of different design strategies is the use of simulation-based design optimisation.

This study is the first comprehensive research that assesses design strategies for energy-efficient hotel buildings in Nepal using building energy simulation. The overall objective is to develop design recommendations for hotels in Nepal focusing on passive design and envelope optimisation to reduce energy consumption for heating and cooling. Thereby, this study covers all climates of Nepal and considers different typical construction technologies.

Table 1
Climate conditions in bioclimatic zones of Nepal (Bodach, 2014).

Bioclimatic zone	Temperature in Summer	Temperature in Winter	Relative Humidity
Warm temperate	22–35 °C	9–26 °C	25–90%
Temperate	18–35 °C	5–25 °C	20–90%
Cool Temperate	14–26 °C	−2–20 °C	30–90%
Cold	7–22 °C	−10– −2 °C	10–90%

2. Methodology

2.1. Research framework

The overall research framework of this study is illustrated in Fig. 1. The main method used is dynamic building energy simulation which is a common approach to explore the energy performance of design alternatives and estimate the energy saving potentials of passive design strategies and energy-efficient building technologies (Stevanović, 2013). Based on an extensive field research, typical building typologies for hotel design were developed and different construction materials were assigned. In order to come up with recommendations for passive design on one side and for insulation levels on the other side, two sets of simulation runs were necessary; 1. Passive design optimisation run and 2. Thermal insulation optimisation. A secondary input for determining insulation levels was a literature review on international and regional standards and building codes. All used methods are described in more detail in the following section.

2.2. Climate data

Hourly climate data are one of the most important inputs for building energy simulation. In order to cover the whole climatic diversity of the country, two locations in each bioclimatic zone were selected for the simulation (see Table 2 and Fig. 2). The selection was done considering the relevance of the location for tourism activities as this research is focused on hotel buildings. For each of these eight locations, monthly weather data of at least 20 years were collected from Department of Meteorology and Hydrology of Nepal (DHMN, 2012) and used to generate the typical meteorological year with the software tool METEONORM (Meteotest, 2014).

2.3. Building typologies

Vernacular Nepalese architecture used building design and construction technologies that were very well adapted to the local climate (Bodach et al., 2014). In the warm temperate region, for example, light materials like wattle and daub were applied as walling and thatch was applied as roofing material. In contrast, in the hilly region with a more temperate climate, walls were built with higher mass like burned bricks or locally available stone masonry and roofing was made out of brick tiles or slates. In the cold and harsh mountains, houses had a compact layout using very thick stone walls to decrease the heat loss of the building.

Some of those traditional elements can be still found in modern hotel architecture. For example, in the warm temperate climate one of the cottage type hotels, which were visited during the field research, was built in lightweight construction as timber frame with thatch roofing. Thatch

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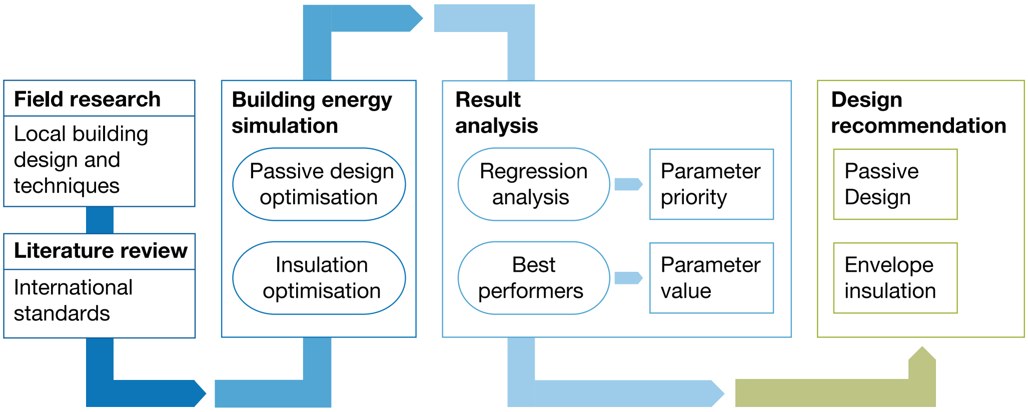

Fig. 1. Methodology of the research.

Table 2
Locations for simulation.

Bioclimatic zone	Location	Elevation	HDD18[a]	CDD18[b]
Warm temperate	Biratnagar	72 m	68	2418
	Rampur	256 m	210	2081
Temperate	Pokhara	827 m	289	1391
	Kathmandu	1337 m	632	930
Cool temperate	Dhulikhel	1552 m	932	491
	Dhunche	1982 m	1147	218
Cold	Thakmarpha	2566 m	2456	20
	Namche	2254 m	5013	0

[a] Heating degree days at 18 °C according to EUROSTAT-method (EEA, 2015).
[b] Cooling degree days at 18.3 °C (65 °F) according to ASHRAE-method (ASHRAE, 2009).

roofing was also found in few hotels in the temperate climate zone.

Although traditional building techniques are very well adapted to the climate and provide a comfortable indoor environment for local people, they might not fulfil increasing thermal comfort requirements for modern building use. The findings of Rijal et al. (2010) show that local people in Nepal are satisfied with indoor temperatures that are out of the average range of international comfort standards (Bodach et al., 2014). However, hotel buildings which mostly serve international tourists have to comply with higher comfort standards that can only be reached using for example modern insulation materials as well as active heating and cooling technology.

Although Nepal's building stock is still very traditional, new construction materials are emerging in the market because they allow faster construction and lead to a better finishing. Reinforced concrete frame construction is the dominant structural system for hotels in urban centres as it is seen as the most earthquake safe building technique and also promoted by the national building code. Dominating walling material is the full brick which is produced in the country using a very old inefficient kiln technology

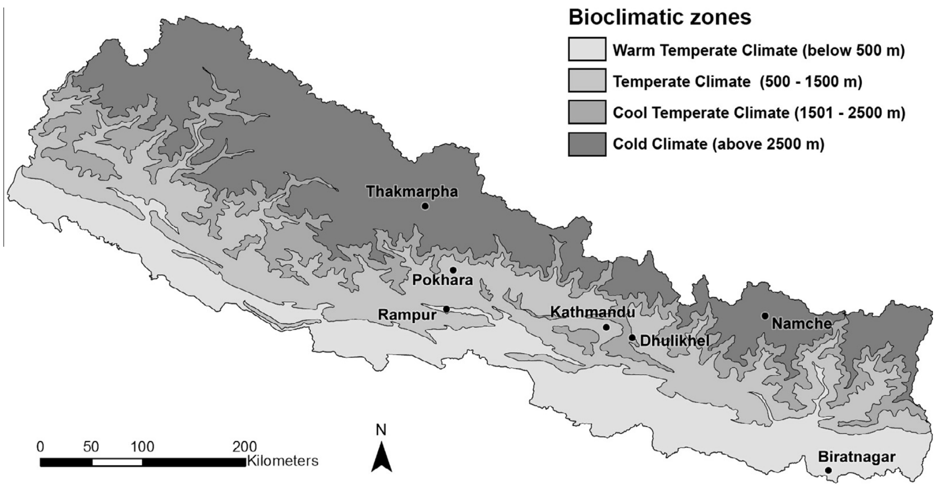

Fig. 2. Bioclimatic zoning map of Nepal with selected locations for energy simulation.

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that is also a major contributor to air pollution. A substitute for walling is the concrete hollow block (CHB) which is also manufactured locally and has less embodied energy. Corrugated galvanised iron (CGI) sheets are often used for pitched roofs combined with tile or thatch roofing. Another new material for lightweight construction is fibre cement board which is mostly imported from India or Thailand. Windows have commonly single glazing. Window frames were still made of timber in the last decade. Due to wood scarcity and the rise in prices, wood is now replaced by aluminium and PVC framing.

According to the findings of the field research, seven building typologies for hotels were developed and assigned to the relevant climate zone (Fig. 3). Single cottage, double cottage and bungalow are small-scale typologies for resort hotels. They have one, two and four guest rooms, respectively. The bungalow typology has a similar layout like the double cottage but is a small two-storey building. The multistorey single-banked typology assumes the linear arrangement of guest rooms at one side of an elongated corridor, while the double-banked typology has guest rooms at both sides. The courtyard type has a square layout with an interior open courtyard whereas in the atrium typology the courtyard is covered by a roof.

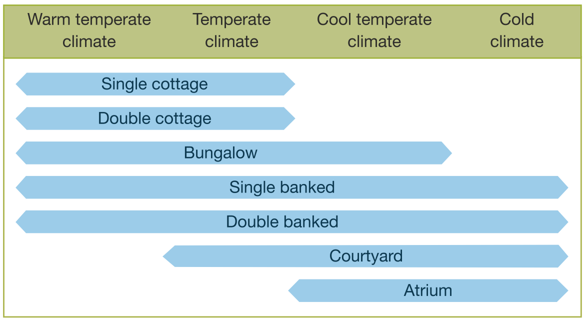

Fig. 3. Building typologies and locations for simulation runs.

Tables 3 and 4 list the construction materials and insulation levels that were considered for the optimisation. The thermal transmittance of all considered opaque envelope components are shown in Table 5. Based on market research, six different window types, which are available in Nepal, were selected for this study (see Table 6).

In order to explore the influence of thermal mass, typical construction practices of high, medium and low thermal mass were taken into account. The fact that walls of brick or concrete hollow blocks are still not common in mountainous regions because of high transportation cost, led to the conclusion that only stone and lightweight materials were studied in the cold climate. The optimisation of passive design parameters considers only three uninsulated base cases of low, medium, and high thermal to keep the number of total solutions at a reasonable size and reduce simulation time.

2.4. Optimisation runs

The most energy-efficient design has to consider multiple and competing design strategies to reduce the energy demand for heating and cooling (Stevanović, 2013). Many studies use parametric analysis to find the most energy-efficient design alternatives (Capeluto, 2003; Hachem et al., 2011; Depecker et al., 2001; Albatici and Passerini,

Table 3
Construction materials considered for optimisation.

	Wall	Roof	Floor
Low mass	Fibre cement board	CGI[a]	Fibre cement board
Medium mass	Concrete hollow block	Thatch on CGI[a]	Screed on brick solids
High mass	Full brick, Stone[b]	Tile on CGI[a], RCC[c] slab	Screed on brick solids

[a] Corrugated galvanised iron.
[b] Only for cold climate.
[c] Reinforced concrete.

Table 4
Thermal insulation levels considered for optimisation.

	Thickness and material of insulation layer		
	Wall	Roof	Floor
Reference case	0 uninsulated	0[a] uninsulated	0 uninsulated
Insulation level 1	0[a]	50 mm GW[c]/100 mm thatch[d]	25 mm XPS[e]
Insulation level 2	50 mm EPS[b]	100 mm GW[c]/150 mm thatch[d]	50 mm XPS[e]
Insulation level 3	100 mm EPS[b]	150 mm GW[c]/200 mm thatch[d]	75 mm XPS[e]
Insulation level 4	150 mm EPS[b]	200 mm GW[c]/200 mm thatch+50 mm GW[d]	–

[a] 50 mm air gap.
[b] Expanded polystyrene (EPS).
[c] Glass wool (GW) for tile and metal roof.
[d] For thatch roof.
[e] Extruded polystyrene foam (XPS).

Table 5
U-Values of building envelope components considered for optimisation.

	Base case (W/m^2K)	Insulation level 1 (W/m^2K)	Insulation level 2 (W/m^2K)	Insulation level 3 (W/m^2K)	Insulation level 4 (W/m^2K)
Exterior wall					
Full brick	2.188	1.600	0.590	0.340	0.238
Concrete hollow block	1.988	1.264	0.537	0.321	0.229
Fibre cement board	1.677	0.819	0.600	0.343	0.240
Stone[a]	1.402	1.385	0.558	0.329	0.233
Roof					
Clay tile	2.775	0.689	0.370	0.253	0.192
Thatch	2.775	0.564	0.402	0.321	0.233
CGI[b]	2.780	0.487	0.256	0.174	0.131
RCC[c] Slab	2.798	0.610	0.346	0.242	0.186
Ground floor					
Screed on brick solids	4.166	0.858	0.478	0.254	–
Fibre cement board	6.115	0.918	0.496	0.259	–
Timber[a]	2.115	0.911	0.580	0.336	–

[a] Only for cold climate.
[b] Corrugated galvanised iron.
[c] Reinforced concrete.

Table 6
Properties of considered window types.

	U-Value (W/m^2K)	SHGC[a]	VT[b]
single-clear	5.38	0.68	0.70
single-tinted	5.38	0.50	0.59
single-tinted-low-e	5.40	0.33	0.22
double	3.15	0.62	0.63
double-low-e	3.14	0.23	0.12
double best	2.44	0.64	0.65

[a] Solar heat gain coefficient.
[b] Visible transmittance.

Aug 2011). However, a high number of design parameters might lead to a huge number of simulation runs to be conducted and, thus, a long simulation time. Therefore, the coupling of the simulation engine with an optimisation method is necessary to find quickly all design alternatives with a high energy performance level (Stevanović, 2013). This research used the open source software tool jEPlus+EA for optimisation (Zhang, 2012). The software sets up optimisations that have complex parametric runs with the EnergyPlus simulation engine (DOE, 2015a). The runs are coupled with an optimisation system that is based on the evolutionary algorithm NSGA-II. The software starts with a random set (population) of solutions, and then repeatedly evaluates the solutions and selects better ones for creating new variants.

The energy model was set up with a standard air-to-air heat pump as individual HVAC system for every guest room using thermostat set points of 20 °C for heating and 26 °C for cooling. As most hotel buildings in Nepal are operated in mixed-mode, natural ventilation for cooling was considered for indoor temperature between 22 °C and 26 °C. That means it is assumed that windows are opened when the indoor temperature increases above 22° C and outdoor temperature is 2 °C below indoor temperature. When windows are closed, the HVAC is activated the moment the indoor temperature goes above 26 °C.

For all models an air infiltration rate of 1 h^{-1} was considered; representing the unintended flow of air which is caused by the opening and closing of exterior doors and cracks around windows. The natural ventilation flow is modelled using the ZoneVentilation:DesignFlowRate object of Energyplus (DOE, 2015a). A design flow rate of 10 h^{-1} was assumed which was then modified by the temperature difference between the inside and outside environment and the wind speed. The ground coupled heat transfer, which is critical in simulating small-scale buildings, is represented by the ground domain model (GroundDomain:Slab). This model uses an implicit finite difference formulation to calculate the ground temperatures at each simulation time step based (DOE, 2015a).

