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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

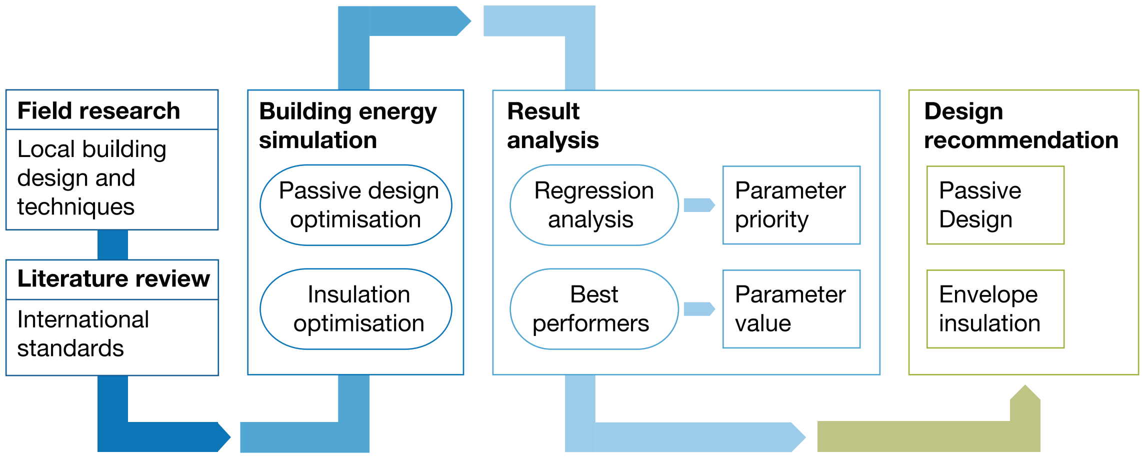


Fig. 1. Methodology of the research.

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

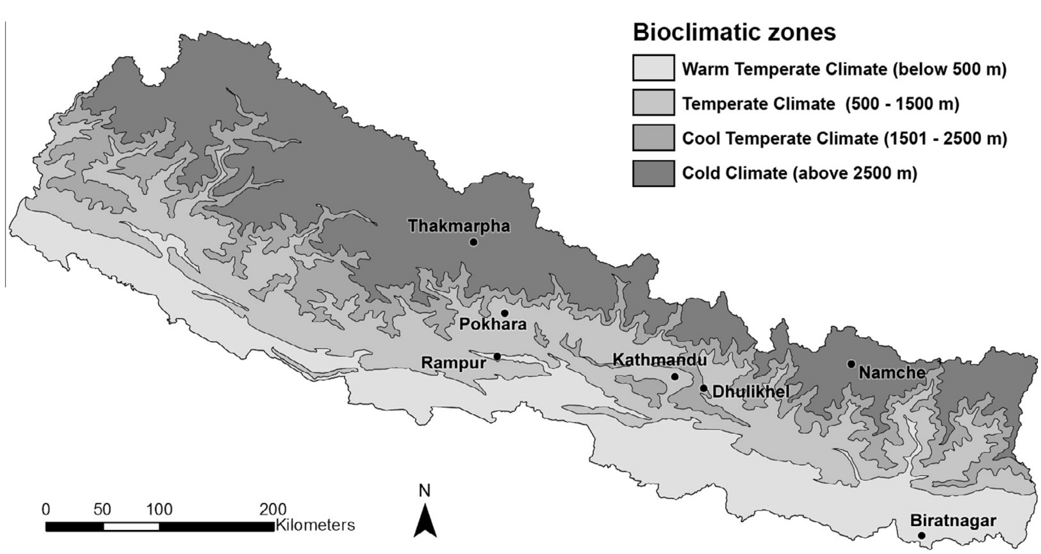


Fig. 2. Bioclimatic zoning map of Nepal with selected locations for energy simulation.

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.

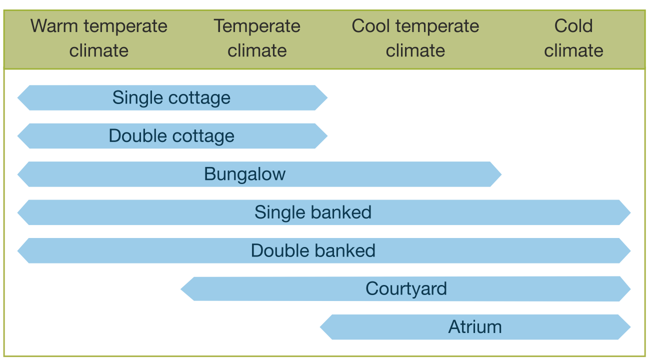


Fig. 3. Building typologies and locations for simulation runs.

