

Regular Article

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Impact of insulation on energy consumption and CO₂ emissions in high-rise commercial buildings at various climate zones

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Abstract: This study investigates the impact of insulation on energy consumption and CO₂ emissions in high-rise commercial buildings across various climate zones. Through a simulation-based approach using the Hourly Analysis Program (HAP), the effectiveness of insulation in reducing energy demand and carbon emissions are evaluated. The research includes multiple climatic regions of Afghanistan, including arid, semi-arid, and mountainous zones. Methodologically, detailed building characteristics, climatic data, and insulation materials are considered, with energy modeling techniques applied to assess the performance of insulation measures. Results indicate varying degrees of energy savings and CO₂ emissions reduction associated with insulation across different climate zones, in cities such as Kabul, Herat, Mazar, and Kandahar. Furthermore, the study calculates CO₂ emissions reduction resulting from insulation addition, emphasizing the importance of sustainable building practices in mitigating environmental impacts. By underscoring the scientific value of this research in addressing a pressing global challenge and providing actionable insights for building design and energy policy, this study contributes to the advancement of knowledge in the field of sustainable construction and environmental engineering.

Keywords: energy savings, insulation, sustainability, energy cost, CO₂ emissions

1 Introduction

In recent years, there has been a growing focus on the challenges related to constructing and operating buildings. Concerns about energy consumption, greenhouse gas emissions, and resource depletion have prompted increased attention in this area [1]. One important aspect of achieving energy efficiency and sustainability goals in buildings is insulation. Insulation refers to the ability of a building envelope to resist heat transfer, playing a role in regulating temperature between the inside and outside environments. Proper insulation reduces the need for heating and cooling and ultimately decreases energy consumption and carbon emissions. Meanwhile, high-rise commercial buildings are features of landscapes worldwide; they serve as economic centers, corporate headquarters, and multifunctional spaces. These structures have demands for energy regarding heating, cooling, and lighting. Currently, 36% of global energy consumption and 37% of energy-related carbon dioxide emissions come from the construction and operation of the building sector [2]. It is imperative to prioritize sustainable building practices that emphasize energy efficiency and environmental responsibility. Research and innovation efforts are now concentrated on insulating commercial buildings as an essential area of focus.

Previous studies also have widely recognized the significance of insulation in improving energy efficiency. A comprehensive analysis conducted by Aditya *et al.* explored types of insulation materials and their potential for conserving energy in buildings while emphasizing the role of insulation in reducing heat transfer, and found that using certain insulation materials can reduce heat transfer by up to 30%, significantly improving energy efficiency in buildings [3]. Another study examined how building envelope insulation affects cooling energy consumption during summer months highlighting the advantages of using insulation to reduce energy consumption [4]. It was shown that building envelope insulation can lead to a 25% reduction in cooling energy consumption during summer months. Schuchardt

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also discussed the integration of storage systems within district heating networks, as a means to optimize energy efficiency underscoring the importance of insulation, demonstrating that the integration of storage systems in district heating networks can optimize energy efficiency by up to 15%, highlighting the role of insulation in this context [5]. Furthermore, various studies have investigated the energy implications of insulation, in climate regions. Bodalal *et al.* analyzed the heating and cooling energy needs of residential buildings across diverse climate zones in Libya, highlighting the importance of customized insulation strategies, analyzed residential buildings across diverse climate zones in Libya and found that customized insulation strategies could reduce heating and cooling energy needs by as much as 40% [6]. Ahmed examined the impact of insulation on building energy efficiency in Northern Upper Egypt underscoring the significance of insulation in climatic conditions, indicating that proper insulation can enhance building energy efficiency by up to 20% in specific climatic conditions [7]. Majumder *et al.* explored the properties of recycled materials for building insulation providing insights into sustainable solutions for insulation, and identified that using such materials can offer sustainable solutions with a potential of 15% improvement in insulation properties [8].

