

Optimizing Passive Design Elements to Improve Building Energy Efficiency in Kabul, Afghanistan

Mustafa Karimi*, Tomoyuki Chikamoto, Myonghyang Lee

Graduate School of Science and Engineering, Ritsumeikan University, Shiga, Japan

Email: *mustafa7karimi@gmail.com, gr0500xx@ed.ritsumeikai.ac.jp

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Abstract

This study explores the potential of passive solar strategies to enhance the energy performance of residential buildings in Kabul, Afghanistan, by analyzing four critical design parameters: building orientation, window-to-wall ratio (WWR), floor-to-ceiling height, and overhang size, considering multiple glazing types (single, double, and triple). Utilizing BEopt™ energy simulation software, the research evaluates the impact of these parameters on heating and cooling energy demands across varying configurations. The findings indicate that the south orientation achieves the lowest total energy demand, while the northwest-facing façade exhibits the highest energy demand, irrespective of glazing type, revealing energy savings of up to 101.7% between the best and worst orientations. Regarding the WWR, significant energy savings are observed only for south-facing windows, with optimal ratios of 25%, 35%, and 55% for single-, double-, and triple-glazed windows, respectively. These configurations yield energy savings of 25.7%, 35.2%, and 36% compared to windowless façades. In contrast, increasing window sizes in other orientations (north, east, and west) leads to higher overall energy consumption. Floor-to-ceiling height, which influences the volume of conditioned space and heat stratification, increases total energy consumption by an average of 8%, 6.5%, and 5.1% for single-, double-, and triple-glazed windows, respectively, with each 30.5 cm (1 foot) increase. Additionally, south-facing windows without overhangs maximize winter solar gains and offer superior energy performance, whereas overhangs reduce efficiency by obstructing beneficial sunlight leading to higher energy demand. These findings provide actionable insights for architects and builders in Kabul and offer guidance for designing energy-efficient residential buildings in similar climates.

Keywords

Building Orientation, Window-to-Wall Ratio, Passive Solar Design, Energy Simulation, Sustainability, Kabul, Afghanistan

1. Introduction

Climate change caused by greenhouse gas (GHG) emissions remains one of the most critical challenges facing the world today [1]-[3]. The building sector is responsible for a significant amount of global energy consumption and related GHG emissions, with a documented annual increase in energy consumption by 1% over the past decade [4] [5]. With the global population projected to reach 9.7 billion by 2050, the demand for housing is expected to increase substantially, exacerbating the already pressing challenge of reducing emissions from buildings [6]. In recent years, the widespread adoption of mechanical heating and cooling systems has overshadowed the potential advantages of passive solar heating and cooling techniques [7] [8]. This shift has led to a notable increase in energy consumption and carbon dioxide (CO₂) emissions in the building sector. Additionally, building energy demand has escalated over the past decades due to factors such as population growth, increased time spent indoors, higher reliance on energy-intensive appliances, and a growing focus on indoor environmental quality [9] [10].

In Afghanistan, the issue of energy consumption and CO₂ emissions from buildings is particularly relevant, given the country's growing population, increasing urbanization, and energy challenges. Kabul, the capital city, has experienced a doubling of its population over the past two decades, driving a sharp increase in housing demand [11]-[15]. This rapid growth has resulted in the emergence of several informal settlements across the city. Afghanistan heavily depends on energy imports from neighboring countries, with only 28% of its electricity generated domestically [16] [17]. Consequently, households and small businesses in the country bear some of the world's highest electricity tariffs, paying up to six times the regional average [18]. Limited access to reliable electricity and frequent power outages further exacerbated the issue, driving the widespread use of alternative energy sources, such as liquefied petroleum gas (LPG), fuelwood, charcoal, domestic waste, agricultural and animal waste, contributing to air pollution and greenhouse gas emissions [19] [20].

Residential buildings in Kabul are major contributors to the city's energy consumption, accounting for an estimated 70% of its total energy demand due to the need for heating and cooling [19] [21]-[24]. However, inadequate energy-efficiency regulations and building design and construction guidelines have led to a stock of substandard buildings in Kabul. These buildings are often poorly designed and constructed using low-quality materials, and lack proper insulation, leading to significant energy waste, high consumption rates, and increased CO₂ emissions [25] [26]. Such inefficiencies not only exacerbate the issue of energy poverty in the country but also contribute to serious environmental problems.

Given these challenges, it is imperative to enhance the energy performance of buildings in Afghanistan, particularly in urban areas where the demand for housing and energy is peaking. Passive solar design techniques can significantly reduce energy consumption for new and existing buildings [27], as well as contribute to the country's efforts to reduce its dependence on energy imports and mitigate the impact of climate change. The term "passive" refers to the use of natural energy

sources from the ambient environment to maintain a comfortable indoor environment without relying on electromechanical appliances [28]. Given Afghanistan's abundant solar potential, passive solar strategies represent an efficient and cost-effective approach to mitigating energy consumption and supporting the country's broader climate goals.

Numerous studies and successful implementations of passive solar techniques have been documented globally [29]-[34], highlighting the influence of contextual factors such as geographical location and climatic conditions. Therefore, it is imperative to consider the distinctive socio-economic and geoclimatic context of Kabul, Afghanistan. Situated within a cold semi-arid climate, characterized by scarce and costly energy resources alongside poorly designed and insulated buildings, Kabul faces considerable challenges in enhancing energy efficiency. Moreover, the absence of advanced building materials, such as high-performance windows and insulation, as well as energy-efficient mechanical systems, compounds the issue of energy wastage within the built environment. These materials, often expensive and limited in availability within resource-constrained regions like Kabul, present obstacles to the implementation of energy-efficient building designs [18]. Therefore, this paper exclusively focuses on passive solar design techniques that do not require any additional material cost, and to identify the most cost-effective passive strategies for optimizing building design in Kabul. Given the fundamental role of a high-performance building envelope in passive designs, this study focuses on building envelope modification, including building orientations, WWR, floor-to-ceiling height, and overhangs to minimize energy consumption. By demonstrating the feasibility and effectiveness of cost-effective passive strategies, this study helps to accelerate the transition towards sustainable building practices in Kabul, reduce energy poverty, and mitigate climate change in the region.

2. Literature Review

The design of energy-efficient buildings is an important consideration for reducing energy consumption and achieving sustainability goals in the building sector. Various building envelope parameters, such as building orientation, WWR, glazing types, floor-to-ceiling height, and overhangs, can significantly influence the energy performance of buildings. These parameters have been studied individually in different climatic conditions and locations, and their impact on energy consumption has been documented.

Building orientation is a fundamental factor that significantly influences the energy performance of the building [35] [36]. Renukla *et al.* [37] identified that the optimal building orientation in Delhi, Chennai, and Mumbai is north direction, and can result in energy savings of up to 26.42%, 20.9%, and 13.18%, respectively. However, due to its humid sub-tropical climate, the optimal building orientation in Shillong is south, and can save energy up to 4.85%. Similarly, Mulyani *et al.* [38], reported that in the hot and humid climate of Padang city, Indonesia, a south-southwest orientation is the most efficient, while an east orientation is the

least favorable. Their study demonstrated that proper orientation could reduce energy use intensity (EUI) by up to 4% compared to existing buildings, with the disparity between the best and worst orientations reaching as much as 8%. Additionally, appropriate building orientation was shown to reduce life cycle costs by up to 4%. Elhadad *et al.* [39] found that in Cairo, Egypt, a North-facing orientation minimizes energy consumption, while a south-facing orientation results in the highest energy use, with a variation of approximately 7.5%. Furthermore, Karimi *et al.* [40] emphasized that the optimal building orientation can vary significantly within a country, underscoring the importance of location-specific studies to accurately evaluate its impact on energy performance.