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/mK)	Insulation level 1 (W/mK)	Insulation level 2 (W/mK)	Insulation level 3 (W/mK)	Insulation level 4 (W/mK)
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/mK)	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.

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).

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).

2.5. 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.

2.6. 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

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

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.

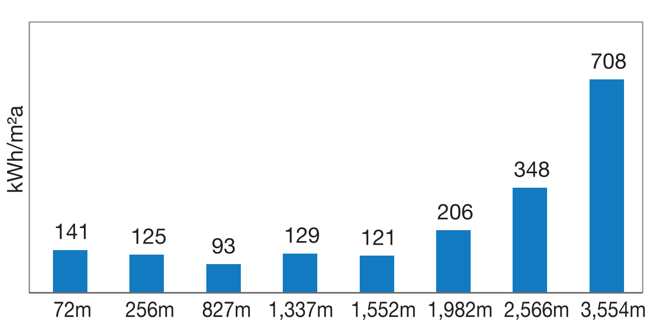


Fig. 4. Estimated energy use intensity for hotels in Nepal based on uninsulated reference model for different elevations.

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.

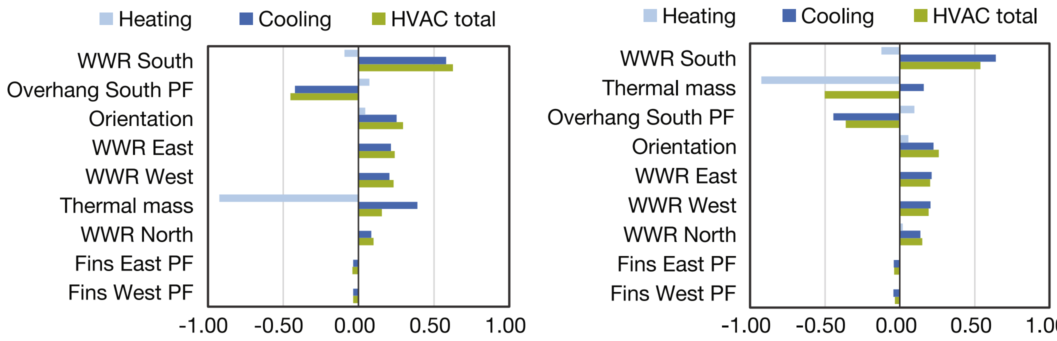
3. Passive design optimisation

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.



(a) Biratnagar (b) Rampur

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

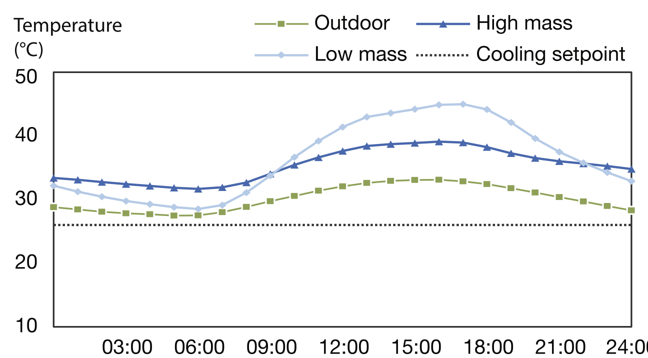
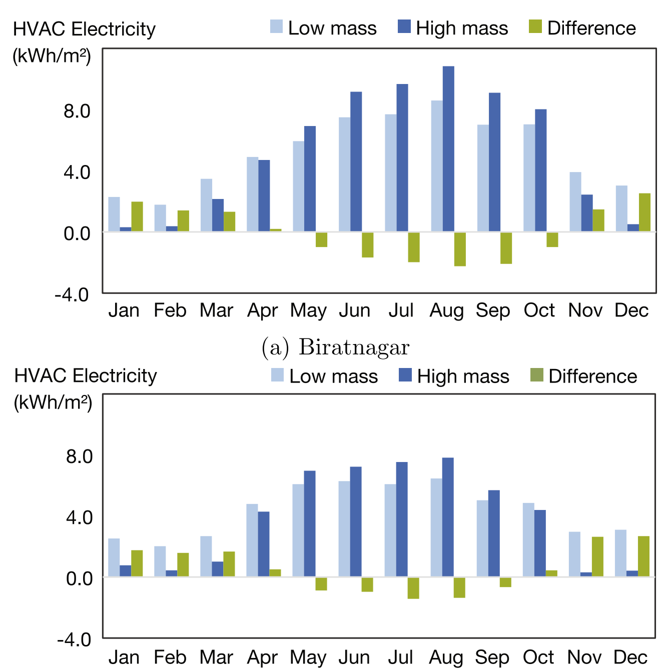


Fig. 6. Comparison of non-conditioned thermal performance in summer of bungalow typology for Biratnagar.