While evaluating the performance of an insulation material, it is crucial to select a proper optimal thickness. Because, the use of thick insulation layers, while beneficial for reducing heating loads and energy consumption during colder periods, can lead to a higher risk of overheating in the summer. Overheating risk during the summer months has been a subject of concern in moderate climates [9–12].

Research has shown that buildings with enhanced thermal performance in their envelopes, coupled with factors like urban heat island effects and global warming, are experiencing varying degrees of overheating during the summer months [13]. Similarly, passive-house buildings known for their airtight and well-insulated design can also face challenges with overheating in the summer due to their high level of insulation [14].

In the realm of sustainable construction, recent research has also emphasized the use of advanced technologies and green building practices to optimize energy efficiency and reduce carbon emissions. Studies focusing on machine learning (ML) for energy consumption prediction, automated energy analysis systems utilizing Building Information Modeling (BIM), and the impact of renewable energy sources on green building standards provide valuable insights into improving sustainability in commercial and residential buildings. These research efforts highlight the significance of innovative approaches in addressing climate change and promoting eco-friendly construction practices. A study

in Morocco highlights the effectiveness of ML and statistical methods in predicting heating energy consumption in commercial buildings. Specifically, the artificial neural network model outperformed with a correlation coefficient of 0.97, emphasizing the importance of selecting appropriate modeling techniques based on data availability and accuracy requirements when predicting energy consumption in commercial buildings [15].

Another study developed an automated energy analysis system using BIM plugins and the Revit API to optimize building design for energy efficiency. The system facilitated effective building design decisions, ensuring compliance with energy efficiency standards during the design phase. Future research aims to refine energy efficiency measurements through optimization techniques such as the Firefly Algorithm and Particle Swarm Optimization [16].

Additionally, research focusing on high-rise residential buildings in Indonesia underscores the importance of green buildings in addressing climate change and promoting sustainable development. The study investigated the influence of renewable energy sources, particularly solar modules, on the application of green building standards. The findings offer valuable insights for green building initiatives and highlight the growing demand for green properties in Indonesia [17].

About Afghanistan, Sabory *et al.* discussed the building industry in Kabul city from a sustainability standpoint, shedding light on both challenges and opportunities for sustainable construction practices, in that area [18]. It is crucial to comprehend Afghanistan zones for our research purposes as this landlocked country encompasses arid, semi-arid, and mountainous regions [19]. Kabul, being the capital and largest city, experiences arid climate conditions characterized by cold winters and hot summers [20]. Kandahar, a city in Afghanistan, experiences clear winters and long, hot, and dry summers [21]. On the other hand, Mazar e Sharif, situated in the region of the country, has cold and wet winters along with hot and arid summers [22]. These varying climate conditions make Afghanistan an excellent case study for evaluating how insulation affects energy efficiency in buildings across different climates. The country's rapid urbanization and the challenges presented by construction practices highlight the need to address energy efficiency in building design and operation [18].

Previous research has recognized the significance of insulation, in boosting energy efficiency. But, there has been limited exploration of how it interacts with climate conditions, especially in high-rise commercial buildings. To fill this research gap, this study delves into how energy usage, CO₂ emissions, and insulation correlate in climate

regions within structures. This research specifically investigates the impact of insulation thicknesses on real-world building scenarios concerning energy efficiency and environmental friendliness. Through the utilization of simulation modeling, facilitated by the Hourly Analysis Program (HAP) software and data collection from the site, the effectiveness of insulation in reducing energy consumption and CO₂ emissions across various climates were assessed. This study also seeks to provide insights into how insulation contributes to making buildings eco-friendly and energy-efficient. Moreover, discussions encompass research avenues, economic considerations, and broader implications for sustainable construction practices. Based on these findings, implementing an optimum thick insulation leads to a reduction in energy usage (up to 62.28%) and CO₂ emissions (36.01%). By highlighting the critical role of insulation in enhancing energy efficiency and supporting environmental sustainability, this research provides valuable insights for stakeholders to advance towards a more sustainable urban future.