WWR is another energy-saving design parameter that affects indoor thermal comfort, and the overall energy performance of a building. In a study by F. Goia [41], the optimal WWR for office buildings in various European climates was investigated. Results indicate that, while there is an optimal WWR for each climate and orientation, the WWR ranging from 0.30 to 0.45 is optimal for the countries located in the mid-latitude region (35° to 60° N). In extreme cold and warm climates, only south-oriented windows require a WWR outside the aforementioned range. The study concluded that proper WWR configuration can lead to energy savings of 5 - 25%. F. Kheiri [42] studied the relation of orientation and window size with building energy consumption in four different climates of Köppen classification. The study concluded that a 20 - 32% WWR for total exterior walls is an efficient ratio as an optimum for reducing HVEC and lighting loads. Kim *et al.* [43] studied the effect of window size, position, and orientation on the energy demand of a residential building in Vancouver, Canada. The result shows that with an increase in WWR, energy demand also increases; however, the position of windows also affects energy usage as the energy demand is minimized when windows are placed in the mid-height of the façades in all orientations.

Floor-to-ceiling height is an important parameter that affects the energy consumption of buildings [44]. Guimaraes *et al.* [45] found that reducing the ceiling height can cause a small increase in indoor temperature in buildings located in hot tropical regions. Their study also revealed up to a 4°C variation between the temperatures of upper and lower layers of an internal environment. Ghafari *et al.* [46] studied the influence of ceiling height on the heating energy consumption of a classroom in the cold climatic condition of Tabriz, Iran. Their findings indicated that heating energy demand increased by 1% for every 10 cm increase in ceiling height. Similarly, Golkarfard *et al.* [47] examined the impact of building height on the energy consumption of radiator and floor heating systems. Their results showed that as the height doubles, the heat loss from the wall for the radiator system almost doubles, whereas for the floor heating system, it only increases by 60%.

The size of overhangs is a key factor in designing energy-efficient buildings, as they significantly reduce cooling energy consumption. Their optimal dimensions depend on the orientation of the building's windows and the prevailing climatic conditions [48]-[50]. Mohammad *et al.* [50] found that in a town hall building

situated in Darwin, Australia, overhangs were more effective than fins, resulting in energy savings of 9.2%. Moreover, variations in design and length of overhangs led to up to 15.5% reduction in cooling energy. According to Nikolic *et al.* [51], incorporating optimally sized roof and balcony overhangs into a residential building in Belgrade, Serbia resulted in a 7.12% decrease in primary energy consumption for heating, cooling, and lighting compared to a building without overhangs. Furthermore, the study found that the inclusion of overhangs led to a significant 44.15% reduction in cooling energy consumption.

The reviewed studies highlight the significant impact of various passive solar design parameters—such as building orientation, WWR, floor-to-ceiling height, overhangs, and glazing types—on thermal comfort, resident satisfaction, and overall energy consumption. While ongoing research in different climates and locations seeks to optimize these parameters, the documentation and implementation of energy-efficient building techniques in Afghanistan remain limited. Furthermore, the effectiveness of such measures is not adequately illustrated in the existing literature. Most studies recommend design configurations tailored to specific climatic regions, which may not be directly applicable to Kabul's semi-arid climate. Moreover, these parameters are often studied in isolation, neglecting the critical interactions between design factors and glazing types that influence energy performance in real-world scenarios. The absence of studies addressing the combined effects of building orientation, WWR, ceiling height, and overhangs—particularly when considering multiple glazing types (single, double, and triple)—within Kabul's unique environmental and socio-economic context, creates a notable gap in localized data. This gap limits the development of effective design strategies tailored to the region's challenges, including restricted access to advanced construction materials, resources, and technologies.

To address these gaps, this study evaluates the mutual effects of four key design parameters—building orientation, WWR, floor-to-ceiling height, and overhang size—on the energy performance of residential buildings in Kabul. By incorporating three types of glazing, this research provides practical and energy-efficient configuration options applicable to both new construction and retrofitting projects. The findings aim to support the development of sustainable building solutions that align with Kabul's specific climatic, environmental, and resource constraints.

Additionally, this study provides local recommendations for improving building energy performance, contributing to the development of building codes and urban planning regulations tailored to the region's specific needs. The findings are not only for enhancing the sustainability of the built environment in Afghanistan but also for advancing energy efficiency goals across the country's residential sector.

3. Method

The methodological framework of this study is outlined in **Figure 1**. The study categorizes building parameters into two groups: constant parameters, such as location, building type, construction materials, heating and cooling systems, set

points, internal gains, and variable parameters, including glazing types, building orientation, window-to-wall ratio (WWR), floor-to-ceiling height, and overhang size. Moreover, climatic data specific to Kabul, Afghanistan, were processed using an EnergyPlus weather (EPW) file obtained from climateonebuilding.org [52] and cross-verified and adjusted using supplementary data from data obtained from some governmental resources and analyzed with climate consultant software to understand the city’s climatic characteristics. This simulation-based study evaluates the impact of the selected design parameters on the energy performance of a residential building model in Kabul. The analysis considers three glazing types—single, double, and triple (Figure 2)—and investigates optimal configurations to minimize energy demand for heating and cooling while maintaining indoor comfort. To achieve these objectives, the BEopt™ energy simulation software, integrated with EnergyPlus, was employed to model and simulate energy performance. The study analyzed 303 design cases, accounting for varying configurations of the selected parameters, to provide insights into energy-efficient building design tailored to Kabul’s climatic context.

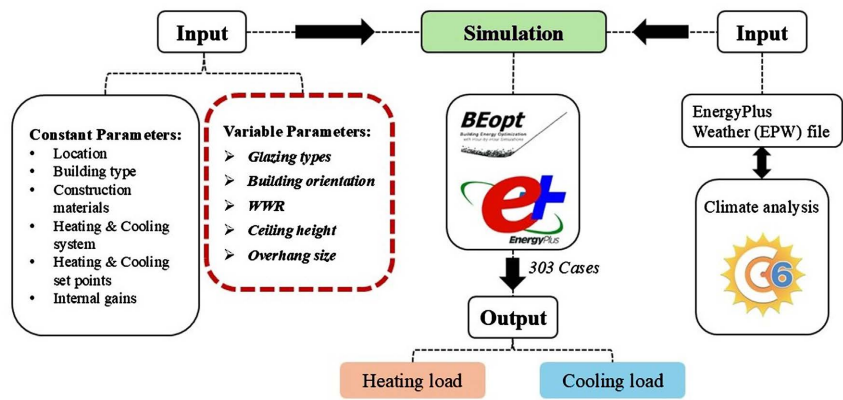


Figure 1. Study flowchart.