(a) Biratnagar

(b) Rampur

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

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.

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.

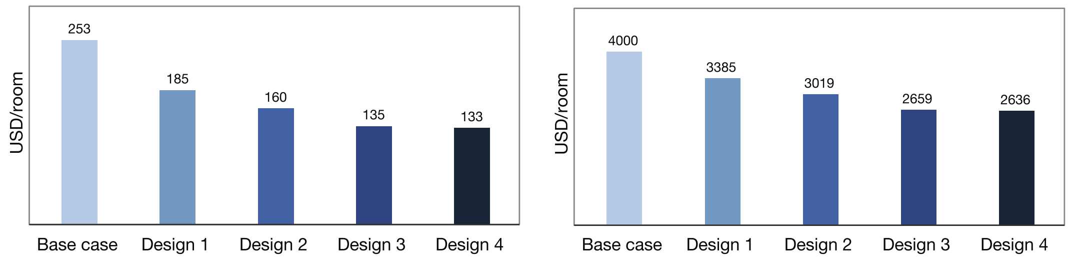
	Cost saving potential			
	Annual electricity costs		Life cycle costs	
Thermal mass	USD/m^2	USD/room	USD/m^2	USD/room
High	0.30	8.79	3	79
Medium	0.29	8.53	3	76
Low	0.28	8.21	2	73
Average	0.29	8.51	3	76

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 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



(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.

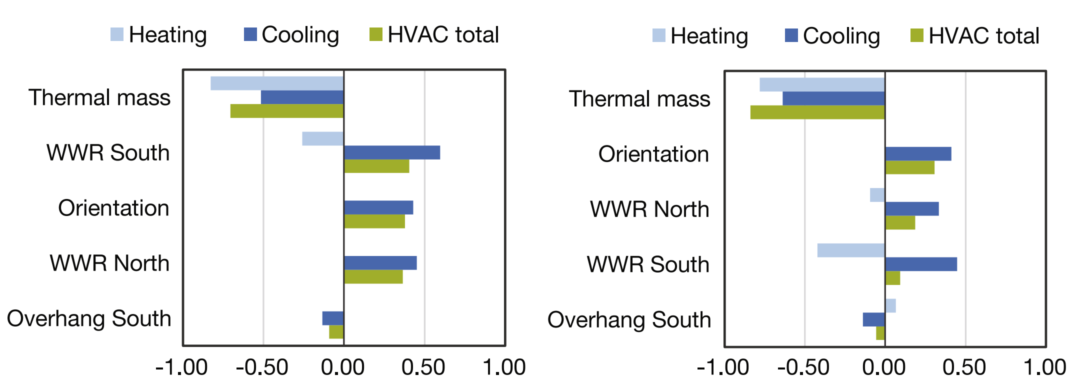
The second most important passive design factor for Pokhara is minimising the WWR South while it is optimising the orientation for Kathmandu. Due to the higher share of cooling demand in Pokhara as compared to Kathmandu, window areas, particularly those facing south, should be kept as small as possible 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.

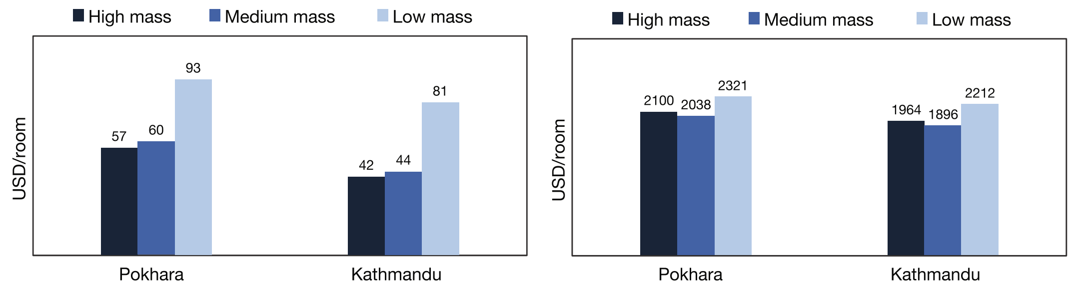
Energy cost savings are also considerably high when optimising the WWR according to passive design. Fig. 11 (a) indicates the cost optimum for annual electricity costs at a WWR of 40%. However, LCC present value is lowest for designs with a WWR of 20% due to the fact that the share of investment for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