2 Climate variations

Recognizing the importance of climate change resilience, this study assessed the importance of insulation by analyzing its effectiveness under various climate scenarios. Due to the substantial amount of mountainous and arid areas, Afghanistan has significant climatic differences. So that it may be examined more accurately, it has been divided into arid, semi-arid, and mountainous climate zones. Four representative and most developed cities (Kabul, Herat, Mazar, and

Kandahar) are examined in this research. Figure 1 shows the climate classification map for Afghanistan [23].

The classification map of Afghanistan's climate reveals a diverse pattern of zones within this landlocked country. In the lowlands of the southwest, a considerable portion of Afghanistan experiences a desert climate, characterized by scorching summers with temperatures often exceeding 40°C and limited rainfall. Moving towards the east, the climate gradually shifts into an arid zone where temperatures are milder ranging from 20 to 30°C during summer months while rainfall remains scarce. However, what stands out most on Afghanistan's climate map is the stretch of mountain ranges such as the Hindu Kush and Pamirs. These high-altitude regions have a mountain climate with cold winters where temperatures can drop to −30°C along with cool summers averaging around 10–20°C during the day. The combination of elevation and topography causes variations in climate throughout the country, impacting agriculture, water resources, and daily life for its people [24]. Kabul, which is the capital of Afghanistan, is positioned within the coordinates of 34°31'41" north latitude and 69°10'20" east longitude [25]. The climate in Kabul can be described as semi-arid, with cold winters and hot summers. The highest temperature ever recorded in the city reaches 34°C, while during winter months temperatures drop as low as −8°C. The heating degree days (HDD) for 1 year are about 1,957, and the cooling degree days (CDD) are about 405 [26]. Due to its location, Kabul does not experience rainy days in spring, summer, or fall; instead, the rainiest months are usually during winter and early spring. Kandahar, the second largest city, often seems to have clear winters followed by long spells of hot and dry summers. In Kandahar, temperatures typically range from 1 to 40°C annually. Rarely the temperature goes

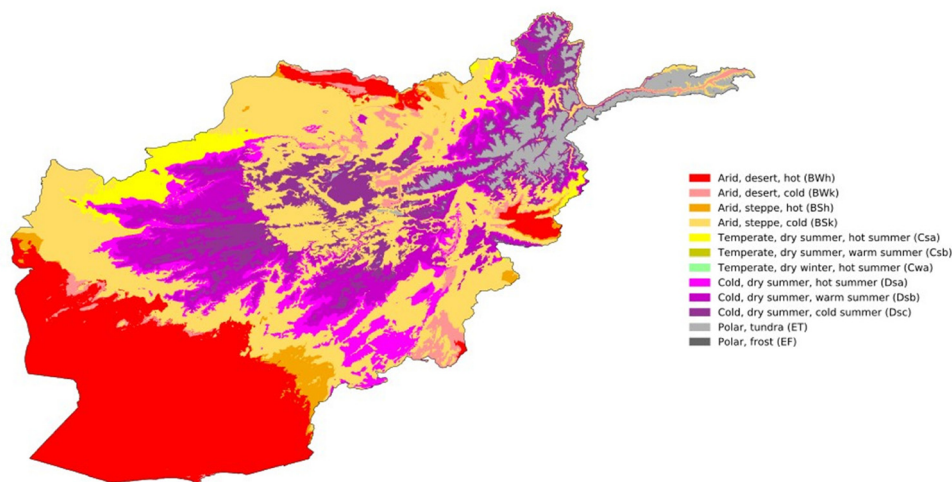


Figure 1: Koppen-Geiger climate classification map for Afghanistan [23].