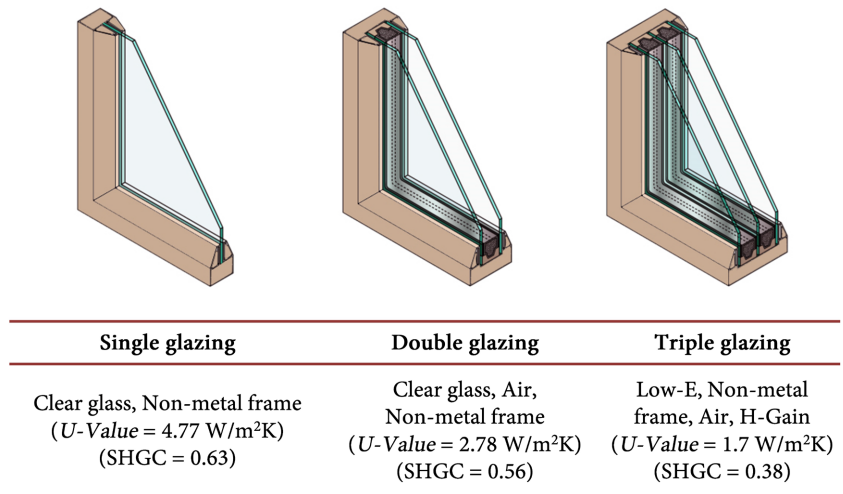


Figure 2. Characteristics of various glazing types.

As shown in **Figure 3**, to determine the optimal building orientation, the building model is systematically rotated in 22.5° increments enabling the main windows façade to face all sixteen cardinal, intercardinal, and secondary intercardinal directions. This rotation facilitates comprehensive analysis of orientation-dependent energy performance. Subsequently, the analysis explores the impact of WWR, for all three glazing types, varying between 0% to 80%, across all four façades (south, north, east, and west). To isolate the specific effect of WWR in each orientation, window openings on the other three façades are kept at 0% during simulations. The study further investigates the impact of varying floor-to-ceiling heights, ranging from 2.45 m to 4.57 m, on energy efficiency.

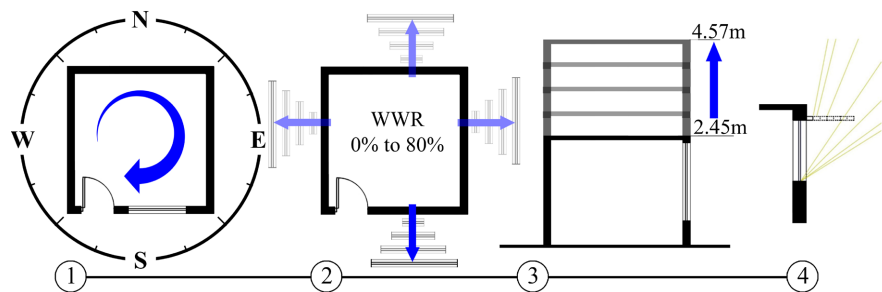


Figure 3. Workflow of the building energy simulation process.

Finally, the analysis considers the effect of overhang dimensions on the southern façade, identifying configurations that optimize thermal performance. To ensure the reliability and validity of the findings, all other variables potentially influencing building energy performance are held constant throughout the simulation process.

3.1. Simulation Tool

Building energy simulation (BES) tools are crucial in optimizing building systems throughout various stages, including pre-design, commissioning, and operation, with their usage expanding in both research and business, leading to frequent releases of updated and new tools [53]. The BEopt™ (Building energy optimization tool) is used for this study. BEopt™ is a user-friendly energy simulation software that evaluates residential buildings to identify cost-efficient and energy-saving strategies with the objective of achieving low or net-zero energy buildings [54]-[56]. It has a simple input interface with a variety of pre-defined settings, allowing users to design and simulate a building's energy performance without the need for additional software.

BEopt™ is developed by national renewable energy laboratory (NREL) in support of the U. S. department of energy's building America program. BEopt™ provides detailed simulation-based analysis for new and existing houses, based on factors, such as size, architecture, occupancy, vintage, location, and utility tariff [54] [55]. Additionally, BEopt™ can assess both single and multi-family dwellings, as well as new builds and retrofits of existing homes, using single building designs,

parametric sweeps, and cost-based optimizations. The software uses EnergyPlus™, the department of energy's main simulation engine, and simulation assumptions are based on the Building America Housing Simulation Protocols [55].

3.2. Study Model

To enhance the accuracy and efficiency of the energy simulation process, a rectangular, single-story residential building with two rooms and a bathroom was selected as the model for this study. The use of a rectangular shape offers several advantages, particularly in building energy simulations. Firstly, it simplifies the geometric complexity of the model, facilitating easier setup, analysis, and systematic variation of design parameters. The straightforward design minimizes computational errors and ensures consistency across simulations. Moreover, rectangular shapes are widely representative of typical residential building designs in Kabul, making the results more relevant and applicable to real-world scenarios. The shape's predictable thermal behavior further aids in isolating and analyzing the impacts of key variables, such as orientation, WWR, and glazing type, without interference from irregular geometries or edge cases such as uneven solar gains or wind effects. The chosen model (**Figure 4**), a standalone one-story building measuring 11 m × 7 m (length × width), was designed to reduce the influence of extraneous factors such as neighboring structures, building height, construction materials, and thermal mass on the simulation results. The floor-to-ceiling height is set at 2.75 m, with a WWR of 30% on the main façade, 5% on the side façades, and no windows on the back façade. These baseline parameters align with current building design practices in Kabul, ensuring that the study accurately reflects local construction norms and conditions. Additionally, rectangular buildings provide an efficient surface-to-volume ratio, which is critical in evaluating energy performance under varying conditions.

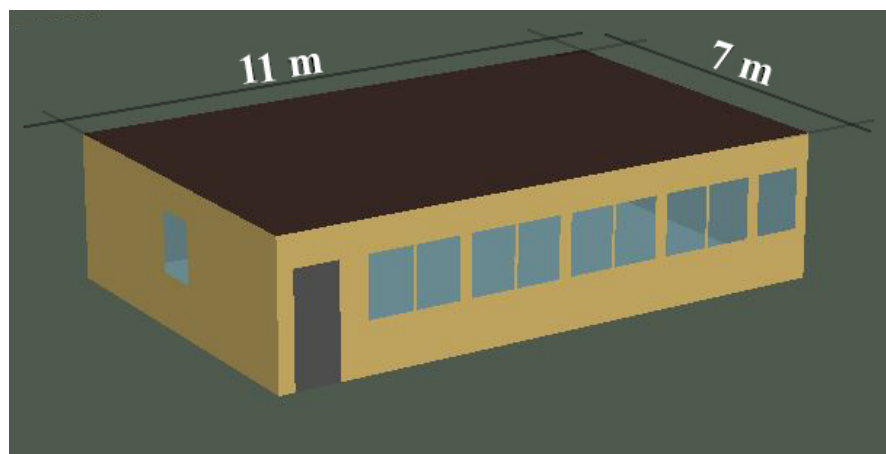


Figure 4. The schematic view of the study model.