During the first set of runs passive design parameters like orientation, thermal mass, window-to-wall-ratio, overhang and fins were considered. Table 7 shows the parameters and values for one building typology. The optimisation objective of the passive design runs was set to reduce heating as well as cooling demands.

Table 7
Design parameters for passive design optimisation of double-banked typology.

Parameter	Values
Orientation	−90°, −60°, −30°, 0°, 30°, 60°, 90°
WWR South	20%, 40%, 60%
WWR North	20%, 40%, 60%
Overhang South PF[a]	0, 0.2, 0.4, 0.6
Thermal mass	low, medium, high

[a] Projection factor.

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Table 8
Design parameters for insulation level optimisation of single-banked typology.

Parameter	Values				
Wall material	Full brick	CHB[a]	FCB[b]	Stone	
Roof material	CGI[c]	Thatch	Concrete		
Floor material	Concrete	FCB[b]	Timber		
Wall insulation	none	50 mm air cavity	50 mm EPS[d]	100 mm EPS	150 mm EPS
Roof insulation	none	50 mm GW[e]	100 mm GW	150 mm GW	200 mm GW
Floor insulation	none	25 mm XPS[f]	50 mm XPS	100 mm XPS	

[a] Concrete hollow block.
[b] Fibre cement board.
[c] Corrugated galvanised iron.
[d] Expanded polystyrene (EPS).
[e] Glass wool (GW).
[f] Extruded polystyrene foam (XPS).

For the second set of runs the double-banked building typology was selected. The building design was kept the same while varying envelope materials and insulation levels (Table 8). However, for the passive design runs, only the reduction of heating and cooling demand was taken into account, the economic dimension was included at this time by adding the minimisation of life cycle cost (LCC) present value to the optimisation objective.

The LCC analysis considers investment and maintenance cost for the exterior building envelope as well as energy costs during the operation of the building.[2] Construction costs of partition walls, intermediate floors and ceilings were not included because they are not insulated in any case and, thus, do not result into higher investment cost. During the time of power outages an increased unit price of 0.35 USD (for the first year) was assumed representing the cost of the diesel generator operation. Table 9 illustrates the economic parameters of the LCC analysis (LCCA).

2.5. Thermal comfort

While using the building energy model with thermostat set points between 20 °C and 26 °C, it was noticed that the Predicted Mean Vote (PMV) for thermal comfort did not stay within the range (±0.5) as recommended by Fanger (1970) and ASHRAE (2010). That means this model only fulfils minimum comfort requirements that were considered to be sufficient for small-scale hotels which serve national and regional tourists.

However, for large-scale hotels in Nepal that have international clients with maximum comfort requirements, the Fanger Comfort should be reached. Therefore, another set of runs was conducted with a modified Energyplus model that integrates a dynamic model for thermostat set points. That means the HVAC thermostat is automatically adjusted at every time step to meet the Fanger comfort. Additionally, instead of using the static clothing insulation value of 0.5 in the cooling season and 1.0 in the heating season, the more recent dynamic predictive clothing insulation model developed by Schiavon and Lee (2013) was incorporated into the model.

[2] Cost data were collected from several building contractors in Kathmandu in the beginning of 2015.

Table 9
Parameters for life-cycle cost analysis.

Description	Method or value
Inflation approach	ConstantDollar
Real discount rate	10%
Length of study period	20 years
Electricity tariff	Commercial TOD[a]
Electricity price	0.925/0.105/0.055/0.35 USD[b]
Electricity price escalation	4% per year[c]
Daily power outage	2.5 h in winter, 1h in summer[d]
Room occupancy rate	57%[e] / 70%[f] / 80%[g]

[a] Time of the day NEA (2014).
[b] Normal/peak/off-peak/power outage.
[c] Forecaset based on 15 years historical price data.
[d] Own estimation based on interview (Dr. Shree Raj Shakya, Assistant Professor at Tribhuvan University Kathmandu, April 20, 2015).
[e] Off season (Dec–Feb and Jun–Sep).
[f] Mid season (Mar–Apr).
[g] High season (Oct–Nov).

2.6. Model validation

The quality of the simulation results is strongly dependent on the software and the user. EnergyPlus is a recognised building energy simulation programme developed by US Department of Energy (DOE). The programme has been validated by ANSI/ASHRAE Standard 140–2011 and has successfully completed several analytical and comparative tests (DOE, 2015b). Therefore, it can be expected that the results are valid and representative for real buildings. However, insufficient or wrong data input might lead to inaccurate results.

The most detailed approach to validate a simulation model is to compare its performance with measured data which was out of the scope of this study. This research has developed several reference models to represent all different typologies which do not completely match with existing buildings. In order to validate the plausibility of the results a comparison with existing data was conducted. However, there is lack of measured data from Nepal. As a result, energy consumption surveys from other countries were used.

Energy consumption in hotel buildings might vary considerably depending on the location, climate, hotel standard (number of stars), facility size and additional services provided (swimming pool, restaurants, laundry, etc.) as well as the occupancy rate and the efficiency of the equipment (Bohdanowicz and Martinac, 2007). A review of several surveys conducted all around the world concluded that the average energy use intensity of hotels is between 69 and 689 kWh/m^2 per year (Wang, 2012). The share of energy used for space conditioning ranges between 32% and 57% of total energy consumption (Deng and Burnett, 2000; Shiming and Burnett, 2002; Trung and Kumar, 2005; Chedwal et al., 2015).

The simulation results of this study show similar variation because of the climatic diversity of the country. Assuming a share in energy demand for room conditioning of 40%, the uninsulated reference hotel design would have an energy intensity between 93 and 708 kWh/m^2 per year depending on the location (Fig. 4). Therefore, the highest energy intensity is reached in the cold climate at 3354 m elevation and the lowest in the temperate climate. Considering the geographical distribution of hotels (Central Bureau of Statistics(CBS), 2004), an average energy use intensity of 197 kWh/m^2 per year was estimated. This value is comparable with the Indian benchmark of 260 kWh/m^2 per year considering that the share of luxury hotels in India is much higher than in Nepal (BEE, 2011).

2.7. Regression analysis

Regression analysis is widely used by building energy simulators either to predict energy performance of buildings or to assess the influence of design parameters (Lam and Hui, 1996; Hopfe, 2007; Hygh et al., 2012; Daly et al., 2014). Regression analysis is a statistical method to estimate relationships among different variables. Hygh et al. (2012) suggest that a linear regression model can help to make early design decisions to reduce the energy demand of buildings.

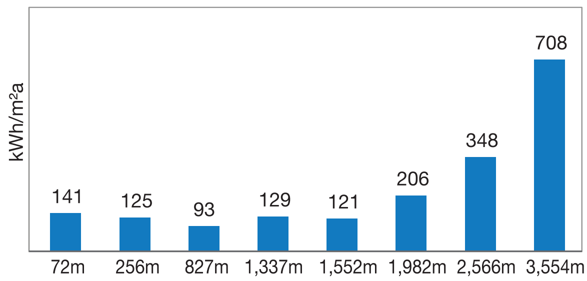

Fig. 4. Estimated energy use intensity for hotels in Nepal based on uninsulated reference model for different elevations.

In this research multivariate, regression analysis was used to analyse the influence of design parameters for energy performance. The linear regression coefficient was normalised into the standardised regression coefficient (SRC) to make comparison possible. The standardised regression coefficient (SRC) is a tool to quantify the sensitivity of heating and cooling loads as well as the total energy demand with regard to the different design parameters (Hopfe, 2007). The ranking of the SRC shows the importance of each design parameter for heating, cooling and total energy demand.

For instance, the regression analysis for cooling electricity (dependent variable) leads to a positive SRC for WWR South. That means, the higher the window area on the southern facade the higher the cooling electricity. It indicates that reducing the window-to-wall ratio (WWR) South will reduce the need for active cooling.

In order to include thermal mass and orientation into the regression analysis, dummy variables had to be introduced into the model. The dummy variable for orientation has the lowest value of 0.1 for all design alternatives where the long building facades were facing exactly north- and southwards (north axis is 0°). The dummy variable was increased by 0.1 for every 30° that the model differs from the optimum orientation. The dummy variable for thermal mass had the value of 0.1, 0.2 and 0.3 for low, medium and high thermal mass buildings, respectively.

3. Passive design optimisation

The following section investigates the importance of design parameters for reducing heating and cooling energy demands in each bioclimatic zone. Building design parameters like window-to-wall-ratio (WWR), thermal mass, orientation and shading (fins and overhang) were considered. The impact of thermal insulation of roof, exterior walls and ground floor is investigated in a separate section due to its high relevance to achieve low-energy designs (see section "Thermal insulation optimisations" below).

3.1. Warm temperate climate

For all locations below an elevation of 500 m (Biratnagar and Rampur) the simulation results show that HVAC energy consumption is dominated by cooling demand with an average share between 80% and 95%.

Minimising solar gains is the most important passive design strategy for all building typologies in this climate. Therefore, the design parameters window-to-wall-ratio (WWR), overhang and orientation have the highest absolute Standardized Regression Coefficients (SRC). Fig. 5 illustrates the results of the regression analysis for the bungalow typology in Biratnagar. It shows on the top ranks: WWR South (0.63), Overhang South (−0.45), Orientation (0.30), WWR East (0.24) and WWR West (0.23). All these design parameters can reduce solar penetration of the building.

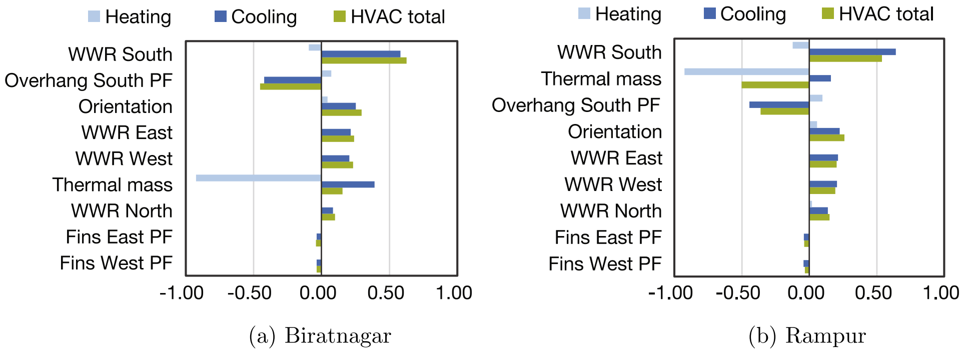

Fig. 5. Standardised regression coefficient (SRC) of design parameters for bungalow typology.

The positive SRC for the WWR South means that the higher the window area, the higher the total HVAC energy demand. Being on the top rank shows that reducing the WWR South has the highest impact on energy reduction. Similarly, the SRC for WWR East and West is positive demonstrating that windows in these direction should be also small or even avoided. In contrast, the SRC for the overhang projection factor (PF), is negative. This negative relation means that the larger the overhang, the lower the energy consumption.

Consequently, best performers in this climate have a WWR South and North of 20% and an overhang with a projection factor (PF) between 0.4 and 0.6. Furthermore, they have small or no windows facing East and West and have an optimum orientation which means that the long facades are facing north and south.

A less important passive design strategy for energy reductions in this climate is the thermal mass effect. The regression analysis shows that higher thermal mass has a positive impact on reducing the heating demand (negative SRC) while it tends to slightly increase cooling demand (positive SRC) due to the effect of overheating. The thermal mass effect can be illustrated by the thermal performance of a non-conditioned building.

During a warm summer day, the indoor temperature in the low mass design increases more than in the high mass building (Fig. 6). However, during night time the low mass building can cool down faster and at a lower level than the high mass design which reduces the need for cooling. The fact that the hotel room is occupied and air-conditioned less hours during the day than during the night time results in a slight performance advantage for low mass buildings in the warm temperate climate.

From Fig. 7 it can be seen that low mass buildings perform better than high mass designs in summer but worse in winter. The combined effect leads to annual energy savings, depending on the location. For example, a low mass design of the bungalow typology results in marginal annual energy savings of 1 kWh/m^2 in Biratnagar compared to the high mass design. However, the same low mass design in Rampur consumes 6 kWh/m^2 more electricity than a high mass

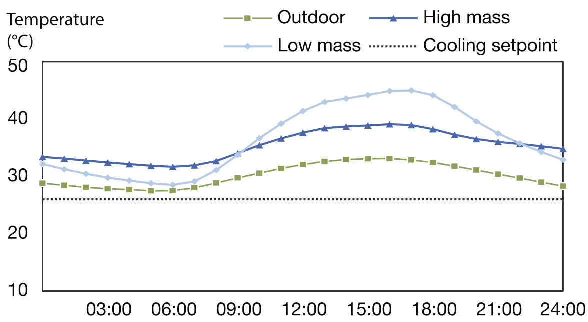

Fig. 6. Comparison of non-conditioned thermal performance in summer of bungalow typology for Biratnagar.

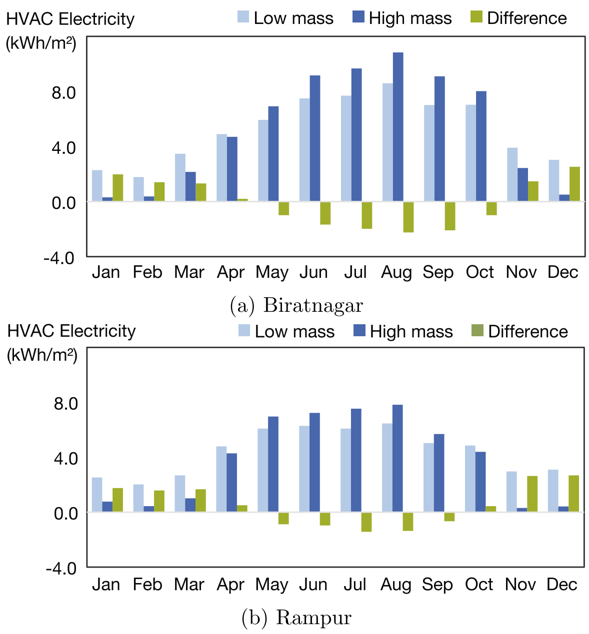

Fig. 7. Monthly HVAC energy demand of low mass and high mass bungalow typology in warm temperate climate.

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design. This indicates that the combined effect results in a marginal lower annual energy demand for low mass designs in Biratnagar but not in Rampur.