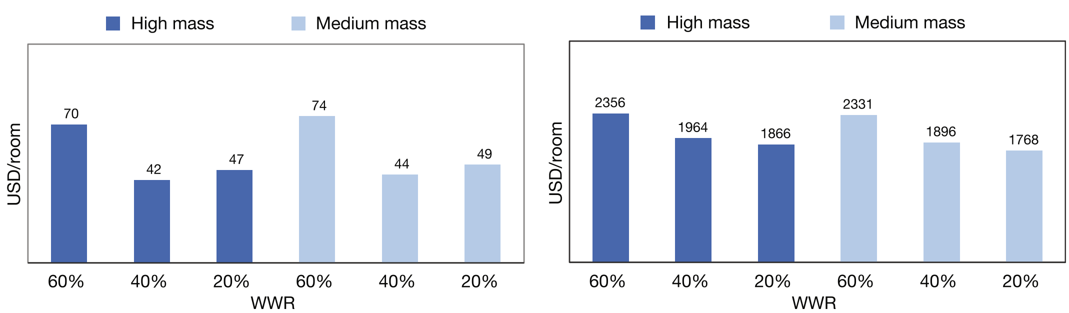
(a) Pokhara (b) Kathmandu

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

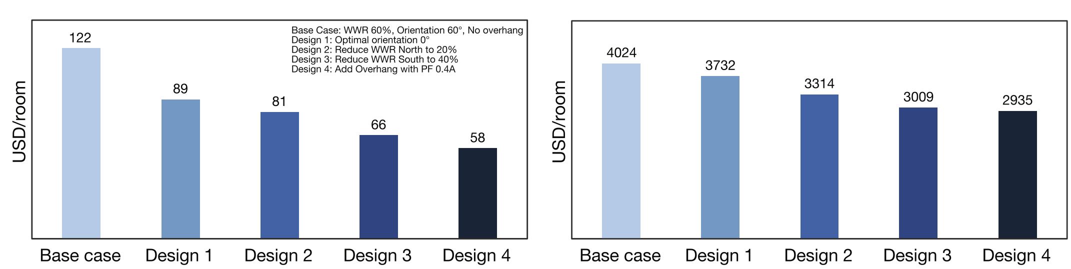
Fig. 11. Cost analysis for double-banked typology with different WWRs in Pokhara.

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.

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.

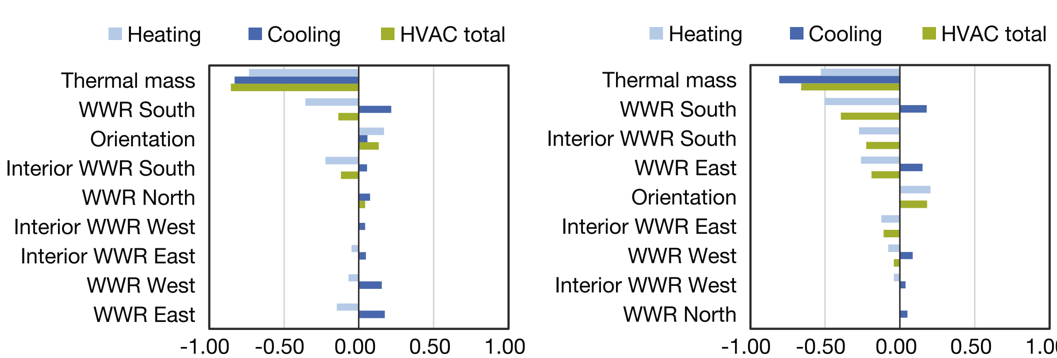
In contrast to all lower locations, the SRC for WWR South in regard to total HVAC energy demand is negative (Fig. 13). This illustrates that a larger window area facing south results in more reduction of heating demand in winter than it increases cooling demand in summer. In interpreting these findings, 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.

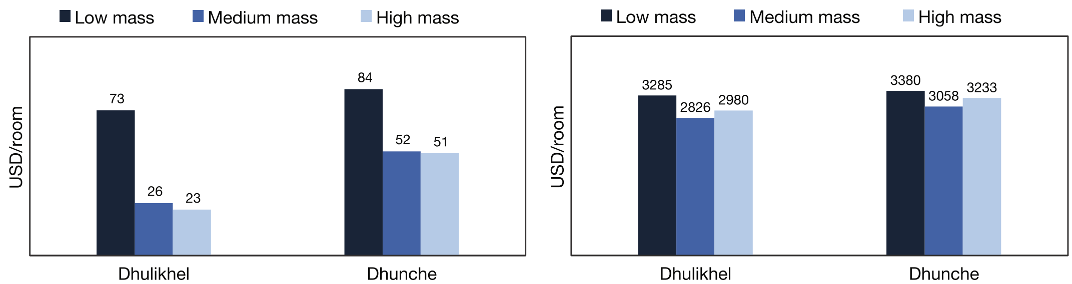
Having the highest impact on energy demand reduction, high thermal mass does also reduce energy and life cycle costs (LCC). Annual HVAC energy costs for single-banked typology in Dhulikhel with low mass materials amount to 73 USD per guest room while medium and high mass solutions have energy costs of 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