Wall, roof, and floor assemblies, along with their respective thicknesses and material layers are (detailed in **Table 1**), are listed in sequential order from exterior to interior. Moreover, three types of glazing are evaluated for studying each

parameter including orientation, WWR, ceiling height, and overhang size.

Table 1. Characteristics of building materials and design parameters of study models.

Characteristics	Unit	Properties			
Floor Area	m ²	77			
External Walls	-	Stucco 2.5 cm + R-15 Extruded Polystyrene Insulation (XPS) – 7.6 cm + Hollow Concrete Masonry Unit (CMU) 20 cm + Drywall 1.6 cm			
	R-Value	0.036 + 2.7 + 0.936 + 0.1 = 3.772 m ² K/W			
Internal Walls	-	Hollow CMU 20 cm + Drywall 1.6 cm			
	R-Value	0.936 + 0.1 = 1.036 m ² K/W			
Roof	-	Medium color terracotta tiles + R-30C Fiberglass Batt – 23.5 cm + Drywall 1.6 cm			
	R-Value	0.005 + 5.508 + 0.1 = 5.613 m ² K/W			
Floor	-	Whole slab R10, R5 Gap XPS – 10 cm + Carpet			
	R-Value	1.8 + 0.374 = 2.174 m ² K/W			
WWR	%	Front	Back	Left	Right
		30	0	5	5
Door	-	Wooden			
	m ²	1.85			
	U-Value	2.72 W/m ² K			
Cooling Set Point	°C	24.4 = 76 °F			
Heating Set Point	°C	20 = 68 °F			
Internal Load	Occupancy	1.5 person			
	Sensible load	232 kJ/person/h			
	Latent load	173 kJ/person/h			
Air Flow	Air leakage	1 ACH50			
	Natural Ventilation	Year-round			
	Air Conditioner	EER 8.5			
Space Conditioning	Electric Baseboard	100% Efficiency			
	Ceiling Fan	National Average			

For space heating and cooling, we considered electrically operated space conditioning equipment such as an air conditioner with an average energy efficiency ratio (EER) of 8.5 EER, a 100% energy efficient electric baseboard, and a ceiling fan with an average efficiency rating. To ensure consistency in our analysis, all the space conditioning equipment uses the same source of energy by which we simplify the task and focus more accurately on the energy consumption patterns of space. We have intentionally excluded lighting, water heating, and energy-consuming appliances from our study to isolate the energy demand associated with space heating and cooling.

In this study, infiltration through leakages and natural ventilation (**Table 1**) are

considered as Airflow sources. Natural ventilation is enabled year-round through operable windows, which are opened based on specific criteria: outdoor airflow capacity to maintain the cooling set point, an outdoor humidity ratio below 0.0115, and relative humidity under 70%. This approach leverages cooler outdoor temperatures during early mornings and late evenings in summer to enhance indoor thermal comfort. Windows are assumed to close when the indoor temperature exceeds the heating set point by 0.5°C or if air change rates surpass 20 air changes per hour. Infiltration is modeled at a rate of 1 ACH50 (air changes per hour at 50 pascals of pressure). However, achieving an airtightness of 1 ACH50 is challenging in the context of Afghanistan due to limited access to insulation materials, poor sealing practices, and variability in construction quality.

Thermal comfort, which refers to the psychological state of mind that expresses satisfaction with the thermal environment, is a complex and multifaceted phenomenon [57] [58]. Since it varies considerably from person to person and is influenced by a variety of environmental and personal factors, it is difficult to express thermal comfort in a strictly numerical range. The most commonly used indicator of thermal comfort, however, is air temperature, with the American society of heating, refrigerating and air-conditioning engineers (ASHRAE) defining the comfort range as between 20 - 23.5°C in winter and 23 - 26°C in summer [58]. Personal factors such as clothing insulation also play a significant role in determining thermal comfort [59], with clothing culture being an important consideration in certain geographic regions. In Afghanistan, where most people wear clothes that cover the whole body, the heating set point is typically set to the minimum of the thermal comfort range, or 20°C (68°F), while the cooling set point is set to 24.4°C (76°F). These values are chosen to align with the clothing culture and ensure optimal thermal comfort for the majority of the population.

3.3. Geographical Location and Climatic Condition

Kabul, located in the eastern part of Afghanistan, was chosen as the study location. Kabul is the country's capital and largest city, with a high population density [60] [61]. It is situated in a narrow valley between the Hindu Kush mountains, with the Kabul river bounding it. The city's elevation is 1,798 meters (5,899 feet) above sea level (Figure 5).

Kabul has a continental, cold semi-arid climate (classified as "BSk" according to the Köppen climate classification) [62]. Precipitation is most frequent in the spring and winter seasons. Due to its high altitude, temperatures in Kabul are cooler than many other cities in southwest Asia. The average daily temperature in January, the coldest month, is -2.3°C (27.9°F). Summer in Kabul is generally dry, and July is the hottest month of the year, with low humidity providing some relief from the heat. In autumn, warm afternoons are followed by much cooler evenings. Kabul receives abundant sunshine throughout the year. The city's average annual temperature is 12.1°C (53.8°F), which is significantly lower than other major cities in Afghanistan.

Figure 6 presents the psychrometric chart for Kabul city, generated using

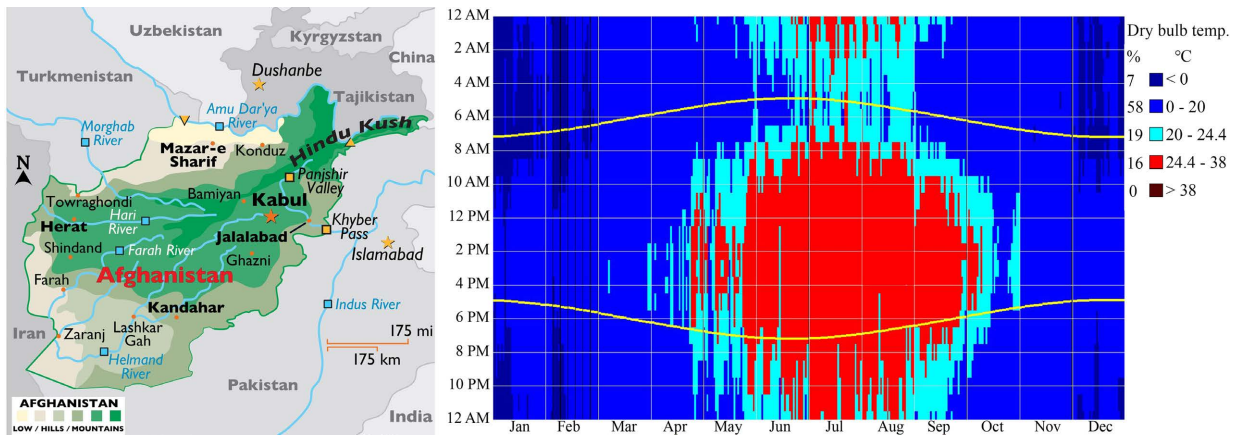


Figure 5. Location and average hourly temperature—developed in climate consultant using the weather data used for simulation.