The simulation results indicate that the combined thermal mass effect (passive heating and passive cooling) is positive in Biratnagar but negative in Rampur. While in Biratnagar about one third of best performers are low mass solutions, in Rampur only 15% have low mass materials. This shows a slightly better performance for low mass buildings in Biratnagar compared to high mass solutions. Consequently, low mass buildings are recommended for Biratnagar but not always for Rampur.

Another strategy for reducing energy consumption in hot climates are shading devices like vertical fins for east and west facing windows. For Nepal's cooling dominated climate increasing the projection factor (PF) for the fins brings only little reduction. For all typologies in both locations the SRC of fins had the lowest rank which means that fins have only marginal impact on energy reduction. However, if larger windows facing east or west are necessary, fins with a projection faction between 0.4 and 0.6 should be foreseen to prevent overheating.

Similar to the impact on energy reduction, reducing the WWR in this climate leads to considerable high energy cost savings. Table 10 illustrates the cost saving potential when the WWR South and North of the double-banked typology is reduced from 60% to 20%. Annual electricity cost savings of up to 53 US Dollars (USD) per guest room can be achieved. Furthermore, construction costs are reduced by 330 USD per room in average due to the fact that opaque wall area is less expensive than window area.

Optimising the orientation of the design does also result into cost savings although the reduction potential is not as high as in the case of WWR (see Table 11). Annual electricity costs can be decreased by between 18 and 53 USD per guest room depending on the base case orientation while life cycle cost (LCC) savings amount up to 471 USD. Similar savings can be reached by adding an overhang with a projection factor of 0.6 (see Table 12).

Fig. 8 is an example of cost savings that can be achieved when the design is optimised step by step. Annual electricity costs for air conditioning can be reduced to almost 50% from 253 USD to 133 USD per guest room by considering all important passive design strategies starting from optimal orientation (Design 1), reducing WWR (Design 2 and 3), and adding an overhang to the south oriented window (Design 4). Correspondingly, life cycle cost savings amount to 1364 USD per guest room compared to the base case design (Fig. 8(b)).

In conclusion, all passive design strategies that reduce the solar penetration and, thus, the overheating of the hotel building have priority in the warm temperate climate of Nepal. Designers should minimise the window area, avoid openings in the east and west facade and provide shading devices like overhangs for south facing windows and fins for larger east and west facing openings. The layout of the hotel building should be elongated with the longer facade facing south and north to reduce solar gains. Optimising passive design does also lead to substantial cost savings.

3.2. Temperate climate

In temperate climate of Nepal heating and cooling are required but in a moderate way. Simulation results show that hotel buildings in this climate have the lowest energy

Table 11
Cost saving potential for Double-banked typology in Biratnagar by optimising the building orientation.

	Cost saving potential			
	Annual electricity costs		Life cycle costs	
Compared to	USD/m^2	USD/room	USD/m^2	USD/room
−30°	1	18	5	160
30°	1	19	6	170
−60°	1	43	13	383
60°	2	44	13	397
90°	2	53	16	471
−90°	2	53	16	471

Table 12
Cost saving potential for Double-banked typology in Biratnagar by adding overhang with PF 0.6.

	Cost saving potential			
	Annual electricity costs		Life cycle costs	
Thermal mass	USD/m^2	USD/room	USD/m^2	USD/room
High	0.30	8.79	3	79
Medium	0.29	8.53	3	76
Low	0.28	8.21	2	73
Average	0.29	8.51	3	76

Table 10
Cost saving potential for Double-banked typology in Biratnagar by reducing WWR from 60% to 20%.

	Cost saving potential					
	Construction costs		Annual electricity costs		Life cycle costs	
Thermal mass	USD/m^2	USD/room	USD/m^2	USD/room	USD/m^2	USD/room
High	11	313	2	49	25	727
Medium	13	380	2	51	27	799
Low	10	296	2	53	25	739
Average	11	330	2	51	26	755

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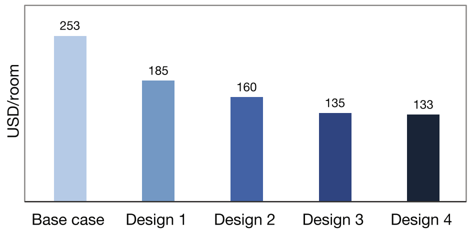
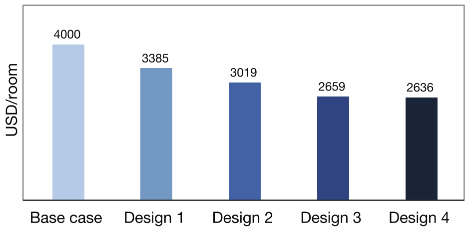


(a) Annual electricity costs



(b) Life cycle costs

Fig. 8. Cost analysis of optimised design for double-banked typology in Biratnagar.

demand for air conditioning compared to all other climate regions. Depending on the building typology heating demand has a share of between 15% and 35% of total HVAC energy demand in Pokhara (827 m). In Kathmandu (1337 m), the share of heating amounts to between 35% and 70%.

The regression analysis indicates that thermal mass is the most influential passive design factor in this climate. In contrast to locations in warm temperate climate, the SRC for thermal mass is negative for both heating and cooling demands (Fig. 9). In other words, the higher the thermal mass of the building the lower the energy demand for heating and cooling.

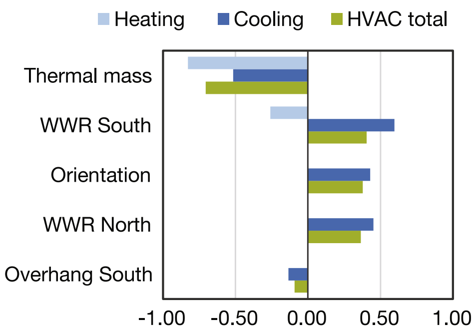
The second most important passive design factor for Pokhara is minimising the WWR South while it is optimising the orientation for Kathmandu. Due to the higher share of cooling demand in Pokhara as compared to Kathmandu, window areas, particularly those facing south, should be kept as small as possible in order to avoid overheating. In contrast, in Kathmandu moderate window areas between 20% and 60% can be used for passive solar heating during the colder month and, thus, reduce, heating demand. The results of some typologies for Pokhara show that a moderate WWR South (20–40%) with an overhang (PF 0.4) leads to the optimum combination of passive solar heating in winter and protection from overheating in summer.

In Pokhara best performing design alternatives have an overhang with a projection factor of 0.2 or 0.4. Fig. 9(a) illustrates the small but still negative SRC (−0.092) for Overhang South. Instead, the SRC for Overhang South (−0.057) in Kathmandu is so small that the majority of best performers have no overhang. Optionally, an overhang with a projection factor (PF) of 0.2 can be foreseen for the south facades with a WWR of 40% and larger. Alternatively, a more flexible shading device like external blinds or shutters can be used in Kathmandu whenever overheating occurs.

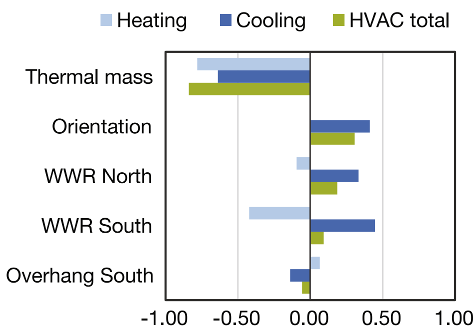
The cost analysis shows that annual electricity costs for room conditioning in high and medium mass hotel designs are almost half compared to the low mass design (Fig. 10). For example in Kathmandu, the high mass design of double-banked typology with WWR North and South of 40% has annual HVAC electricity costs of 42 USD per guest room while the same design using low mass materials needs 81 USD per guest room (Fig. 10). LCC cost savings of the same design amount to 248 USD per guest room. This indicates a clear cost advantage for high and medium mass designs in this climate.

Energy cost savings are also considerably high when optimising the WWR according to passive design. Fig. 11 (a) indicates the cost optimum for annual electricity costs at a WWR of 40%. However, LCC present value is lowest for designs with a WWR of 20% due to the fact that the share of investment for additional window area is higher than the annual energy cost savings (Fig. 11(b)).

Likewise in warm temperate climate, optimising the orientation of the hotel building results also in considerable

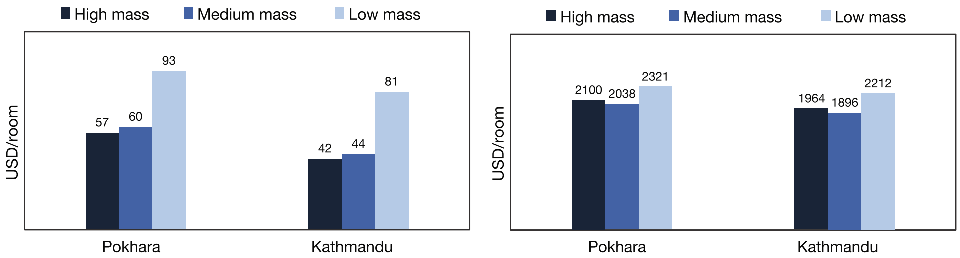


(a) Pokhara



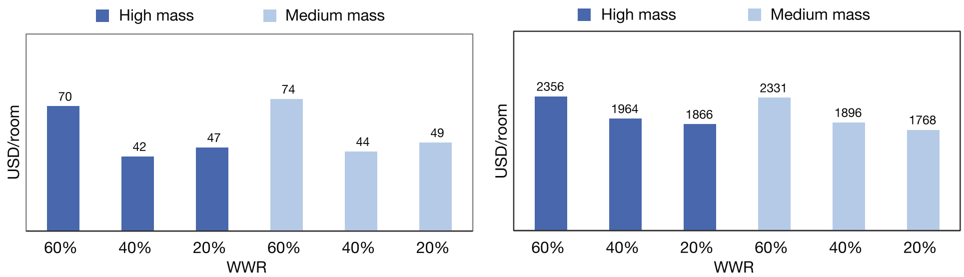
(b) Kathmandu

Fig. 9. Standardised regression coefficient (SRC) of design parameters for double-banked typology.



(a) Annual electricity costs (b) Life cycle costs

Fig. 10. Cost analysis for double-banked typology in temperate climate by thermal mass.



(a) Annual electricity costs (b) Life cycle costs

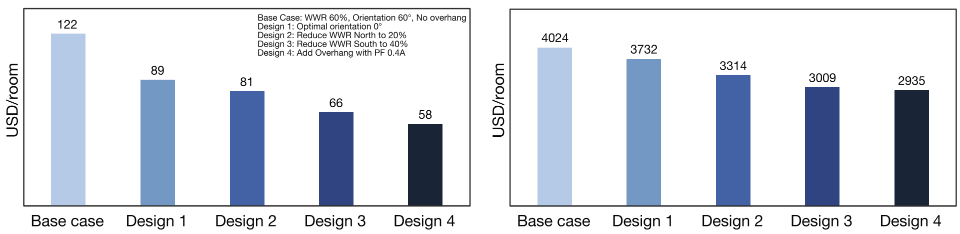
Fig. 11. Cost analysis for double-banked typology with different WWRs in Pokhara.

Table 13
Cost saving potential for Double cottage typology in Pokhara by optimising the building orientation.

	Cost saving potential			
	Annual electricity costs		Life cycle costs	
Compared to	USD/m^2	USD/room	USD/m^2	USD/room
−30°	0.40	10	3.57	89
30°	0.35	9	3.10	78
−60°	0.81	20	7.28	182
60°	0.79	20	7.08	177

cost savings in Nepal's temperate climate (Table 13). For instance, annual electricity costs for double cottage typology with a WWR of 40% in Pokhara can be reduced between 9 and 20 USD per guest room. LCC savings for the same design amount to between 78 and 182 USD per guest room. Although, building orientation might be influenced by other factors like site constraints or the panoramic view, if possible, optimum orientation should be considered to prevent unnecessary high energy costs.

To illustrate the cost saving potentials of the most important passive strategies, a step-by-step design optimisation of the single-banked typology was conducted and the cost implication analysed (see Fig. 12). The base case is an inefficient design with large window areas of 60% and the long building facade facing south-west (orientation 60°). The annual electricity cost for the base case design of 122 USD per guest room can be reduced to 58 USD per guest room through optimal orientation (Design 1), reducing the WWR North to 20% (Design 2) and WWR South to 40% (Design 3) and adding an overhang (Design 4).



(a) Annual electricity costs (b) Life cycle cost present value

Fig. 12. Cost analysis of optimised design for single-banked typology in Pokhara.

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To summarise, passive design optimisation can lead to annual electricity cost savings of more than 50% and life cycle cost savings of about 30%.

Concluding, the results of the passive design optimisation running for the temperate climate zone shows that different recommendations are needed for the two locations. Although higher thermal mass is a critical passive design strategy for Pokhara and Kathmandu, the WWR South should be minimised in Pokhara while in Kathmandu a moderate WWR South is favourable. Furthermore, in Pokhara an overhang for the south facing window is required, while flexible shading devices are recommended for Kathmandu. The cost analysis shows that passive design optimisation in temperate climate results in considerable energy cost and life cycle cost savings.

3.3. Cool temperate climate

The simulation results indicate that hotel buildings in Nepal's cool temperate climate conditions require considerably more heating than cooling. For the analysed typologies in Dhulikhel (1552 m) the share of HVAC demand is between 60% and 85% of total HVAC energy demand while in Dhunche (1982 m) it rises to 99%.

Likewise in temperate climate, increasing thermal mass has the highest impact on HVAC energy reduction. Fig. 13 shows the SRC for thermal mass on the first rank. Therefore, the application of building materials with high thermal mass should be prioritised.

In contrast to all lower locations, the SRC for WWR South in regard to total HVAC energy demand is negative (Fig. 13). This illustrates that a larger window area facing south results in more reduction of heating demand in winter than it increases cooling demand in summer. In interpreting these findings, it has to be considered that cooling demand in cool temperate climate is much lower that in warm temperate and temperate climate. For higher locations like Dhunche, cooling might even not be required. According to the simulation results, best performers have a south facing window area between 40% and 80% to maximise passive solar heating.

Illustrating opposed passive design strategies, the regression analysis for east and west facing WWR results in a negative SRC for heating and positive SRC for cooling (e.g. Fig. 13(a)). Simply put, larger openings might decrease the heating demand but at the same time increase the need for cooling. The regression with the annual HVAC energy demand as dependent variable shows no significant relation (p-value is greater than 0.05). This indicates that both effects cancel each other out. Looking at best performing design alternatives in Dhulikhel, openings towards east, west and north should be kept as small as possible (10–20%). In Dhunche, east and west facing WWR can amount up to 30% while north facing windows should be as small as possible or avoided.