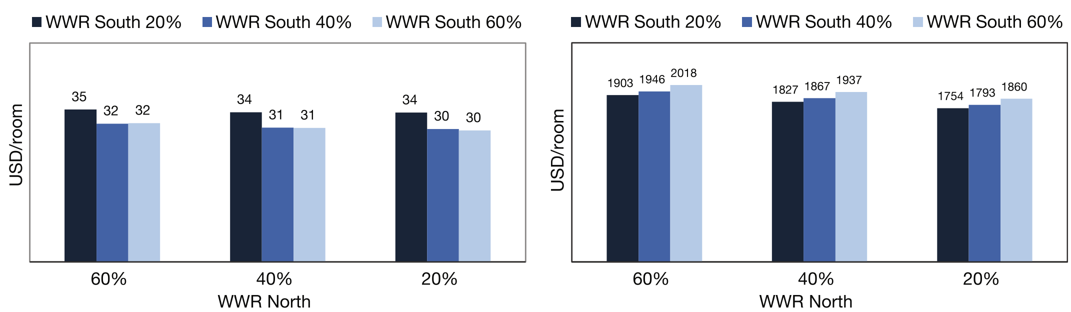
(a) Dhulikhel (b) Dhunche

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.

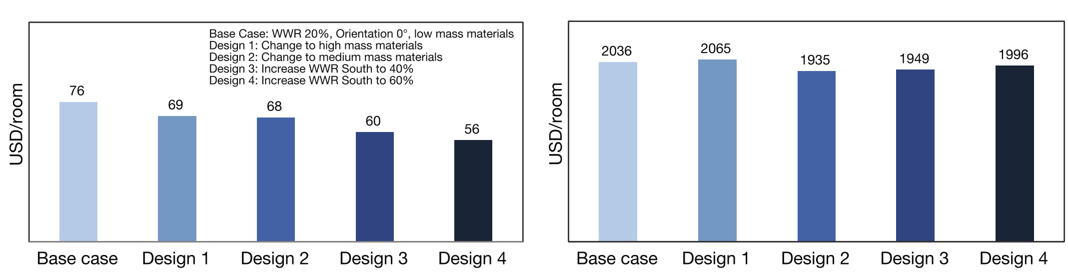
Passive design optimisation can lead to moderate energy cost savings. Fig. 16 illustrates the annual HVAC energy costs for the double-banked typology in Dhunche. It can be seen that passive design can lead to savings of up to 20 USD per guest room annually. Although total window area of the building 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

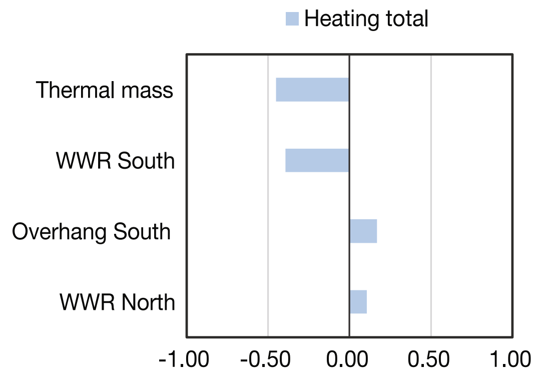
HVAC energy demand of hotel buildings in locations above 2500 m are dominated by heating. Simulation results for Thakmarpha (2566 m) indicate a share of heating between 98% and 100% of total HVAC energy demand. In Namche Bazar (3354 m) annual energy demand for room conditioning is 100% based on heating.