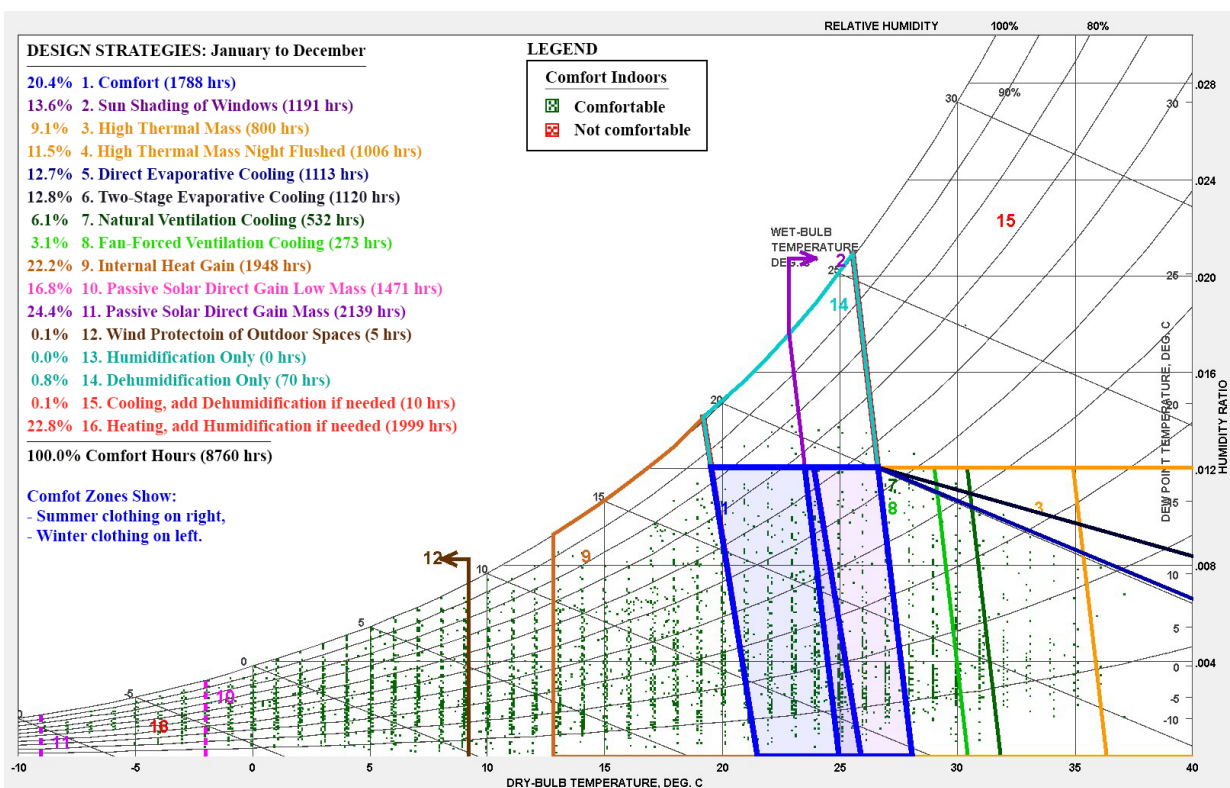


Figure 6. Psychrometric chart of Kabul city.

climate consultant software with the Energy Plus weather (EPW) file used for energy simulation and in accordance with the ASHRAE standard 55-2004 guidelines. The chart shows that 20.4% of the year, Kabul experiences weather conditions that naturally fall within the thermal comfort zone, requiring no additional design interventions. Additionally, nearly 57% of the remaining period can be made thermally comfortable through the application of passive design strategies such as passive solar direct gain, effective shading of windows, natural ventilation, the use of thermal mass, etc. Moreover, due to Kabul’s predominantly dry climate, the need for dehumidification is negligible and can effectively be disregarded in

achieving indoor thermal comfort.

4. Results and Discussion

4.1. Building Orientation

Figure 7 presents a spider chart illustrating the relationship between building orientation and annual energy consumption for heating, cooling, and the combined total energy requirements under Kabul's climatic conditions. The graph illustrates that the heating load significantly contributes to the total annual energy consumption in Kabul's climatic conditions, primarily due to the region's low temperatures during autumn and winter seasons. The results indicate that the north and south orientations, including their adjacent secondary intercardinal directions, exhibit lower cooling energy demands in all three types of glazing. Conversely, for all glazing types, only the south and its adjacent directions demonstrate low heating energy demand. The orientations extending from south-southeast (SSE) to south-southwest (SSW) are identified as the most energy-efficient, exhibiting the least total energy consumption for cooling and heating compared to the alternative orientations.

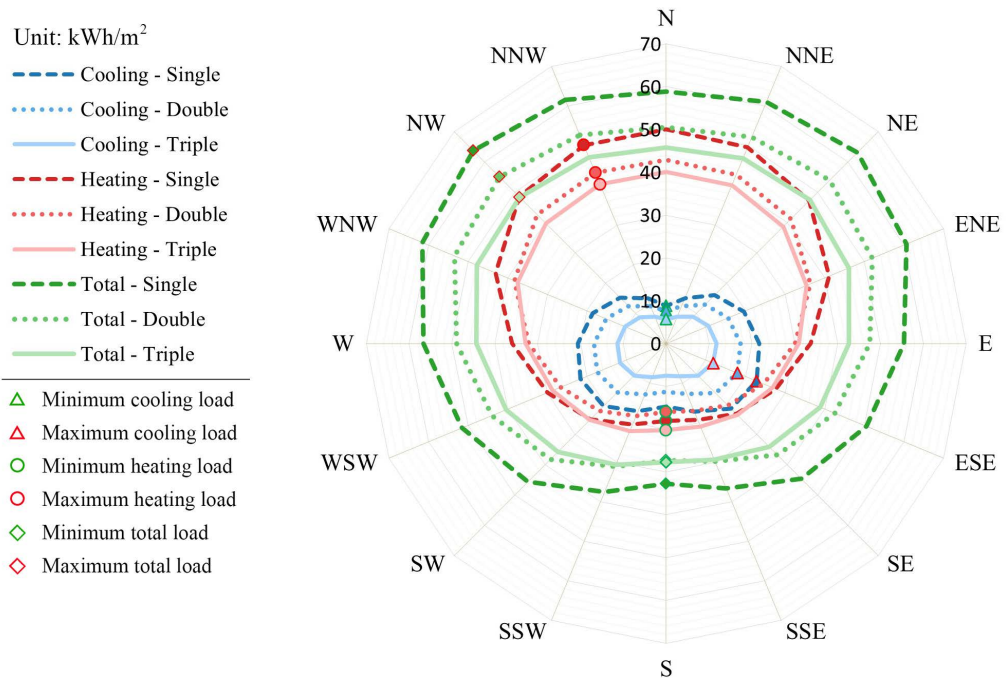


Figure 7. Impact of building orientation on energy consumption-Kabul.

The results show that the south orientation has the lowest total energy demand, while the northwest (NW) orientation demonstrates the highest total energy consumption. Interestingly, the impact of glazing type does not alter the general trend of orientation-dependent energy performance, although absolute energy consumption values differ. Single-glazed windows show the highest energy demand across all orientations, followed by double-glazed and triple-glazed windows.