Orientation and shading have also less importance for passive design in this climate. Actually, orientation is only relevant for elongated layouts: long facades should be oriented south-east, south or south-west wards. The majority of the best performing design alternatives in this climate have neither overhang nor fins. Consequently, overhang and other shading devices are not required.

Having the highest impact on energy demand reduction, high thermal mass does also reduce energy and life cycle costs (LCC). Annual HVAC energy costs for single-banked typology in Dhulikhel with low mass materials amount to 73 USD per guest room while medium and high mass solutions have energy costs of only 26 and 23 USD per guest room, respectively (Fig. 14(a)). While high mass solutions have lowest annual electricity costs, medium mass design performs best in life cycle costs due to the fact that the construction costs for walls made of concrete hollow blocks (medium mass) are lower than for full brick walls (high mass).

The cost analysis for different WWRs shows that increasing window area facing south and decreasing WWR North result in marginal energy savings (Fig. 15). For instance for the double-banked typology in Dhulikhel, annual electricity cost savings amount up to 4 USD per guest room when WWR South is maximised, and up to 2 USD per guest room when WWR North is minimised (Fig. 15(a)). Life cycle costs decrease slightly when WWR

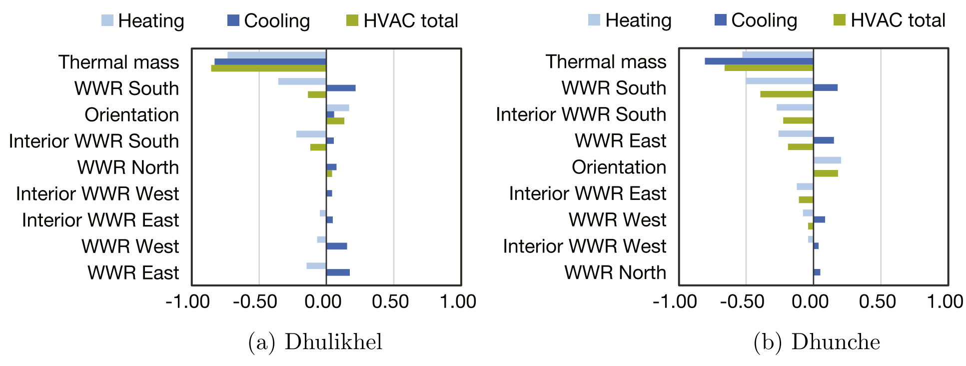
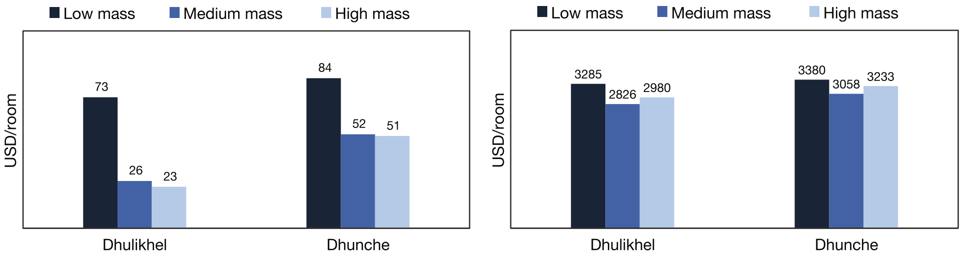
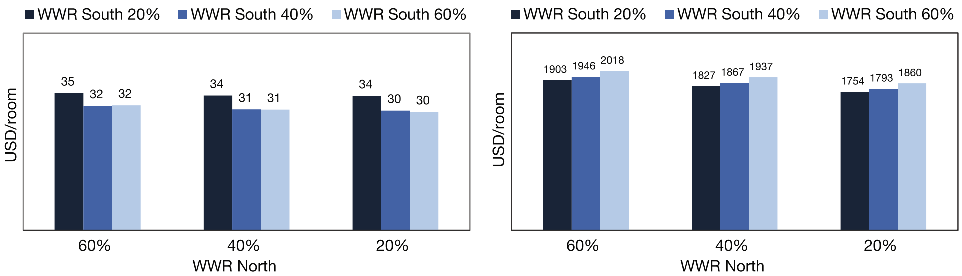


Fig. 13. Standardised regression coefficient (SRC) of design parameters for courtyard typology.



(a) Annual electricity costs (b) Life cycle costs

Fig. 14. Cost analysis for single-banked typology in cool temperate climate by thermal mass.



(a) Annual electricity costs (b) Life cycle costs

Fig. 15. Cost analysis for double-banked typology with different WWRs in Dhulikhel.

North is reduced but increases slightly when WWR South is increased (Fig. 15(b)). This means that in the long run reducing window area northwards leads to LCC net savings due to reduced energy costs. The annual energy cost savings due to passive solar heating cannot fully compensate the high investment costs for increased window area facing South.

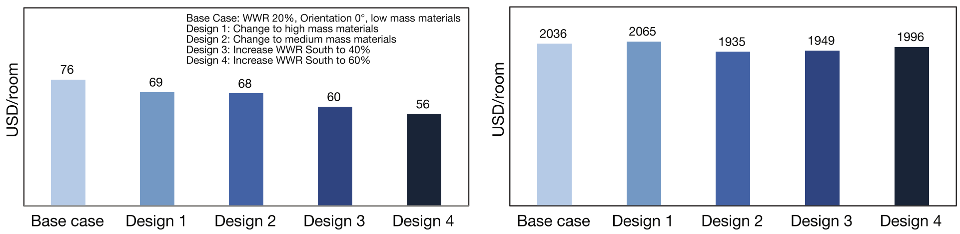
Passive design optimisation can lead to moderate energy cost savings. Fig. 16 illustrates the annual HVAC energy costs for the double-banked typology in Dhunche. It can be seen that passive design can lead to savings of up to 20 USD per guest room annually. Although total window area of the building has increased in the most energy-efficient design (Design 4), the life cycle costs have decreased slightly. In other words, the energy cost savings pay back the initial investment for additional window area.

To conclude, the most important design strategy for cool temperate climate is passive solar heating through high thermal mass and large window areas facing southwards. WWR North, East and West should be kept small. Shading devices are not required. Envelope optimisation towards passive design results in moderate energy cost savings in this climate.

3.4. Cold climate

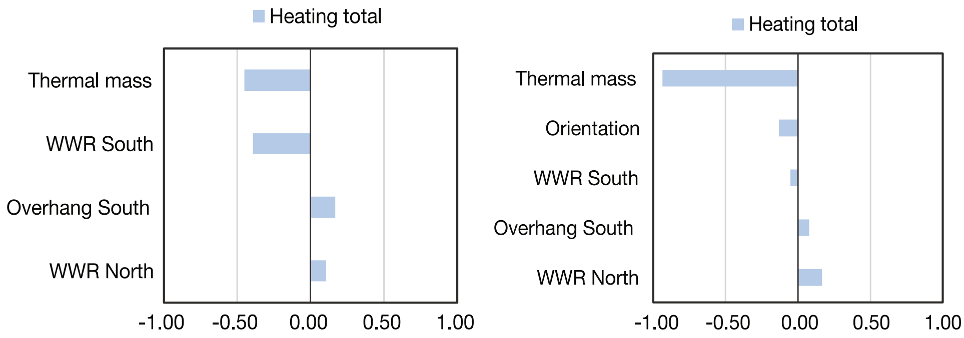
HVAC energy demand of hotel buildings in locations above 2500 m are dominated by heating. Simulation results for Thakmarpha (2566 m) indicate a share of heating between 98% and 100% of total HVAC energy demand. In Namche Bazar (3354 m) annual energy demand for room conditioning is 100% based on heating.

Likewise in cool temperate climate, the regression analysis indicates that thermal mass has the highest impact on total HVAC energy demand (Fig. 17). On the one hand, due to elevation, temperatures are low in this climate. On



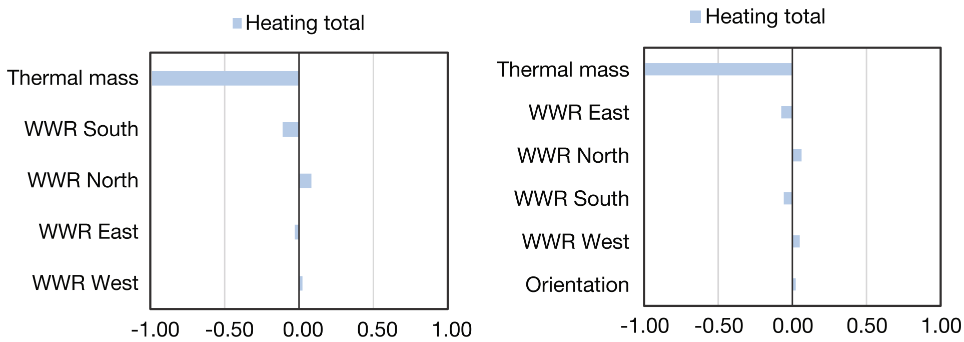
(a) Annual electricity costs (b) Life cycle costs

Fig. 16. Cost analysis of optimised designs for courtyard typology in Dhunche.



(a) Thakmarpha (b) Namche

Fig. 17. Standardised regression coefficient (SRC) of design parameters for double-banked typology.



(a) Thakmarpha (b) Namche

Fig. 18. Standardised regression coefficient (SRC) of design parameters for atrium typology.

the other hand, solar radiation is high and can be used for passive heating which requires a high building mass.

According to the low SRC, window-to-wall ratio (WWR) plays a secondary role for passive design optimisation (Fig. 18). Depending on the orientation of the openings, higher window area might reduce (negative SRC) or increase (positive SRC) total HVAC consumption. A positive SRC means that the heat loss through the openings is higher than the solar gains. A negative SRC indicates that passive heating through window in this direction is effective. For example, the results of the atrium typology indicate that larger windows facing South and East reduce energy demand while North and West facing windows increase energy demand (Fig. 18). Best performing designs in this climate have a WWR South and East between 20% and 40% and a WWR North and West between 10% and 20%.

The SRC for orientation in cold climate has a very low rank which means orientation does not have a strong impact on energy consumption. For some typologies, there is no significant relationship between orientation and HVAC energy consumption (p-value > 0.05). Best performers of elongated layouts have the facade with the largest window area facing south-east or north-east to increase solar gains of the low-standing morning sun. The facade with the largest WWR of the atrium and courtyard typologies is south-facing.

The cost analysis shows that in Nepal's cold climate passive design can only lead to marginal energy cost savings. Fig. 19 compares the annual HVAC electricity costs of different hotel building typology by thermal mass. Compared to the cool temperate and temperate climate absolute cost savings through the application of high mass materials amount to between 11 and 17 USD per guest room for Thakmarpha and between 11 and 28 USD per guest room for Namche. Relative savings are marginal at a level of 2% to 9% of annual HVAC energy costs.

Similar to the thermal mass strategy, the optimisation of window areas can lead to modest energy cost savings. For example, increasing the window area facing South and East of the atrium typology from 10% to 40% results in annual electricity cost savings of 5 USD per guest rooms (Fig. 20(a)). Equally low are cost savings for optimised design in Namche (see Fig. 21(a)). Due to the higher additional investment cost for the increased window area, life cycle costs of the optimised designs are slightly higher than the inefficient design (Figs. 20(b) and 21(b)).

Combining all passive design strategies for the cold climate, Fig. 22 indicates that absolute energy cost savings are at a similar level as in cool temperate

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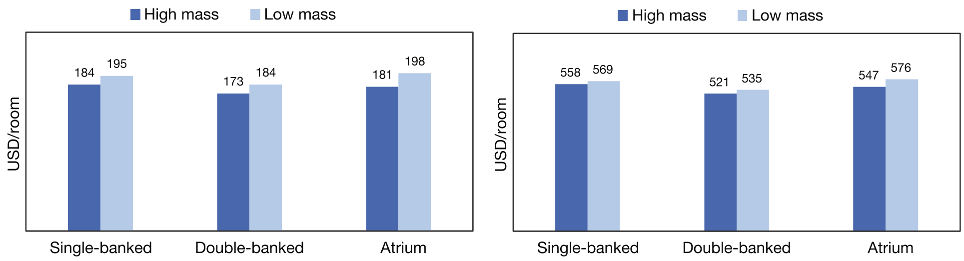
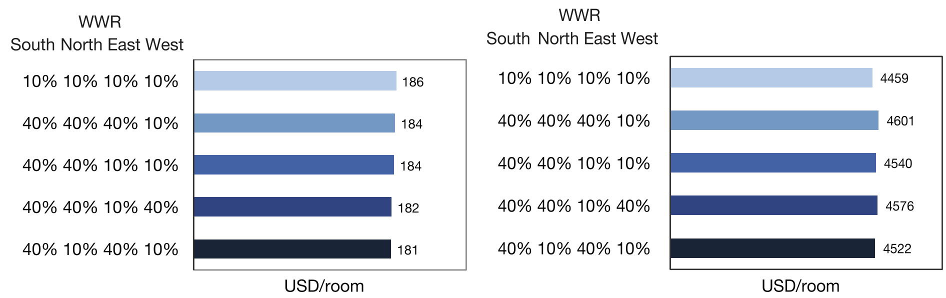


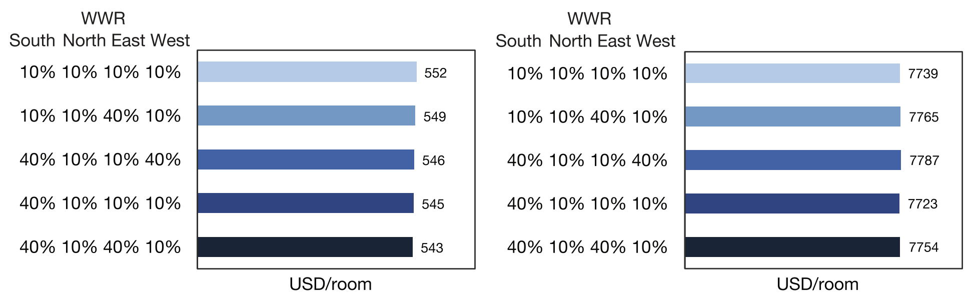
(a) For Thakmarpha (b) For Namche

Fig. 19. Annual electricity costs for different typologies by thermal mass in cold climate.