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

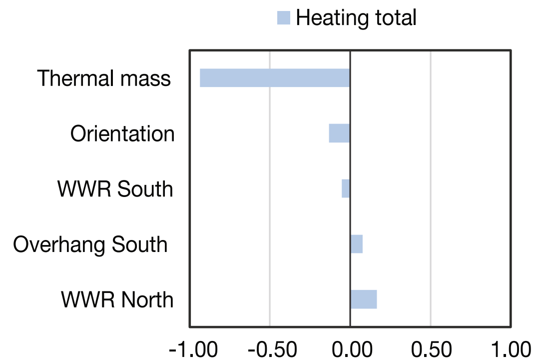


(a) Annual electricity costs (b) Life cycle costs

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

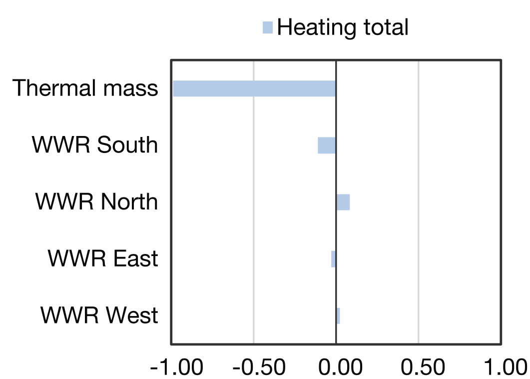


(a) Thakmarpha

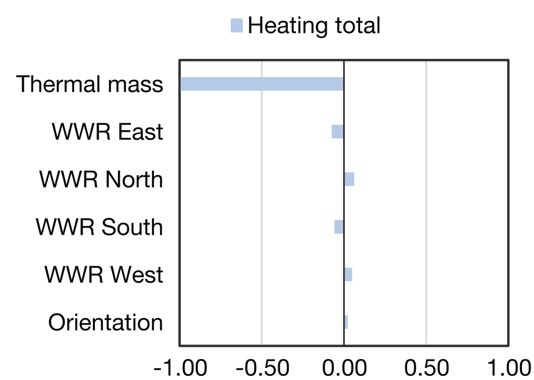


(b) Namche

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.

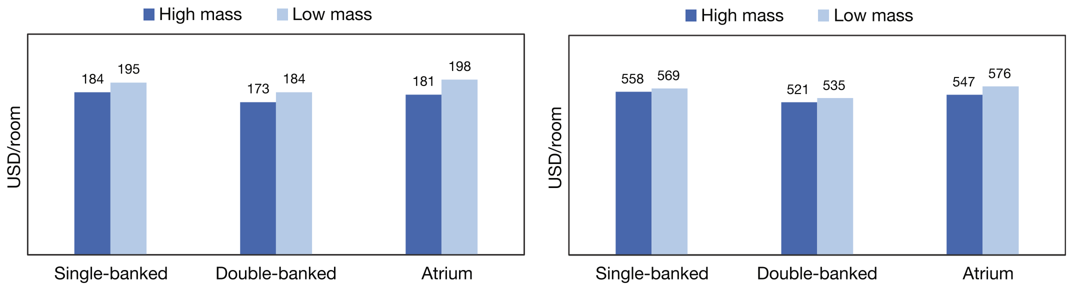
According to the low SRC, window-to-wall ratio (WWR) plays a secondary role for passive design optimisation (Fig. 18). Depending on the orientation of the openings, higher window area might reduce (negative SRC) or increase (positive SRC) total HVAC consumption. A positive SRC means that the heat loss 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.

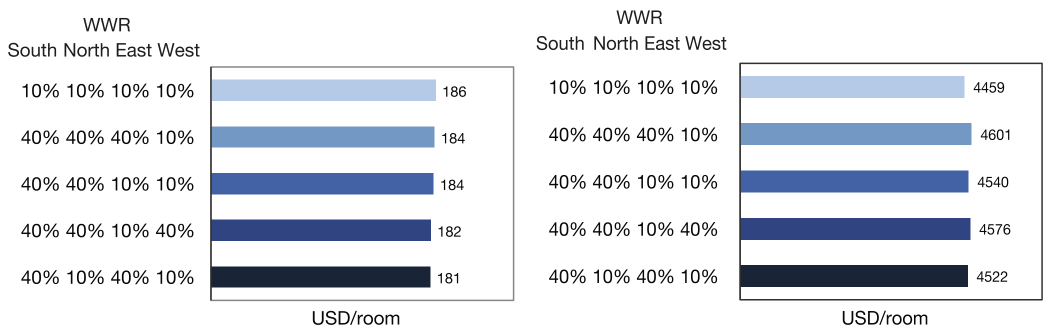
Similar to the thermal mass strategy, the optimisation of window areas can lead to modest energy cost savings. For example, increasing the window area facing South and East of the atrium typology from 10% to 40% results in annual electricity cost savings of 5 USD per guest rooms (Fig. 20(a)). Equally 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