However, in the optimal southern orientation, buildings with double-glazed windows exhibit lower total annual energy consumption compared to triple-glazed windows, suggesting that proper orientation can enhance performance while reducing construction costs. This is due to the balance between solar heat gain and thermal insulation in the south orientation. In this orientation, abundant solar radiation during the winter season significantly contributes to reducing heating energy demand. Double-glazed windows allow slightly more solar heat to penetrate the building compared to triple-glazed windows, enhancing energy efficiency by leveraging passive solar gains. Triple-glazed windows, while offering superior insulation, often block a larger portion of beneficial solar radiation due to their lower solar heat gain coefficient (SHGC). As a result, triple-glazing may lead to higher heating loads despite better insulation. Thus, in a south-facing building in Kabul's climate, double-glazing strikes a better balance between retaining indoor heat and allowing solar gains, reducing total energy consumption more effectively than triple-glazing.

Furthermore, the findings underscore the potential for significant energy savings through optimal building orientation. Compared to the worst-performing northwest orientation, the south orientation offers potential reductions in annual energy consumption of approximately 94.7%, 101.7%, and 74.1% for single, double, and triple glazing windows, respectively.

4.2. Window-to-Wall Ratio (WWR)

Figure 8 illustrates the influence of varying WWR on the energy performance of buildings across north, east, south, and west façades in Kabul's climate. The results show that cooling load increases with higher WWR across all façades and glazing types. This rise is primarily attributed to enhanced solar heat gains resulting from direct solar radiation penetrating through larger window areas, which elevates indoor temperatures. Additionally, the reduced thermal resistance of transparent surfaces compared to opaque walls amplifies heat transfer, making the building envelope less effective at mitigating external temperature fluctuations. Long-wave radiation transfer from the indoor further contributes to diminished thermal performance. However, north-facing windows (**Figure 8(a)**) exhibit a minimal rise in cooling load due to the absence of direct sunlight in the northern hemisphere, limiting solar heat gain. The findings also show that energy required for heating decreases with increasing WWR for south-, east-, and west-facing windows, while it increases for north-facing windows. This is primarily because solar radiation enters from these façades during cold seasons in Kabul.

From a thermal performance perspective, larger WWRs increase heat exchange between the interior and exterior environments, leading to greater cooling loads in warmer seasons. Conversely, for heating loads, the results indicate that increasing WWR reduces energy demand for south-, east- and west-facing windows, as these orientations allow greater solar heat gains during the cold seasons. North-facing windows, however, show an increase in heating load due to limited solar exposure.

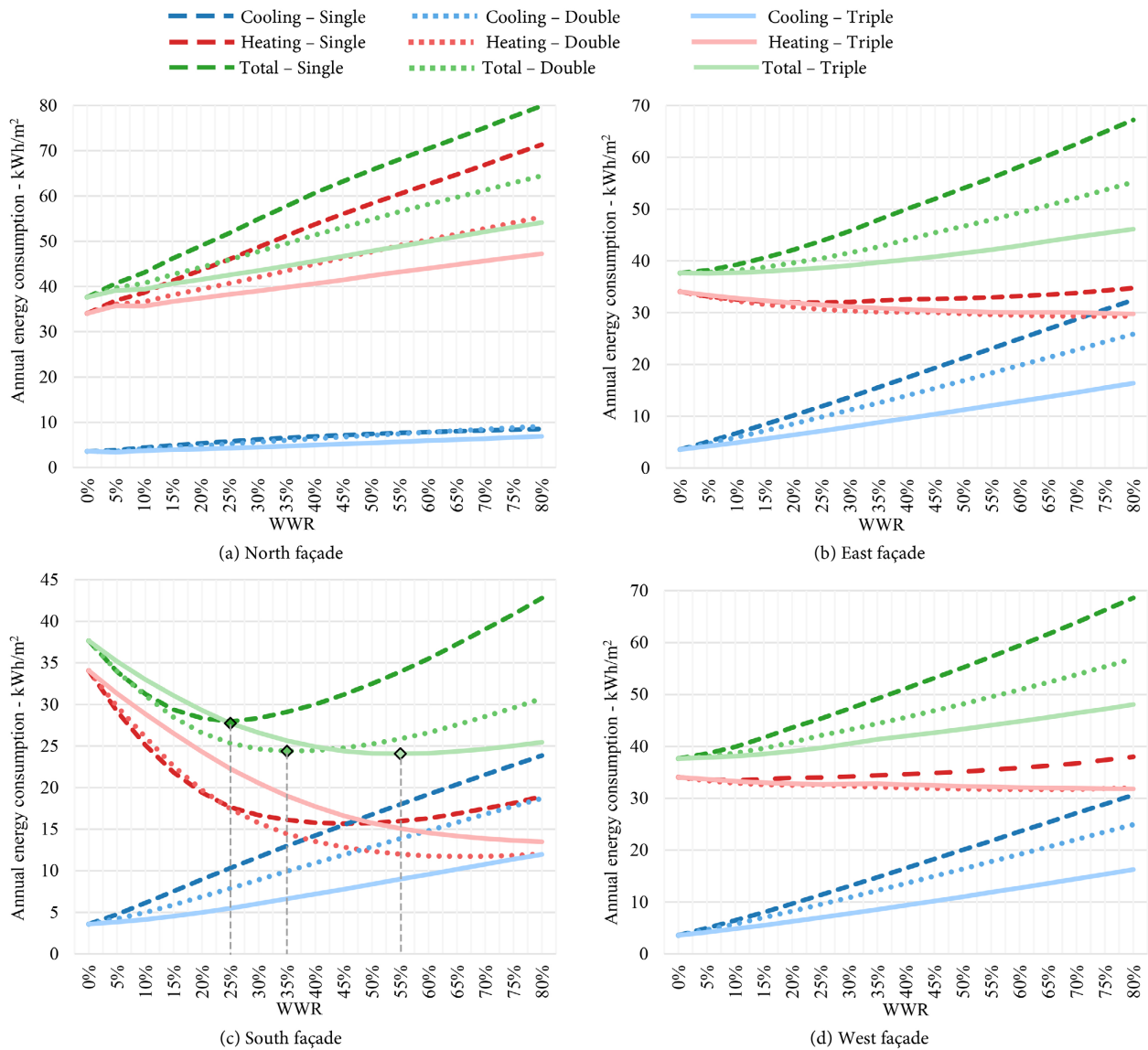


Figure 8. Impact of WWR on energy consumption—(North, East, South, and West).

As shown in **Figure 8(b)** & **Figure 8(d)**, the reduction in heating load for east and west façade windows is relatively small compared to the significant increase in cooling load, leading to an overall rise in total energy consumption. It is due to the fact that in the northern hemisphere, east and west façades receive direct sunlight during the morning and late afternoon, respectively, for a short period during colder seasons. Therefore, smaller windows on east and west façades with effective shading devices, such as vertical louvers or openable blinds, can reduce total energy consumption. Among these two orientations, the east façade is preferable for optimizing energy efficiency, as morning sunlight is generally less intense than the afternoon sun received by west-facing windows, resulting in comparatively lower cooling loads.