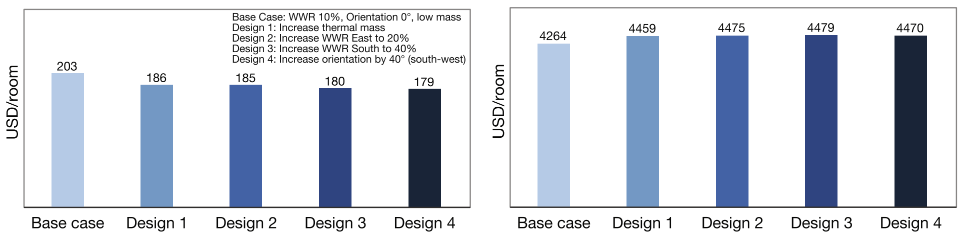
(a) Annual electricity costs (b) Life cycle costs

Fig. 20. Cost analysis for atrium typology with different WWRs in Thakmarpha.



(a) Annual electricity costs (b) Life cycle costs

Fig. 21. Cost analysis for atrium typology with different WWRs in Namche.



(a) Annual electricity costs (b) Life cycle costs

Fig. 22. Cost analysis of optimised designs for atrium typology in Thakmarpha.

Table 14
International and regional standards for envelope insulation IEA (2013), Dicke et al. (2003), ICC (2014), MoHURD (2015) and BEE (2006).

Region	Climate	Wall U-Value [W/m^{2}K]	Roof U-Value [W/m^{2}K]	Floor U-Value [W/m^{2}K]	Windows U-Value [W/m^{2}K]	SHGC
IEA Global	Hot	0.35	0.35	–	1.8	0.05–0.5
	Cold	0.15	0.15	–	1.8	0.05–0.6
Europe	Moderate	0.4–0.65	0.45–0.9	0.4–0.65	2.5–3.25	–
	Cold & Temperate	0.15–0.4	0.22–0.45	0.15–0.4	1.25–2.5	–
USA	Very cold	0.40	0.16	0.31	0.37	0.45
	Warm & mixed-humid	0.59–0.7	0.18–0.22	0.43	0.45–0.60	0.25–0.40
	very hot & hot	0.86	0.22–0.27	0.61–1.83	0.65	0.25
China	HSWW	0.8–1.5	0.5–0.8	1.5	2.0–5.2	0.18–0.52
	Temperate	0.8–1.5	0.5–0.8	–	2.0–5.2	0.24–0.48
	Cold	0.45–0.50	0.40–0.45	1.00	1.4–3.0	0.35–0.52
India	Warm-humid	0.35	0.26		3.18	0.25
	Composite	0.35	0.26		3.18	0.25
	Cold	0.37	0.26	–	4.09	0.51

climate. For instance in Thakmarpha, energy cost savings for atrium typology amounts to up 24 USD per guest room when all passive design strategies are considered. However, the relative saving potential amounts to only 12% due to the fact that total energy costs are twice as high in cold climate compared to cool temperate climate. The most energy-efficient design (Design 4) has marginal higher life cycle costs like the base case design (Fig. 21(b)).

To summarise, high thermal mass is very important for passive design optimisation in Nepal's cold climate region. North and west facing windows should be kept small while south and east facing windows can be moderate for optimising passive solar heating. Marginal energy cost savings can be achieved through passive design.

Without considering insulation measures, passive design strategies have the potential to reduce HVAC energy demand between 9% and 23% in this climate. Compared to all other climate zone the reduction potentials are moderate. Therefore, the next section analyses in detail the energy savings that can be achieved by insulating the hotel buildings.

4. Thermal insulation optimisation

4.1. International standards

In order to keep the indoor environment comfortable, envelope insulation is necessary to reduce heat loss during cold weather and keep out excess heat during hot weather. Finding the optimal insulation level for the building envelope means maintaining a balance between the investment cost in insulation material during the construction of the building and the energy cost for mechanical room conditioning low during the operation of the building. Primary factors for determining the optimal insulation thickness are climate, cost of energy, cost of the insulation materials and the efficiency of the air conditioning system. Many countries have already established standards for optimal insulation levels which can serve as reference.

Table 14 shows a summary of international and regional standards that are relevant for the climatic context of Nepal. It can be seen that standards are more stringent in colder climates than in warmer climates. For instance, in Sweden (Stockholm), cost-effective wall, roof and floor insulation reaches U-Values of 0.20, 0.17 and 0.25 W/m^{2}K, respectively (Boermans and Petersdorff, 2007). In comparison, in southern Italy (Palermo), U-Values of 0.48 W/m^{2}K for walls, 0.34 W/m^{2}K for roofs and 1.44 W/m^{2}K for floors are cost-efficient. Furthermore, developed countries have higher thermal insulation standards as compared to developing countries, probably because they have a longer tradition of using thermal insulation. Developed countries also have higher requirements for thermal comfort.

Depending on the construction practices, countries differentiate their thermal performance standards according to the thermal mass of the building. Therefore, lightweight construction has to comply much stricter requirements than buildings with high thermal mass. This has to do with the fact that buildings with high mass can benefit more from passive solar heating and cooling effects. For example, in China, buildings with low thermal mass have to fulfil much lower requirement with regard to the U-Value than high mass buildings (Shui et al., 2009). It is also common to set up thermal resistance of windows depending on the window-to-wall-ratio following the principle - the higher the window areas, the lower the U-Value. Some countries also allow trade-offs for low solar heat gain coefficient of window system if shading devices are provided (BEE, 2006; ICC, 2014).

4.2. Minimum thermal comfort

The results of the minimum comfort[3] optimisation runs indicate that in locations above 500 m and below 2000 m increased insulation levels are almost not cost-effective.

[3] As defined in methodology section.

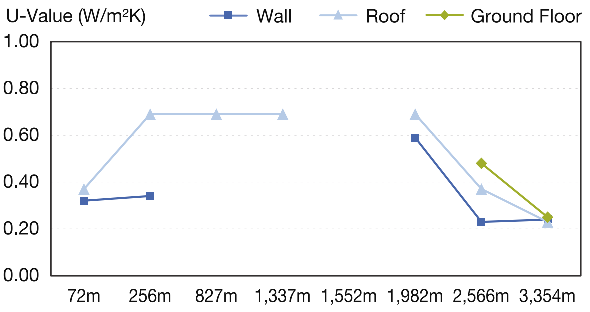


Fig. 23. Cost-effective insulation level of opaque envelope for minimum comfort (Minimum comfort as defined in methodology section) by location.

Fig. 23 and Table 15 illustrate cost-effective insulation levels (U-Values) for the opaque envelope for the different locations. A missing value in this figure indicates that insulation measures for this building element at this location are not leading to positive life cycle cost (LCC) net savings. For example, in Dhulikhel (1552 m) adding an insulation layer to any part of the building envelope is not cost-effective at all. In Pokhara (827 m) and Kathmandu (1337 m), only minimum insulation of the roof is cost-effective.

Looking at the exterior walls, U-Values below 0.35 W/m^2K are cost-effective in the warm temperate climate of Nepal which correspond to a added insulation layer of 100 mm. In the cold climate zone of the country, cost-effective insulation reaches the level below 0.25 W/m^2K equal to 150 mm insulation.

Roof insulation is cost-effective for all locations except Dhulikhel. Dhulikhel has very moderate climate with very low energy demand for cooling and heating. The uninsulated reference cases have a very low annual energy demand between 8 and 12.5 kWh/m^2 per year which means that savings will be also very low and cannot pay back additional investment costs for insulation.

Ground floor insulation with a layer thickness between 50 and 100 mm is only recommended for locations above 1000 m where there is a considerable share of heating energy demand. In the lower locations, the uninsulated ground floor works as a thermal sink and contributes to saving in cooling demand.

Improving insulation level of windows implicates the highest additional investment in Nepal. A simple double glazing window system is about double as expensive compared to the standard single glazing window. For that reason, improving glazing seems to be the least cost-effective energy efficiency measure. According to the simulation results of minimum comfort optimisation runs, improved glazing is only cost-effective for the locations with the highest cooling demand (Biratnagar) and highest heating demand (Namche). For all other locations double glazing is not cost-effective which means the energy savings achieved by replacing single glazing through double glazing do not pay back the high investment costs (Fig. 24).

With regard to the solar heat gain coefficient (SHGC) for the window system, optimisation runs show clearly, that for all locations below 1000 m windows with a low SHGC of at least 0.3 are cost-effective while for locations above 1000 m, a high solar heat gain coefficient is recommended (greater than 0.6). In the warmer climate zone below elevation of 1000 m the lower SHGC can contribute considerably to reduce cooling demand. For higher elevation, a high SHGC will enhance passive solar heating and, thus, decrease the need for mechanical heating.

Fig. 25 summarises the range of cost-effective U-Values by building component for all assessed locations. It has to

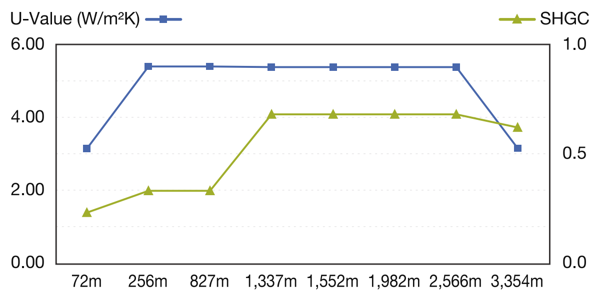


Fig. 24. Cost-effective insulation level and SHGC of windows for minimum comfort by location (Minimum comfort as defined in methodology section).

Table 15
Optimal insulation of building envelope for minimum thermal comfort.[a]

Location	Wall		Roof		Ground Floor		Window	
	W/m^2K	mm	W/m^2K	mm	W/m^2K	mm	W/m^2K	SHGC
Biratnagar 72m	0.32	100	0.37	100	4.17	0	3.14	0.23
Rampur 256m	0.34	100	0.69	50	4.17	0	5.40	0.33
Pokhara 827m	–	–	0.69	50	4.17	0	5.40	0.33
Kathmandu 1337m	–	–	0.69	50	–	–	5.38	0.68
Dhulikhel 1552m	–	–	–	–	–	–	5.38	0.68
Dhunche 1982m	0.59	50	0.69	50	–	–	5.38	0.68
Thakmarpha 2566m	0.23	150	0.37	150	0.48	50	5.38	0.68
Namche 3354m	0.24	150	0.23	150	0.25	100	3.15	0.62

[a] Minimum comfort as defined in methodology section.

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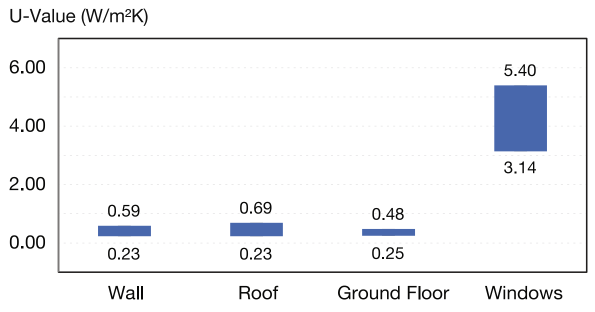

Fig. 25. Range of cost-effective insulation level for minimum comfort (Minimum comfort as defined in methodology section) by envelope component.

be noted that only insulated cases with life cycle net savings are considered in this figure. While U-Values between 0.23 and 0.59 W/m^2K are cost-effective for the exterior wall, roof insulation with thermal transmittance between 0.23 and 0.69 W/m^2K is optimal. Cost-effective design solutions have windows with a thermal transmittance between 5.40 and 3.14 W/m^2K, which corresponds to aluminium windows with single glazing and double glazing, respectively.

4.3. Maximum thermal comfort

Assuming that hotels in Nepal have to fulfil international comfort standards (here called maximum standard[4]), the analysis of cost-effectiveness for additional envelope insulation shows a different picture compared to the previous presented result for minimum comfort (see Figs. 26, 27, 28 and Table 16).

The results show the lowest cost-effective thermal transmittance (below 0.25 W/m^2K) for exterior walls in Dhunche (1982 m), Thakmarpha (2566 m) and Namche Bazar (3354 m) which correspond to an insulation layer of 150 mm. Being the most moderate climate of Nepal, wall insulation in Pokhara and Kathmandu is only cost-effective up to 0.59 W/m^2K which means an insulation layer of 50 mm.

In terms of roofing, up to a 150 mm thick insulation layer (U-Value: 0.25 W/m^2K) is cost-effective in Nepal's cold climate zone (see Fig. 26 and Table 16). For all other locations except Pokhara an insulation layer of 100mm is recommended resulting in a total insulation level of about 0.37 W/m^2K. For the most moderate climate of Pokhara, the simulation results indicate only 50 mm insulation for the roofs equivalent to a U-Value of 0.69 W/m^2K.

For ground floor insulation, lower insulation levels are required for colder climates. All locations below 1000 m should keep insulation layers at minimum level (25 mm) for cost-effectiveness. For Thakmarpha (2566 m) and Namche Bazar (3354 m) in the cold climate zone the best ground floor insulation of 100mm (U-Value: 0.25 W/

[4] Maximum comfort as defined in methodology section

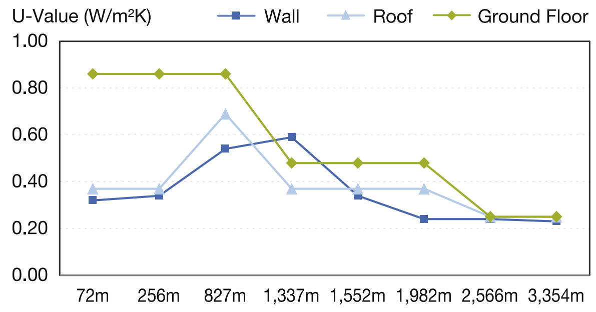

Fig. 26. Cost-effective insulation level of opaque envelope for maximum comfort by location (Maximum comfort as defined in methodology section).

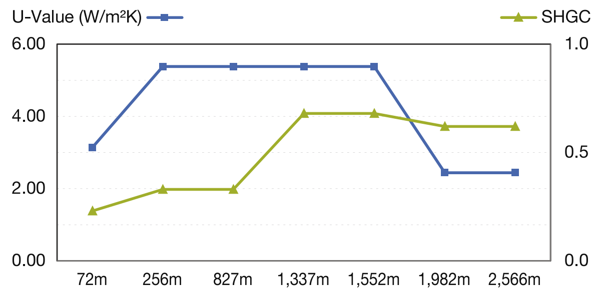

Fig. 27. Cost-effective insulation level and SHGC of windows for maximum comfort by location (Maximum comfort as defined in methodology section).