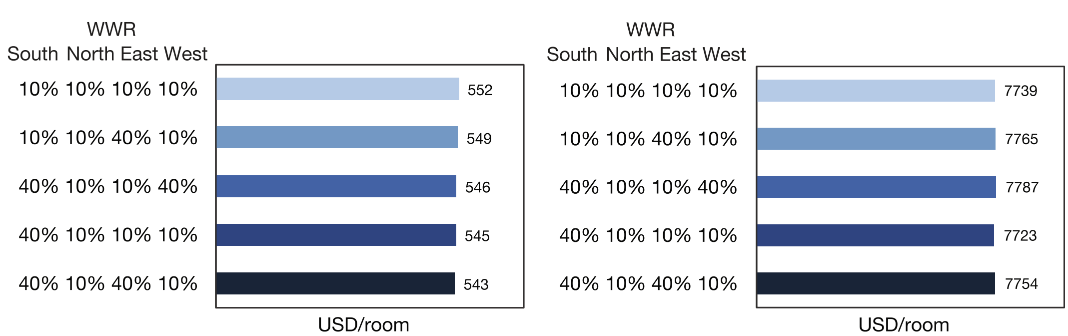
(a) For Thakmarpha (b) For Namche

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



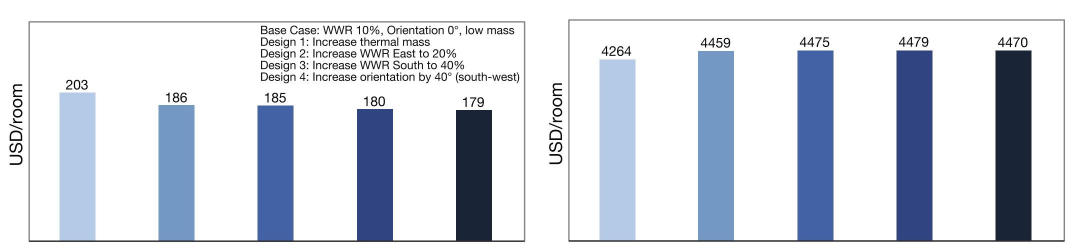
(a) Annual electricity costs (b) Life cycle costs

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.

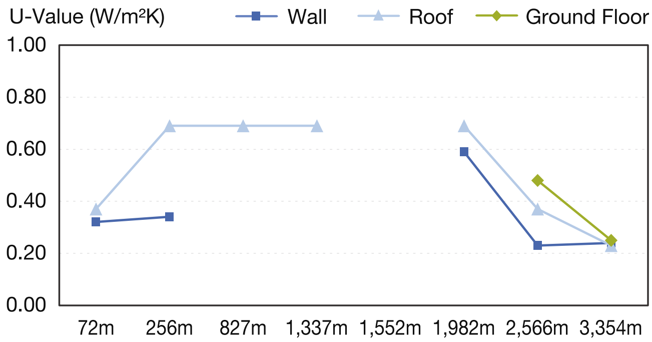


Fig. 23. Cost-effective insulation level of opaque envelope for minimum comfort (Minimum comfort as defined in methodology section) by location.

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

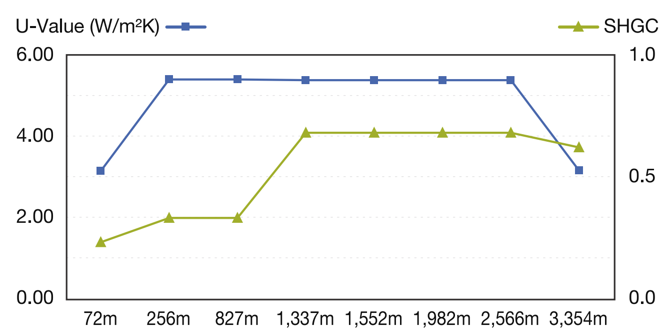


Fig. 24. Cost-effective insulation level and SHGC of windows for minimum comfort by location (Minimum comfort as defined in methodology section).

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.

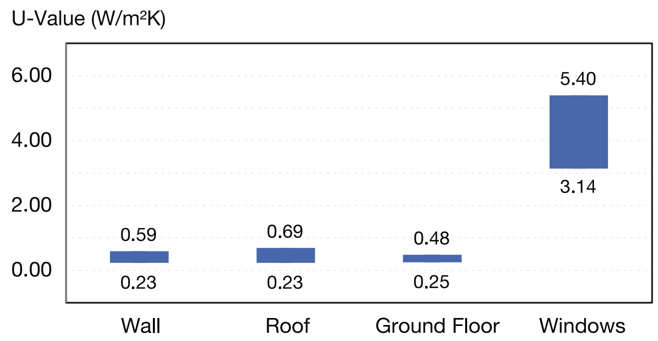


Fig. 25. Range of cost-effective insulation level for minimum comfort (Minimum comfort as defined in methodology section) by envelope component.