The graph illustrating total annual energy consumption for all façades reveals a constant increasing trend with rising WWR, except for the southern façade (**Figure**

8(c)). For the north, east, and west orientations, triple glass windows exhibit the lowest energy demand, followed by double-glazed and single-glazed windows because of the superior thermal insulation properties. In contrast, the total annual energy demand for the southern orientation follows a U-shaped curve, with the lowest annual energy consumption occurring at a WWR of 25% for single-glazed windows, 35% for double-glazed windows, and 55% for triple-glazed windows.

This U-shaped trend in total energy demand for south-facing facades is attributed to the complex interplay between heat gain during the day and heat loss at night, which is influenced by both window size (WWR) and glazing type. For cooling load, single-glazed windows exhibit the highest cooling demands, followed by double-glazed and triple-glazed windows, due to their lower thermal insulation properties. In contrast, heating demand behaves differently making the total energy consumption graph form a U-curve. Smaller windows with single and double glazing tend to have lower heating demand compared to triple glazing, due to their low thermal insulation properties which allow more solar heat gain, reducing the need for additional heating during colder months. However, as the window size increases, the heat-gaining properties of single glazing become less effective as the amount of heat lost through these larger windows outweighs the benefits of solar heat gain, making them less energy efficient. On the other hand, larger triple-glazed windows not only allow a higher amount of solar heat gain, but their superior insulation properties mitigate heat loss, making them more energy-efficient compared to larger single or double-glazed windows.

The findings suggest that smaller windows with single and double glazing are more energy-efficient in southern façades at lower WWR values, due to their ability to efficiently balance heat gain and heat loss. Conversely, larger windows with triple glazing become more energy-effective at higher WWR values, as their superior insulation properties offset the increased surface area and reduce cooling loads during the warmer months.

Figure 9 presents the difference in total energy consumption associated with various WWRs compared to windowless facades across four orientations (north, east, south, and west) and all glazing types. The data indicates that increasing WWR on the north, east, and west façades corresponds to higher energy demands compared to windowless configurations. This is due to the increased cooling load caused by higher solar heat gains during warm seasons and the lower insulation of glazed surfaces compared to opaque walls. Conversely, the south façade consistently shows reduced energy consumption with the increase of window area, except when WWR exceeds 65% for single glazing, where energy demand begins to rise. The study identifies maximum energy savings at specific WWRs: 25.7% for single glazing (WWR 25%), 35.2% for double glazing (WWR 35%), and 36% for triple glazing (WWR 55%).

Interestingly, the results show that the energy savings achieved by optimal double-glazing window (WWR 35%) are comparable to those achieved by larger triple-glazing windows (WWR 55%). While triple glazing offers superior insulation, the additional energy savings from larger windows are marginal since for south-facing

windows, solar heat gain plays a crucial role in reducing heating demand during the day. This suggests that smaller double-glazed windows can provide nearly equivalent energy performance at a lower cost, making them a more economically efficient option. Furthermore, findings emphasize the critical role of window placement, sizing, and glazing selection in optimizing energy performance. For the south façade, window sizes up to certain WWR thresholds provide energy efficiency benefits, with larger windows requiring higher-performance glazing to maintain efficiency.

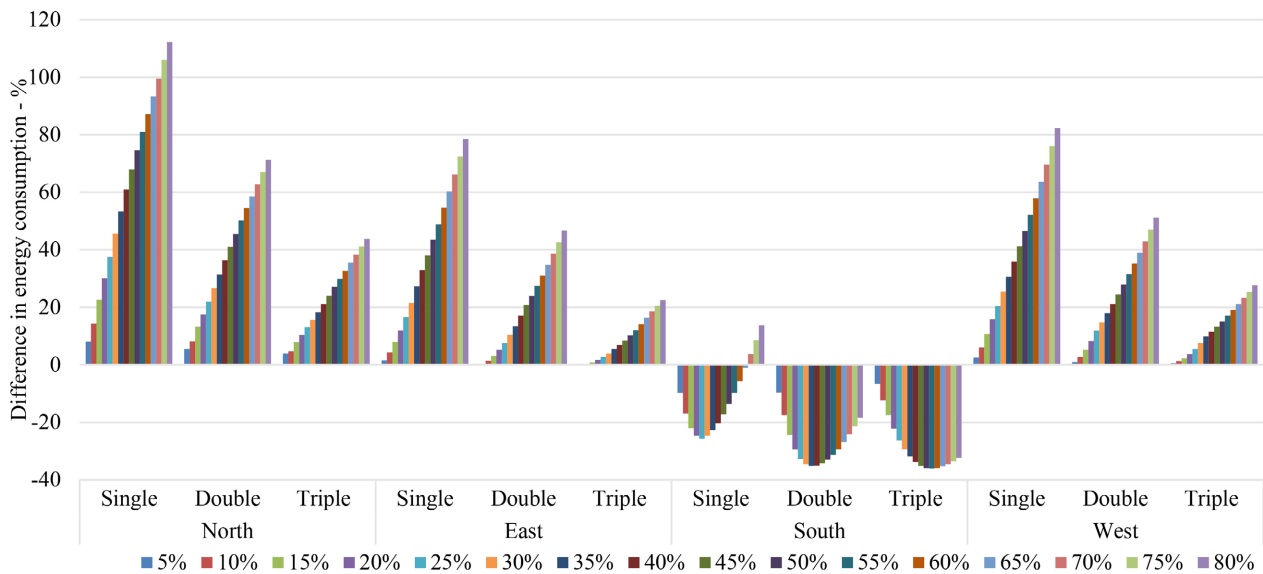


Figure 9. Percentage of the increase or reduction in total energy consumption.

4.3. Floor-to-Ceiling Height

Figure 10 illustrates that an increase in floor-to-ceiling height, consequently enlarging the conditioned volume, corresponds to higher demand for both cooling and heating energy across all glazing types. The increase in energy consumption is most pronounced in buildings with single-glazed windows, followed by double-glazed windows with triple-glazed windows exhibiting the least sensitivity to ceiling height changes. Specifically, raising the floor-to-ceiling height from 2.44 m

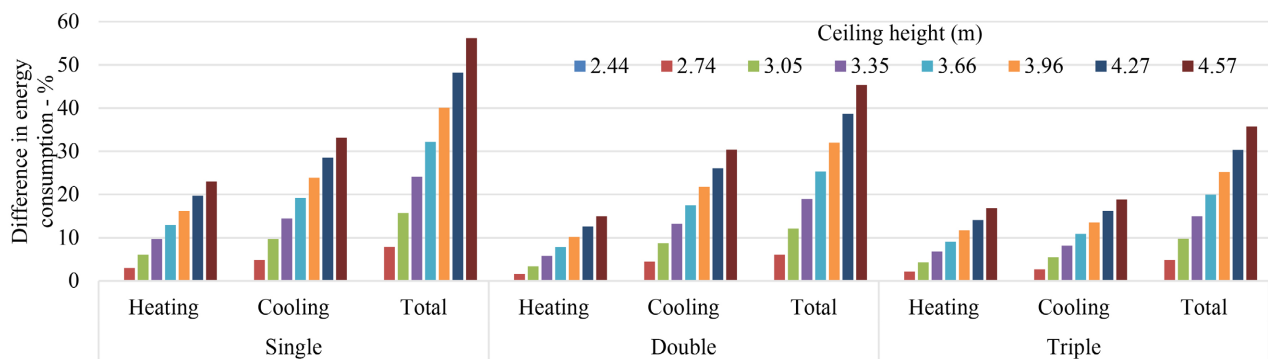


Figure 10. Impact of ceiling height on energy consumption-Kabul.

to 4.57 m leads to a 56%, 45.4%, and 35.7% rise in total annual energy consumption for single-, double-, and triple-glazed windows, respectively.