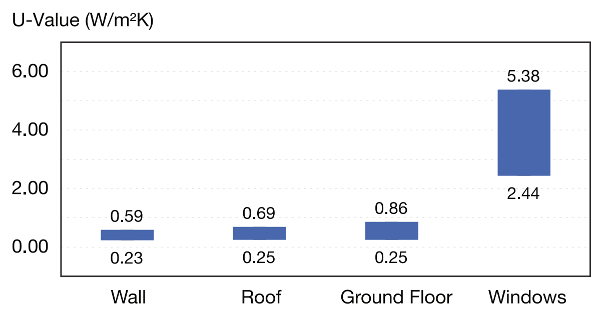

Fig. 28. Range of cost-effective insulation level for maximum comfort (Maximum comfort as defined in methodology section) by envelope component.

m^2K) is recommended while in the other locations an insulation layer of a 50 mm thickness (U-Value: 0.48 W/m^2K) is cost-effective.

Similar to the results of the optimisation for minimum comfort, window improvement hardly pays back when assuming higher comfort requirements. Only for locations below 100 m elevation and above 1500 m double glazing makes sense from a micro-economic point of view (Fig. 27). Energy cost savings through double glazing are not high enough to pay back the high additional investment cost. It should be noted that double glazing is still not a standard technology in Nepal and is very cost-intensive compared to single glazing.

Table 16
Optimal insulation of building envelope for maximum thermal comfort.[a]

Location	Wall		Roof		Ground Floor		Window	
	W/m^2K	mm	W/m^2K	mm	W/m^2K	mm	W/m^2K	SHGC
Biratnagar 72m	0.32	100	0.37	100	0.86	25	3.14	0.23
Rampur 256m	0.34	100	0.37	100	0.86	25	5.38	0.33
Pokhara 827m	0.54	50	0.69	50	0.86	25	5.38	0.33
Kathmandu 1337m	0.59	50	0.37	100	0.48	50	5.38	0.68
Dhulikhel 1552m	0.34	100	0.37	100	0.48	50	5.38	0.68
Dhunche 1982m	0.24	150	0.37	100	0.48	50	2.44	0.62
Thakmarpha 2566m	0.24	150	0.25	150	0.25	100	2.44	0.62
Namche 3354m	0.23	150	0.25	150	0.25	100	2.44	0.62

[a] Maximum comfort as defined in methodology section.

The simulation results clearly indicate cost-effectiveness of glazing with a low solar heat gain coefficient (SHGC) for all locations below 1000 m due to the high cooling demand. Therefore, the best performing window system in Biratnagar has a SHGC below 0.25. For all locations above 1000 m, SHGC should be above 0.6 in order to enhance solar gains for passive heating.

Concluding, Fig. 28 illustrates the range of cost-effective thermal resistance by building component for all analysed locations. For exterior walls, U-Values between 0.23 and 0.59 W/m^2K lead to life cycle cost savings. Roof insulation reaching thermal transmittance between 0.25 and 0.69 W/m^2K is profitable and, thus, recommended. For the windows, the thermal transmittance of cost-effective solutions ranges between 2.44 and 5.38 W/m^2K, which corresponds to aluminium windows with double glazing and single glazing, respectively.

The comparison between simulation runs for minimum and maximum comfort shows that considering maximum comfort requirements insulation measures for walls, roof, ground floor and windows become economically more feasible in all assessed locations. Fig. 23 and Table 15 indicates that for Pokhara (827 m), Kathmandu (1337 m), Dhulikhel (1552 m) and Dhunche (1982 m) insulation measures of at least one building component are not cost-effective (missing values). In contrast, Table 16 lists cost-effective U-Values for all locations and building components.

5. Energy saving potentials

The quantity of energy that can be saved by passive design and improving envelope insulation depends upon the climate and the building typology. Table 17 illustrates the energy saving potentials by optimising passive design parameters like orientation, thermal mass, window-to-wall-ratio, overhang and fins (excluding insulation). The results for all assessed hotel typologies and locations are listed as relative savings compared to the worst performing design.

Fig. 29 shows energy saving potentials for the assessed locations by adding a cost-optimum insulation layer to the analysed typology. Values here are also listed as relative savings in comparison to the uninsulated base case.

Savings between 9% and 73% of total energy consumption for air conditioning can be achieved by only adopting the best passive design strategies (excluding envelope insulation). Highest savings up to 73% can be obtained in the most moderate climate of Pokhara, Kathmandu and Dhulikhel. In cold climate region, passive design optimisation will lead to energy savings of up to 23%. On average, energy for space conditioning in Nepal's hotels could be reduced by 37% by adopting passive design measures.

Improvement of envelope insulation can bring further energy savings between 26% and 50% (see Fig. 29). Different from passive design optimisation, adding insulation results in similar relative savings in all climate regions of

Table 17
Energy saving potential through passive design by location and typology.

	Building typology						
Location	Single cottage	Double cottage	Bungalow	Single-banked	Double-banked	Courtyard	Atrium
Biratnagar 72 m	22%	32%	29%	38%	36%		
Rampur 256 m	22%	25%	29%	34%	29%		
Pokhara 827 m	41%	39%	50%	47%	50%	44%	
Kathmandu 1337 m	49%	48%	58%	64%	55%	50%	
Dhulikhel 1552 m		49%	57%	73%	56%	49%	28%
Dhunche 1982 m			33%	54%	31%	53%	14%
Thakmarpha 2566 m				15%	13%	23%	15%
Namche 3354 m				13%	9%	23%	11%
Average	34%	39%	43%	42%	35%	40%	17%

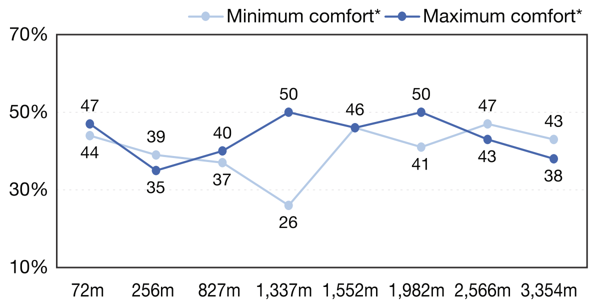

Fig. 29. Energy saving potential through envelope insulation by location (*min/max comfort as defined in methodology section).

the country. However, it has to be noticed that absolute savings might be much larger in hot and cold regions considering the fact that total energy demand is considerably higher than in the moderate climate zone. On average, about 42% of HVAC energy demand can be reduced by increasing the envelope insulation in hotel buildings to a cost-effective level.

6. Recommendations

The objective of this study was to develop design strategies for energy-efficient hotel buildings in Nepal. For this purpose, two sets of building energy simulation runs were conducted. Firstly, the passive design of seven building typologies for hotels was optimised in all bioclimatic zones considering parameters like orientation, thermal mass, window-to-wall-ratio (WWR) and shading device. Secondly, optimisation of roof, wall and ground floor insulation for one typology was done to find the cost-effective insulation level for each building element and climate.

The results of passive design optimisation show that in warm temperate climate minimising the solar gains by keeping the window-to-wall-ration (WWR) small and using shading devices is the most important design strategy. In all other bioclimatic zones, high thermal mass has priority to achieve lower energy demand because of passive cooling and passive heating effects. Additionally, large window areas facing south are recommended for temperate and cool temperate climate zone. In the cold climate zone, passive solar heating can be also effective but window areas should be kept moderate in order to minimise heat losses.

Furthermore, the findings indicate coherent passive design strategies for the locations in the same bioclimatic zone except for Pokhara (827 m) and Kathmandu (1337 m), both located in the temperate zone. For Pokhara, minimising solar gains by reducing the WWR and adding an overhang has priority while in Kathmandu, WWR South can be larger to optimise passive solar heating. Shading has no priority. Consequently, a differentiation of temperate climate might become necessary.

Outcomes of the envelope optimisation runs can be summarised as follows: envelope insulation is cost-effective at different levels depending on the bio-climatic zone and the assumed comfort level that needs to be reached. Highest insulation levels are recommended for the cold climate zone with U-Values of 0.25 W/m^2K. Minimum insulation between 0.4 and 1.6 W/m^2K is required for the temperate climate of Nepal. In the warm temperate climate zone, ground floor insulation is not recommended or at very low level (0.9 W/m^2K) for minimum or maximum comfort,[5] respectively. At current levels of prices, double glazing for windows is only cost-efficient in warm temperate and cold climate of Nepal. SHGC for windows should be at least 0.3 for locations up to 1000 m and above 0.6 for locations above 1000 m.

The bioclimatic analysis by Bodach (2014) indicates that passive design strategies like thermal mass, optimal building orientation and passive solar heating can be effective in Nepal's climate. The findings of this study confirm this statement and quantify energy savings for heating and cooling through passive design.

Thermal inertia is very important passive design strategy in all climate zones with considerable heating demand (locations above 500 m). High solar radiation in winter combined with high thermal mass can increase the passive solar heating effect and, thus, reduce the need for mechanical heating. Similar to that of Gratia and Herde (2003), this research shows that thermal mass plays an important role in absorbing solar gains during the day and reducing temperature rise inside the building. In locations with moderate cooling needs like the cool temperate climate of Nepal, high thermal mass can reduce cooling demand to almost zero.

With regard to passive solar heating, the window area, particularly towards south is the most relevant design factor. Gasparella et al. (Apr 2011) also concluded that increasing window areas facing south reduce effectively heating loads but might increase cooling energy needs. This is a typical conflicting passive design strategy that has to be balanced. The results of this research reveals that larger windows of the south facade will result in annual energy savings for locations above 1000 m while in lower locations window areas should be kept as small as possible to prevent overheating.

The influence of shading devices and the solar heat gain coefficient (SHGC) to reduce cooling needs was quantified by many authors (Florides et al., 2002; Sozer, 2010; Chen et al., 2015). Chen et al. (2015) could achieve savings up to 42% by optimising window area, SHGC and projection factor of overhangs. This study shows that on average, 37% of HVAC energy demand can be saved by optimising passive design.

The findings of this study are coherent with Bodach (2014)'s study about the importance of building orientation. The optimum orientation has priority in warm temperate and temperate climate and contributes also to

[5] Min/max comfort as defined in methodology section.

energy savings in cool temperate climate. However, in cold climate orientation does not play a significant role. Similar to that of Florides et al. (2002), it can be concluded that, particularly, elongated layouts should orient the long building facade towards south.

However, in hotel design the orientation of the building and its openings is often influenced by other factors like the panoramic view or site constraints. Improving the thermal properties of the window according to the passive design strategies of the climate can still lead to an energy-efficient design. Two examples are explained below:

This research recommends that windows facing east and west should be avoided in warm temperate and temperate climate. If this is not possible, vertical shading devices like fins combined with low-e glazing should be applied to reduce solar gains and prevent overheating in the morning and evening hours. Similarly, windows facing north should be avoided in cool temperate and cold climate to protect from the cold. If this design strategies cannot be fulfilled due to other design priorities, a lower U-Value of the window (double glazing) and, thus, a better insulation might compensate increased heat losses through additional window area.

It is uncontroversial that envelope insulation reduces energy demand in many climates. Using dynamic energy simulation and life cycle cost analysis Florides et al. (2002) showed that roof insulation is cost-effective for the hot climate in Cyprus with a short payback period between 3.5 and 5 years while wall insulation pays only back over a time period of 10 years. In Turkey, an optimised hotel design will have 37% less energy need than a standard design (Sozer, 2010). In India, hotels can save between 33% and 50% by applying insulation measures (Chedwal et al., 2015).

Determining which level of envelope insulation is cost-efficient depends on several factors and makes comparison difficult. In most regions, except Northern Europe, insulation requirements of building regulations do not reach the economically justified level (IEA, 2013). The fact that building energy demand is a major contributor to climate change, performance goals should meet climate change action and not only economically feasible level.

Comparing the findings for cost-effective insulation for Nepal with international standards (Table 14) the following can be concluded:

- Recommended cost-effective insulation for cold climate reaches similar values as North-European standards.
- Cost-effective U-Values for temperate and cool temperate climate are comparable with standards of similar climates in the International Energy Conservation Code (ICC, 2014).
- Results for warm temperate climate reaches thermal resistance very close to Indian regulations (BEE, 2006).
- Similar to standards in India and USA, a low SHGC of at least 0.25 is recommended for locations with high cooling load.

While international and regional standards suggest to apply more insulation on roofs than walls, the results of this study conclude a similar thickness for roof and wall. The reason for that might be the particular multi-storey building typology where the roof surface area is smaller in percentage of total outer surface area than the wall. Furthermore, this research is based on the combined effect of all insulation measures while most studies on cost-effective insulation thickness investigate each building element separately.

There are two insulation measures that are not always justified by economic feasibility: Firstly, floor insulation and, secondly, double glazing. In warm temperate climate the cool ground can be used as thermal sink to reduce needs for active cooling. Additional floor insulation reduces this natural cooling effect and, therefore, increases cooling demand. Regarding glazing it is noticed that, particularly, in temperate climate, the high additional investment for double glazing does not pay back over life time because absolute energy cost savings are very low.

The market for double glazing is still in the early stage and few companies are offering this product in Nepal. A study on hotel design in neighbouring India with similar market conditions concluded that glazing is one of the least cost-effective energy conservation measure with a simple payback period of 10.3 years (Chedwal et al., 2015). Although this payback time is much less than the building's life time, replacing single for double glazing is the most cost-intensive energy saving measure leading to a substantial increase of construction costs. Particularly, small and medium scale hotel entrepreneurs with limited investment capital might not be able to fund additional construction costs.

Floor insulation and double glazing windows might not be justified by economic feasibility for some climate region in Nepal. However, they are necessary for other demands like acoustic comfort, condensation issues or thermal comfort (surface temperature). Therefore, these measures should be considered to ensure a comfortable hotel design.

Finally, the results of the simulation runs led to different design recommendations for the two locations in the temperate climate (from 501 to 1500 masl). A further differentiation of the temperate climate zone is needed and a renaming of all zones proposed. The following consolidated bioclimatic zoning for Nepal with five elevation-based bioclimate zones is suggested:

- Warm climate (below 500 masl).
- Moderate warm climate (from 501 to 1000 masl).
- Moderate climate (from 1001 to 1500 masl).
- Moderate cold climate (from 1501 to 2500 masl) and
- Cold climate (above 2500 masl).

In conclusion, passive design strategies and minimum requirements for insulation levels are suggested for each bioclimatic zone (see Tables 18–20). These energy efficiency

Table 18
Passive design recommendations for hotel buildings in Nepal.