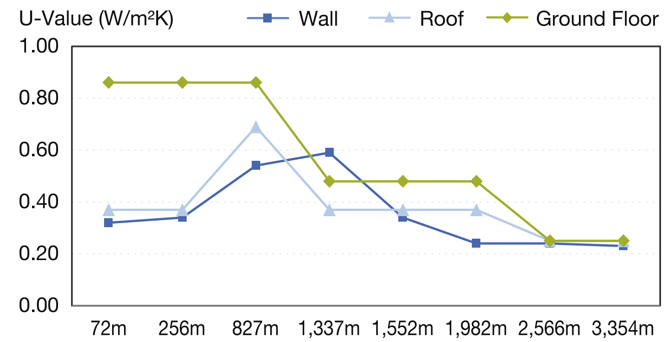


Fig. 26. Cost-effective insulation level of opaque envelope for maximum comfort by location (Maximum comfort as defined in methodology section).

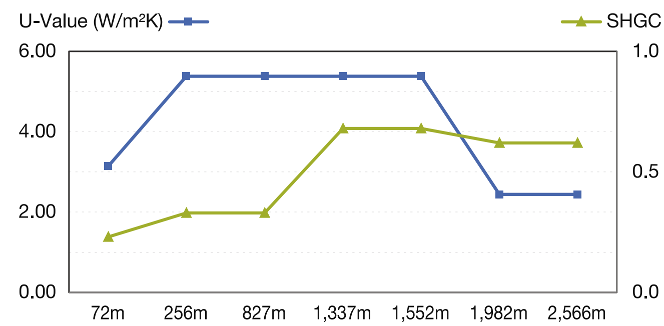


Fig. 27. Cost-effective insulation level and SHGC of windows for maximum comfort by location (Maximum comfort as defined in methodology section).

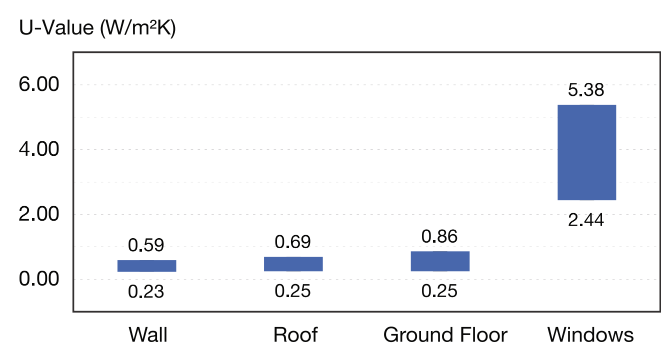


Fig. 28. Range of cost-effective insulation level for maximum comfort (Maximum comfort as defined in methodology section) by envelope component.

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^{2}K are cost-effective for the exterior wall, roof insulation with thermal transmittance between 0.23 and 0.69 W/m^{2}K is optimal. Cost-effective design solutions have windows with a thermal transmittance between 5.40 and 3.14 W/m^{2}K, 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^{2}K) 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^{2}K 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^{2}K) 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^{2}K. 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^{2}K.

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

[4] Maximum comfort as defined in methodology section

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

Location	Wall		Roof		Ground Floor		Window	
	W/m²K	mm	W/m²K	mm	W/m²K	mm	W/m²K	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^{2}K lead to life cycle cost savings. Roof insulation reaching thermal transmittance between 0.25 and 0.69 W/m^{2}K is profitable and, thus, recommended. For the windows, the thermal transmittance of cost-effective solutions ranges between 2.44 and 5.38 W/m^{2}K, 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.

Location	Building typology						
	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%

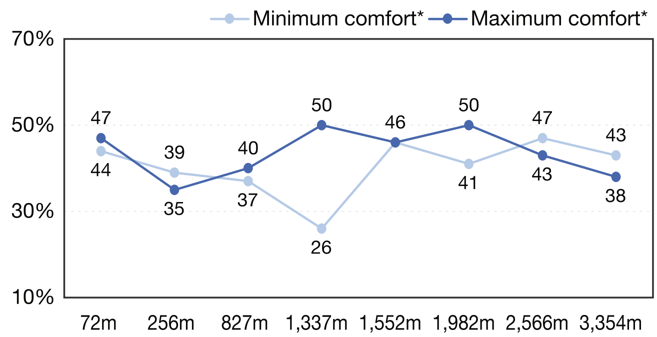


Fig. 29. Energy saving potential through envelope insulation by location (*min/max comfort as defined in methodology section).

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/m²K	Maximum comforta W/m²K	Thickness insulation mm	Minimum comfort W/m²K	Maximum comfort W/m²K	Thickness insulation mm	Minimum comfort W/m²K	Maximum comfort W/m²K	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/m²K	Maximum Comfort[b] W/m²K	
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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