On average, each 30.5 cm (1 foot) increase in floor-to-ceiling height contributes to a corresponding 8%, 6.5%, and 5.1% increase in total energy consumption for buildings with single-, double-, and triple-glazed windows. These results highlight the compounded impact of larger conditioned spaces on thermal loads and emphasize the importance of minimizing ceiling heights in energy-efficient designs. Given the significant energy penalties associated with increased ceiling heights, especially in buildings with lower-performing glazing, lower ceiling heights are recommended for buildings in Kabul to achieve thermal comfort and energy efficiency. Future research could explore the interplay between ceiling height and indoor environmental quality to balance energy efficiency with occupant comfort.

4.4. Overhang Size

Figure 11 presents the influence of overhang depth on the energy performance of a building's south-facing windows. The data indicates a clear trend: as overhang depth increases, cooling energy demand decreases due to reduced solar heat gain, whereas heating energy demand rises as solar exposure diminishes. The total energy demand (heating and cooling combined) remains relatively unchanged up to an overhang depth of 15 cm (0.5 ft). However, for projections beyond this threshold, the total energy demand begins to increase significantly, highlighting the diminishing returns of larger overhangs. Consequently, these results emphasize that overhangs are effective for controlling solar heat gain in cooling-dominated scenarios but can negatively impact heating efficiency in colder months. Therefore, optimal energy performance can be achieved either by omitting overhangs or by designing overhang dimensions tailored to local climatic conditions and building requirements. Overly long overhangs, while reducing cooling loads, can lead to increased total energy consumption, particularly in climates requiring substantial winter heating loads.

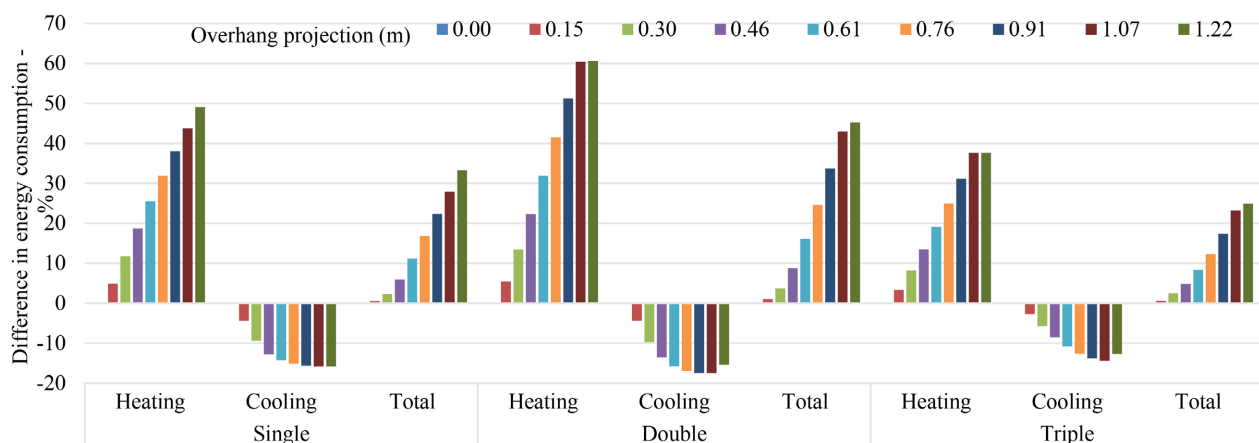


Figure 11. Impact of overhang size on energy consumption-Kabul.

5. Conclusions

This comprehensive study aimed to optimize the energy performance of residential buildings in Kabul, Afghanistan, by examining four key design parameters: building orientation, window-to-wall ratio (WWR), floor-to-ceiling height, and overhang size, considering three glazing types—single, double, and triple glazing. Through comprehensive analysis using BEopt™ energy simulation software, the study assessed the impact of each parameter individually and in combination to determine the optimal configurations that enhance energy efficiency and occupant comfort. The findings provide valuable insights into how these design factors interact and their collective influence on the energy performance of residential buildings.

In terms of building orientation, the study found that the south-facing façade exhibits the lowest total energy demand across all three glazing types, whereas the northwest orientation led to the highest annual energy demand. Notably, the results show that appropriate building orientation could lead to a 94.7%, 101.7%, and 74.1% reduction in annual energy usage for buildings with single-, double-, and triple-glazed windows respectively. Emphasizing the critical role of building orientation in energy-efficient design and construction, this study underscores its potential for significant energy savings and environmental impact mitigation.

Concerning the window-to-wall ratio (WWR), the study demonstrated that south-facing windows offer energy-saving potential, with the most optimal WWR values being 25% for single glazing, 35% for double glazing, and 55% for triple glazing. These configurations achieved energy savings of 25.7%, 35.2%, and 36% compared to a windowless façade. Conversely, increasing the WWR for north, east, and west-facing façades led to higher energy demand due to increased solar heat gain during warm seasons and higher heat loss in colder months. Furthermore, the findings emphasized the superior energy efficiency of south-facing windows and highlighted the comparatively better energy efficiency of east-facing windows in comparison to those situated on the north and west façades.

The analysis of floor-to-ceiling height reveals a clear correlation between increased ceiling height and higher energy consumption. For every 30.5 cm (1 foot) increase in floor-to-ceiling height, the total energy consumption increased by an average of 8%, 6.5%, and 5.1% for buildings with single-, double-, and triple-glazed windows, respectively. This suggests that while higher ceilings may improve aesthetic appeal and perceived spaciousness, they also significantly increase the volume of space to condition, thereby impacting energy efficiency. As such, lower ceiling heights are recommended in Kabul's climate to achieve optimal thermal comfort and energy efficiency.

Regarding overhang size, the study concluded that well-calculated or no overhangs on south-facing windows provide the best energy performance. Larger overhangs, while effective in blocking solar radiation during summer months, hindered passive solar heating in winter, leading to increased overall energy consumption.

In conclusion, this study provides valuable insights and practical recommendations for architects, engineers, and building designers aiming to enhance building performance and reduce energy consumption in a sustainable, cost-effective manner in Kabul, Afghanistan. The comprehensive dataset generated through this research offers a detailed understanding of energy performance across various glazing types, facilitating informed decision-making based on available materials. Additionally, this study highlights the importance of considering multiple design parameters and their interactions to achieve optimal energy performance. These findings carry significant implications for the development of standardized building codes and urban planning regulations to promote sustainability and enhance energy efficiency within Afghanistan's built environment.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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