Bioclimatic zone	Thermal mass	WWR South	WWR North	WWR East	WWR West	Orientation	Overhang South PF	Fins East & West PF
Warm (<500 m)	low, medium, or high	20% [a]/ 30%[b]	20%[a]/ 30%[b]	0–20%	0–20%	South	0.2–0.4	0.4–0.6
Moderate warm (501–1000 m)	high	20%[a]/ 30%[b]	20%[a]/ 30%[b]	0–20%	0–20%	South	0.2–0.4	flexible shading
Moderate (1001–1500 m)	high	40–60%	10–20%	10–20%	10–20%	South	0.2[c]	flexible shading
Moderate cold (1501–2500 m)	high	40–60%	10–20%	20–30%	20–30%	South	flexible shading	
Cold (>2500 m)	high	20–40%	0–20%	0–20%	0–20%	–	–	–

[a] For small-scale hotels with low case depth.
[b] For large-scale hotels with large case depth.
[c] For WWR greater than 40.

Table 19
Recommendations for opaque envelope insulation of hotel buildings in Nepal.

Bioclimatic zone	U-Value for Wall			U-Value for Roof			U-Value for Floor		
	Minimum comfort[a] W/m^{2}K	Maximum comfort[a] W/m^{2}K	Thickness insulation mm	Minimum comfort W/m^{2}K	Maximum comfort W/m^{2}K	Thickness insulation mm	Minimum comfort W/m^{2}K	Maximum comfort W/m^{2}K	Thickness insulation mm
Warm (<500 m)	0.35	0.35	100	0.70	0.40	50–100	–	0.90	0–25
Moderate warm (501–1000 m)	1.60	0.60	50	0.70	0.40	50–100	–	0.90	0–25
Moderate (1001–1500 m)	1.60	0.60	50	0.70	0.40	50–100	–	0.90	0–25
Moderate cold (1501–2500 m)	0.60	0.35	50–100	0.70	0.40	50–100	0.90	0.50	25–50
Cold (>2500 m)	0.25	0.25	150	0.25	0.25	150	0.50	0.25	50–100

[a] Minimum and maximum comfort as defined in the methodology section.

Table 20
Recommendations for window performance of hotel buildings in Nepal.

Bioclimatic zone	U-Value		SHGC
	Minimum Comfort[a] W/m^{2}K	Maximum Comfort[b] W/m^{2}K	
Warm (<500 m)	3.20	3.20	⩽0.25
Moderate warm (501–1000 m)	5.40	3.20	⩽0.3
Moderate (1001–1500 m)	5.40	3.20	⩾0.6
Moderate cold (1501–2500 m)	5.40	2.50	⩾0.6
Cold (>2500 m)	3.20	2.50	⩾0.6

[a] Minimum comfort as defined in the methodology section for small-scale hotels.
[b] Maximum comfort as defined in the methodology section for all other hotels.

guidelines for hotel design are the first step towards a low-carbon development path of the fast growing accommodation sector in Nepal.

Using building energy simulation as the main method, this research has its limitations. The results of the simulation are calculated under predefined boundary conditions. However, those boundary conditions are based on assumptions that might have a certain impreciseness. Absolute energy demand in the real building might vary because of variation in thermal properties of building materials, construction quality and building use.

For the economic analysis, construction prices from Kathmandu in January 2015 were used to make a comparison possible. However, prices in other locations of the country might be higher or lower due to additional or less transportation cost. Furthermore, construction prices are influenced by other factors like labour cost, fuel prices, demand-supply gap etc.

The focus of this study was on hotel buildings as an example typology for commercial buildings. Seven different typical hotel designs were used to conduct the analysis. If a particular hotel design is significantly different to the developed typologies, its thermal performance might also vary. Nonetheless, the findings of this study are an effective starting point for developing a general energy conservation code for commercial buildings in Nepal.

7. Conclusion

Passive design and envelope insulation are effective strategies to reduce energy consumption for air-conditioning in Nepal's hotel buildings. Depending on the climate zone and building typology, different design strategies have priority (Table 18). The most important design strategies can be summarised as followed:

- All locations below 1000 m should have a small window area facing south of between 20% and 30% of total envelope area in order to reduce solar gains. Windows towards east and west should be avoided. Moreover, shading devices are recommended in this climate.
- Larger window areas facing south with WWR of 40% is recommended for locations above 1000 m to enhance passive solar heating. This leads to annual energy savings.
- High and medium thermal mass is a very effective passive design strategy for all location above 500 m.

Furthermore, the results indicate that improved insulation of the building envelope can be cost-effective over the building's life time although additional investment costs are high and energy prices are still low (Tables 19, and 20).

- An additional roof and wall insulation layer with a thickness between 50 and 100 mm is cost-effective in almost all climates and typologies.
- Ground floor insulation with thickness between 50 and 100 mm is recommendable for locations above 1500 m. For lower locations, an insulation layer of maximum 25 mm is suggested.

With regard to windows, low-e glazing ($SHGC < 0.25$) is recommended for all locations below 1000 m while at higher elevations, SHGC should be at least 0.6 to ensure effective passive solar heating. Switching from single to double glazing can be an option to get the best performing design and maximum thermal comfort. The higher investment is cost-effective in all regions except the temperate climate.

This study concludes that the hotel design that is optimised by passive strategies have potential to consume in average 37% less energy than designs that do not consider those strategies. Additional optimal envelope insulation can bring average HVAC energy savings of 42%.

Finally, the bioclimatic zoning for Nepal was further differentiated and consolidated leading to five elevation-based climate zones.

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Appendix D

Approach for energy saving scenarios

In order to give an outlook on the impact of energy conservation in the future, energy savings scenarios for the Nepalese building sector were developed (see *Energy saving scenarios for the building sector* on page 63). It was envisaged to create a simple model to estimate the impact of the introduction of design concepts and technologies for more energy-efficient buildings and compare the increase of energy consumption with the business-as-usual (BAU) scenario. This study only considers energy consumed for heating and cooling purposes. Due to the lack of data, reasonable assumptions were made for a number of variables illustrated in Table D.1 and Table D.3.

For the energy demand projection in hotel buildings, 2016 was selected as baseline year and the total number of hotel rooms was calculated from data of 2009 assuming a growth rate of 6%. It was assumed that 20% of the hotel rooms are equipped with space condition systems in 2016 and that this percentage increases by 3% every year. According to the conducted energy simulation study the energy consumption of the inefficient reference room and retrofitted energy efficient hotel room is 79 and 47 kWh/m^{2}a, respectively. Furthermore, it was assumed that the share of electricity use for space conditioning is 5% in 2016 and will grow by 1% every year.

For the energy scenarios of the residential sector the total floor area was estimated based on the population, household size, number of households and floor area per household. The year 2011 was used as baseline year with a household size of 4.9 persons and 20% of residential floor area with energy consuming space conditioning. With rising development the household size is assumed to decrease by 1% every year while 1% of air-conditioned floor area is added. The energy consumption per floor area of the base case buildings were calculated using statistical data of energy consumption for heating and cooling from [57] in 2011. Based on the results of the simulation study, it was assumed that energy-efficient residential buildings will consume 42% less energy for heating and cooling than the inefficient base case.

Table D.1: Assumptions for energy scenarios for space conditioning in hotels of Nepal

Description	Value
Hotel rooms	
Total number in 2016	21,460[a]
Annual growth rate	6.0%[b]
Average size	30 m^2[c]
Space conditioning	
Share of air-conditioned rooms in 2016	20%
Annual growth rate	3%
Energy consumption	
Base case buildings	79 kWh/m^2a[d]
Energy-efficient buildings	45 kWh/m^2a[d]
Electricity	
Electricity share of consumption in 2016	5%
Annual growth rate	1%
Scenarios	
Business-as-usual (BAU)	All hotel buildings are inefficient base case buildings
EE-2	Share of energy-efficent hotel rooms is increased by 2% annually
EE-5	Share of energy-efficent hotel rooms is increased by 5% annually

[a] Projections from data of 2009 [34] with annual growth rate of 6.0%
[b] Based on sector growth rate projection of 5% [60] and historical growth rate: 6.5% from 2009 to 2013 [34]
[c] Based on field research
[d] Based on own thermal building simulation

Table D.2: Energy demand projection of hotel buildings in Nepal under different scenarios

Year	2016	2020	2025	2030	2035	2040
Number of hotel rooms	21,460	27,093	36,256	48,519	64,929	86,889
Share of air-conditioned rooms	20.0%	32.0%	47.0%	62.0%	77.0%	92.0%
Number of air-conditioned rooms	4,292	8,670	17,040	30,082	49,995	79,938
Business-as-usual (BAU) scenario						
Energy consumption (GWh)	10.2	20.5	40.4	71.3	118.5	189.5
Share of electricity used for space conditioning (%)	5.0%	9.0%	14.0%	19.0%	24.0%	29.0%
Electricity consumption BAU (GWh)	0.5	1.8	5.7	13.5	28.4	54.9
EE-2 scenario						
Share of energy-efficient air-conditioned rooms (%)	0.0%	8.0%	18.0%	28.0%	38.0%	48.0%
Number of ineffizient conditioned rooms	4,292	7,976	13,973	21,659	30,997	41,568
Number of energy-efficient air-conditioned rooms	0	694	3,067	8,423	18,998	38,370
Energy consumption EE-2 (GWh)	10.2	19.8	37.3	62.7	99.1	150.3
Electricity consumption EE-2 (GWh)	0.5	1.8	5.2	11.9	23.8	43.6
Energy saving potentials (GWh)	0.0	0.7	3.1	8.6	19.4	39.1
Energy saving potentials (%)	0.0%	3.4%	7.7%	12.1%	16.4%	20.7%
EE-5 scenario						
Share of energy-efficient air-conditioned rooms (%)	0.0%	20.0%	45.0%	70.0%	95.0%	100.0%
Number of ineffizient conditioned rooms	4,292	6,936	9,372	9,024	2,500	0
Number of energy-efficient air-conditioned rooms	0	1,734	7,668	21,057	47,495	79,938
Energy consumption EE-5 (GWh)	10.2	18.8	32.6	49.8	70.0	107.9
Electricity consumption EE-5 (GWh)	0.5	1.7	4.6	9.5	16.8	31.3
Energy saving potentials (GWh)	0.0	1.8	7.8	21.5	48.4	81.5
Energy saving potentials (%)	0.0%	8.6%	19.4%	30.1%	40.9%	43.0%

Table D.3: Assumptions for energy scenarios for space conditioning in residential buildings of Nepal

Description	Value
Demography	
Population growth rate	1.35%[a]
Household size in 2011	4.9 persons%[a]
Annual growth rate of household size	-1%
Floor area	
Floor area per household in 2011	43.0 m^2 [b]
Annual growth rate	1.3%
Space conditioning	
Share of air-conditioned floor area in 2011	20.0%
Annual growth rate	1%
Energy consumption	
Base case buildings	198.2 kWh/m^2a[c]
Energy-efficient buildings	134.8 kWh/m^2a[d]
Electricity	
Electricity share of consumption in 2011	1.8% [e]
Annual growth rate	1%
Scenarios	
Business-as-usual (BAU)	All residential buildings are inefficient base case buildings
EE-1	Share of energy-efficent floor area is increased by 1% annually
EE-3	Share of energy-efficent floor area is increased by 3% annually

[a] Acoording to [61]
[b] No data availalable for Nepal. Average per capita floor area of 8.7m^2 taken from India [62]
[c] Calculated using energy consumption for heating and cooling in 2011 and estimated floor area [57]: 12078.194 GWh
[d] Average saving potential based on simulation study: 42%
[e] Acoording to [57]

Table D.4: Energy demand projection of residential buildings in Nepal under different scenarios

Year	**2011**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**
Population	26,494,504	27,954,441	29,893,005	31,966,003	34,182,758	36,553,239	39,088,106
Household size	4.9	4.7	4.5	4.3	4.1	3.9	3.7
Number of households	5,361,813	5,889,330	6,622,297	7,446,487	8,373,254	9,415,362	10,587,169
Floor area per household (m^2)	56.8	60.3	65.0	70.0	75.4	81.2	87.5
Total residential floor area million (m^2)	304.7	355.2	430.3	521.2	631.4	764.8	926.5
Share of conditioned floor area (%)	20.0%	24.0%	29.0%	34.0%	39.0%	44.0%	49.0%
Business-as-usual (BAU) scenario							
Energy consumption (TWh)	12.1	16.9	24.7	35.1	48.8	66.7	90.0
Share of consumption by electricity (%)	1.8%	5.8%	10.8%	15.8%	20.8%	25.8%	30.8%
Electricity consumption (TWh)	0.2	1.0	2.7	5.5	10.2	17.2	27.7
EE-1 scenario							
Share of energy-efficient air-conditioned floor area (%)	0.0%	0.0%	4.0%	9.0%	14.0%	19.0%	24.0%
Ineffizient air-conditioned floor area million (m^2)	60.9	85.2	119.8	161.3	211.8	272.6	345.0
Energy-efficient conditioned floor area million (m^2)	0.0	0.0	5.0	15.9	34.5	63.9	109.0
Energy consumption EE-1 (TWh)	12.1	16.9	24.4	34.1	46.6	62.6	83.1
Electricity consumption (TWh)	0.2	1.0	2.6	5.4	9.7	16.2	25.6
Energy saving potentials (TWh)	0.0	0.0	0.3	1.0	2.2	4.1	6.9
Energy saving potentials (%)	0.0%	0.0%	1.3%	2.9%	4.5%	6.1%	7.7%
EE-3 scenario							
Share of energy-efficient air-conditioned floor area (%)	0.0%	0.0%	12.0%	27.0%	42.0%	57.0%	72.0%
Ineffizient air-conditioned floor area million (m^2)	60.9	85.2	109.8	129.4	142.8	144.7	127.1
Energy-efficient conditioned floor area million (m^2)	0.0	0.0	15.0	47.8	103.4	191.8	326.9
Energy consumption EE-3 (TWh)	12.1	16.9	23.8	32.1	42.2	54.5	69.2
Electricity consumption (TWh)	0.2	1.0	2.6	5.1	8.8	14.1	21.3
Energy saving potentials (TWh)	0.0	0.0	0.9	3.0	6.6	12.2	20.7
Energy saving potentials (%)	0.0%	0.0%	3.8%	8.6%	13.4%	18.2%	23.0%

Appendix E

Comparison of climate data sets

Climate data is the most important input for analysing bioclimatic design strategies and conducting building energy simulation. Commonly a typical meteorological year (TMY) is used for this purpose. A TMY is a combination of selected weather data for a specific location, generated from observed weather data over several decades. It represent the long-term average meteorological conditions of a place while having a realistic frequency distributions and contains hourly values of all relevant meteorological elements.

The lack of TMY data sets for Nepal made is necessary to generate such data sets for the different locations. This was done by using the software tool Meteonorm [27]. Monthly climate normals (temperature, precipitation) from weather stations, either directly collected from Department of Hydrology and Meteorology Nepal [28] or derived from United Nation's Food and Agriculture Organisation climate database [29], were imported into the software with the aim to have more accurate results.

In order to check the plausibility of the generated data sets, it was compared with other existing climate data (see also *Climate and design* on page 13). For the comparison study measured climate observations from recently installed automated weather stations [30] and, if available, hourly data sets from the SWERA project [63] were used.

The following figures illustrate the comparative analysis for the locations Biratnagar and Kathmandu. The density of the data points for 2013, 2014 and 2015 is lower than for the generated TMY data set either because the weather station does not on a hourly bases (but every five hours) or data records are missing. The psychrometric chart shows also that hourly temperatures of the measured data is only available as integer value. Nevertheless, it can be seen that both daily averages and hourly values are in a similar range.

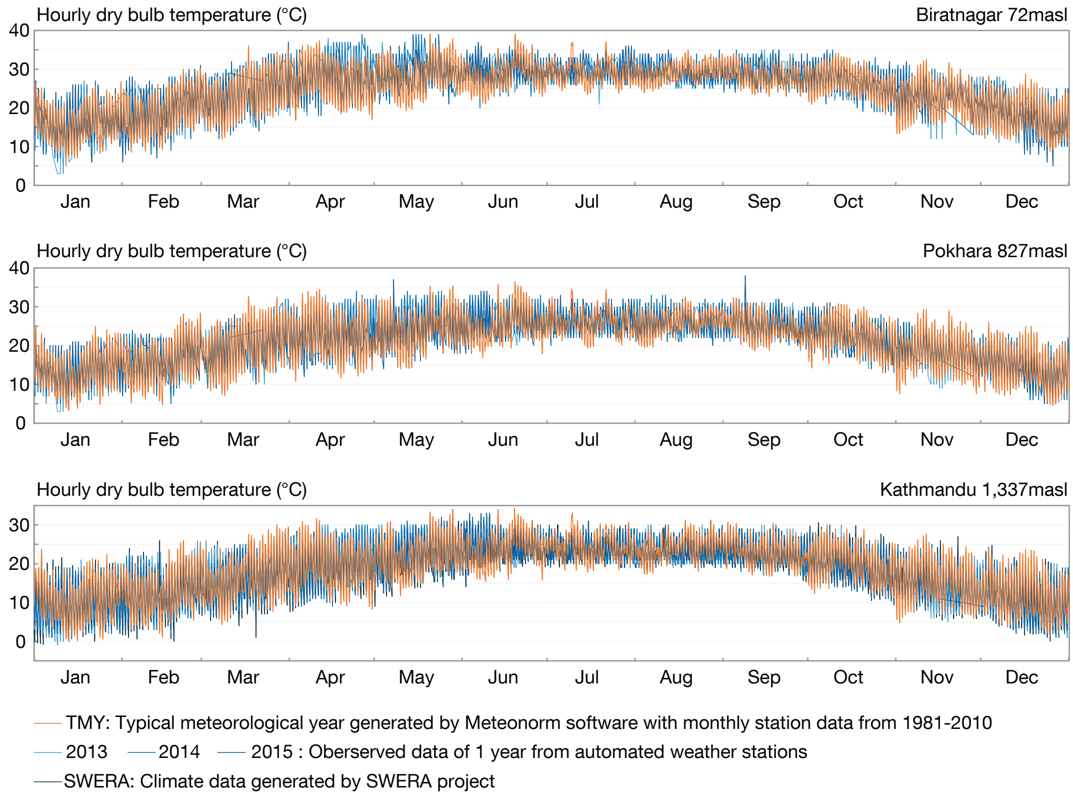

Figure E.1: Comparison of hourly dry bulb temperature from different climate data sets in Biratnagar, Pokhara and Kathmandu (Data sources: [27–30, 63])

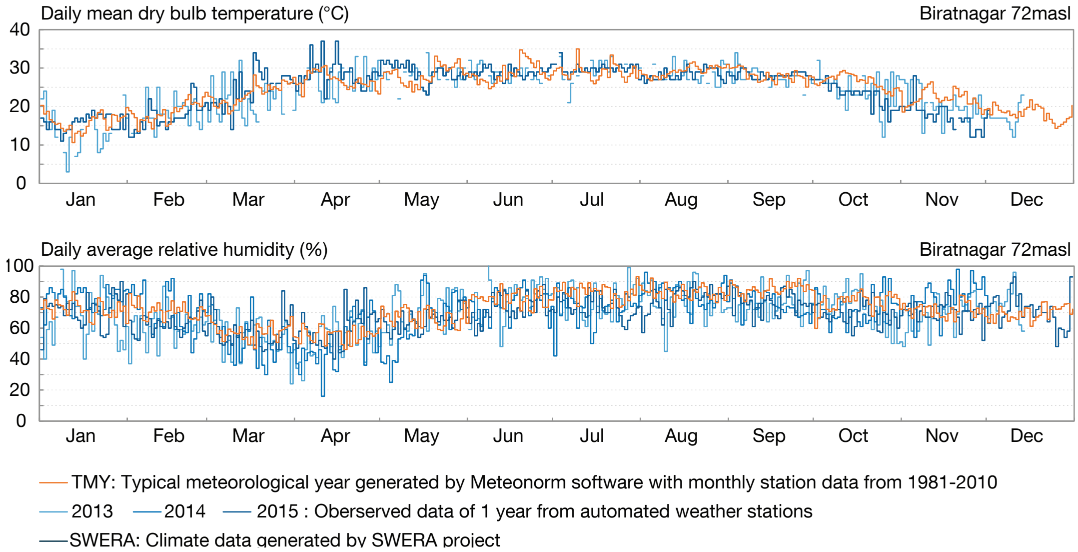

Figure E.2: Comparison of daily climate data from Biratnagar (Data sources: [27–30])

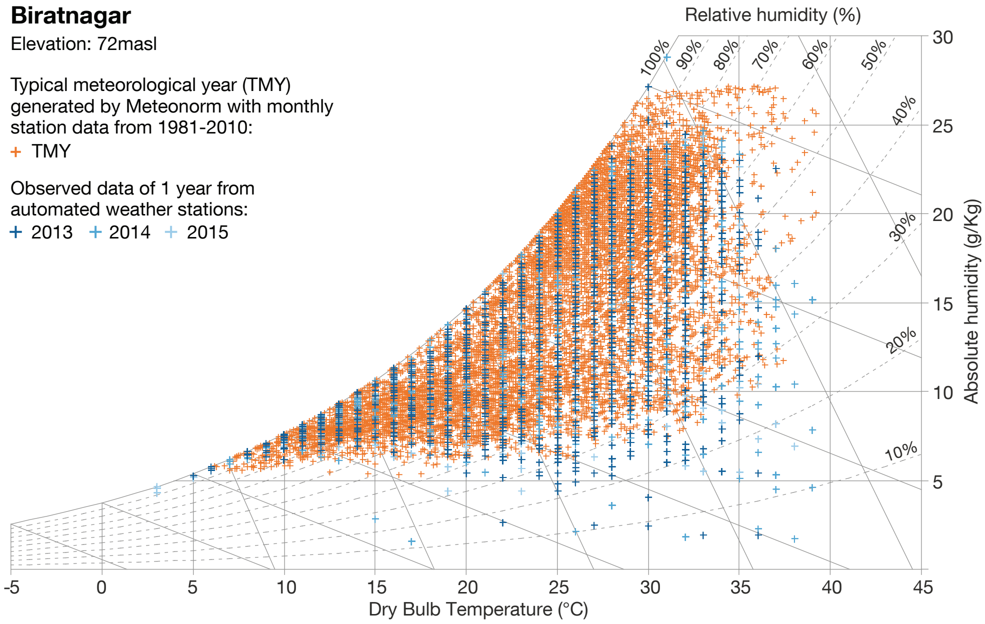

Figure E.3: Comparison of hourly climate data from Biratnagar (Data sources: [27–30])

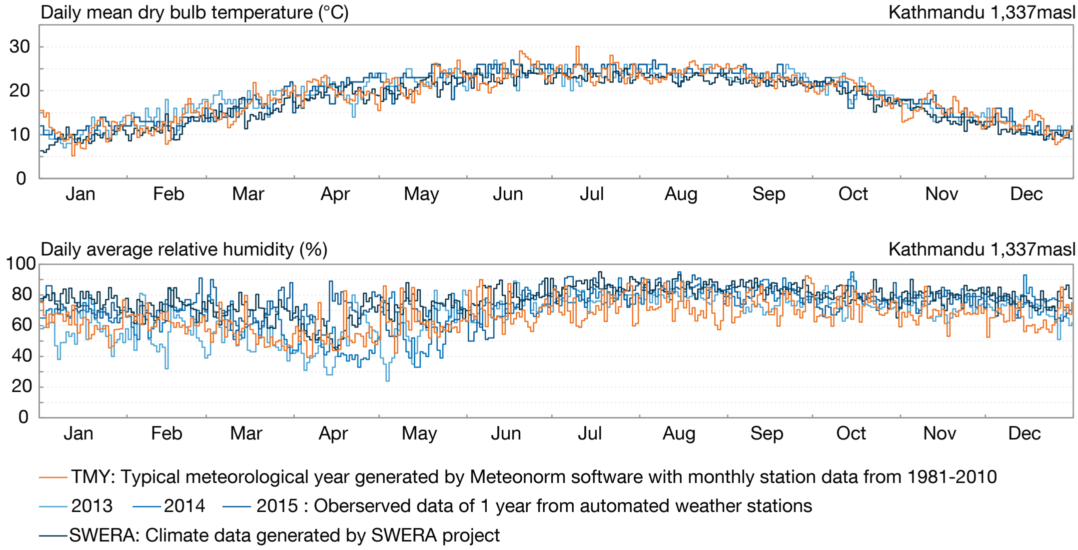

Figure E.4: Comparison of daily climate data from Kathmandu (Data sources: [27–30, 63])

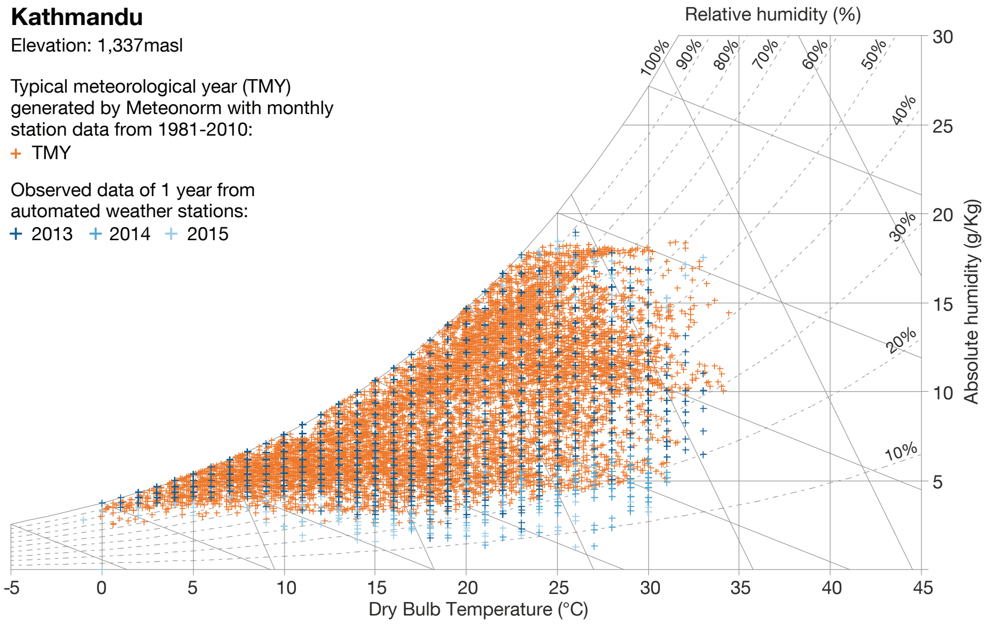

Figure E.5: Comparison of hourly climate data from Kathmandu (Data sources: [27–30])

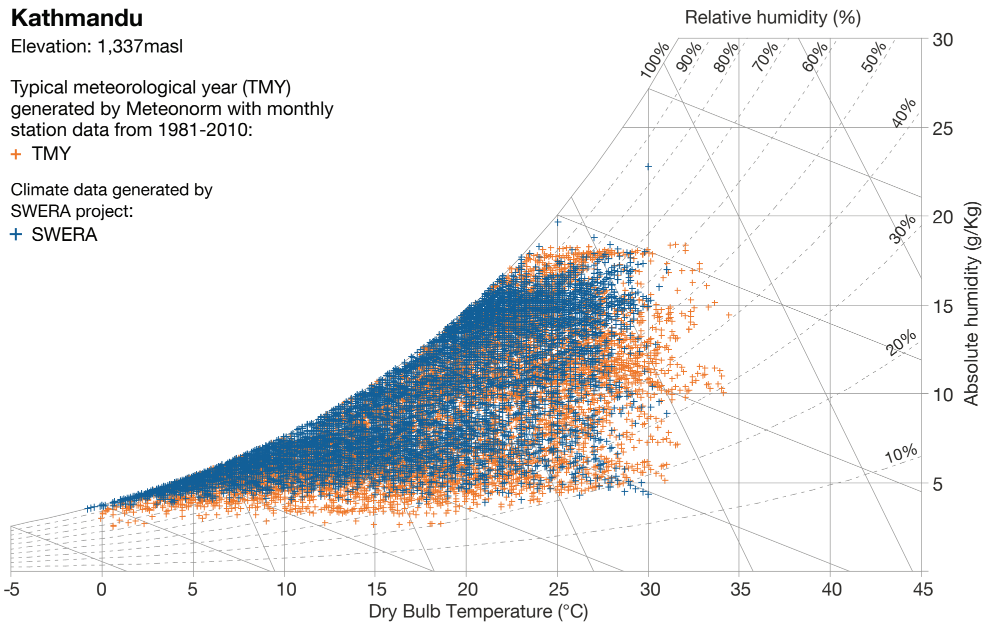

Figure E.6: Comparison of two climate data sets for Kathmandu (Data sources: [27–29, 63])