below -5°C or exceeds 45°C , and the HDDs are 877 and the CDDs are 2,323 [27]. Mazar Sharif is located in the northern part of Afghanistan. It stands as the country's fourth largest city. It witnesses winters with precipitation in the form of snow, along with cloudy conditions. Summers are characterized by arid weather with annual temperatures ranging between 1 and 39°C . Occasionally it may dip below -5°C or peak above 42°C . The HDDs for 1 year are calculated as 1,486, and the CDDs are about 1,943 [22,28]. Herat city, situated in the northwestern corner of Afghanistan, constitutes the predominant northwestern province of the country. Herat stands as Afghanistan's second-most populous province after Kabul province. Herat experiences a continental, arid climate with notable variations throughout the year. Summers, from June to August, are intensely hot, with average highs surpassing 37°C . Winters, spanning from December to February, are quite cold, (below -7°C), especially at night. Precipitation is scarce, primarily occurring in the form of brief rain showers during the spring and early summer months. Herat enjoys abundant sunshine throughout the year, making it a desert climate with extreme temperature differences between summer and winter. The HDDs for 1 year were estimated at 1,195, and the CDDs were about 1,598 [29]. Figure 2 shows the high, low, and average temperatures for four major cities, Kabul, Mazar, Herat, and Kandahar. This representation allows for comparing temperature trends among these cities, highlighting the differences in temperature ranges experienced throughout the year. Understanding these temperature patterns is essential for evaluating comfort needs and energy requirements in buildings across climate zones.

Figure 3 illustrates the hourly temperature for the winter and summer seasons [30]. By displaying data on

temperature variations, this graph provides insights into how temperatures fluctuate during the day. Observing how temperatures vary over a day offers information, for optimizing building design and HVAC systems to ensure comfortable indoor conditions while reducing energy consumption. Analyzing these temperature changes can also help identify energy demand times and improve energy management strategies to enhance building efficiency.

3 Materials and methods

In this section, the outline of the methodological approach is employed to investigate the impact of insulation on energy consumption and CO_2 emissions in high-rise commercial buildings situated in diverse climate zones. The methodology encompasses a multi-faceted process designed to comprehensively address the research objectives. Initially, comprehensive data were collected regarding a representative high-rise commercial building, including architectural and construction specifications, historical weather data for four distinct climate zones, and existing energy usage patterns and insulation levels within the selected building.

3.1 Data collection and building characterization

This research was initiated by gathering comprehensive data about a representative high-rise commercial building. This involved meticulous documentation of architectural

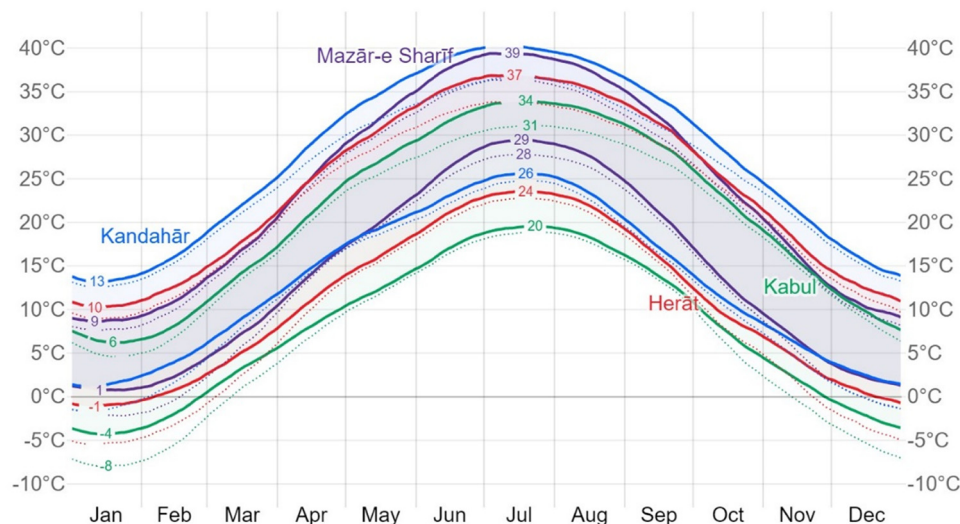


Figure 2: The mean daily temperature of the air at 2 m above the ground. The equivalent perceived temperatures are represented by the thin, dotted lines [30].

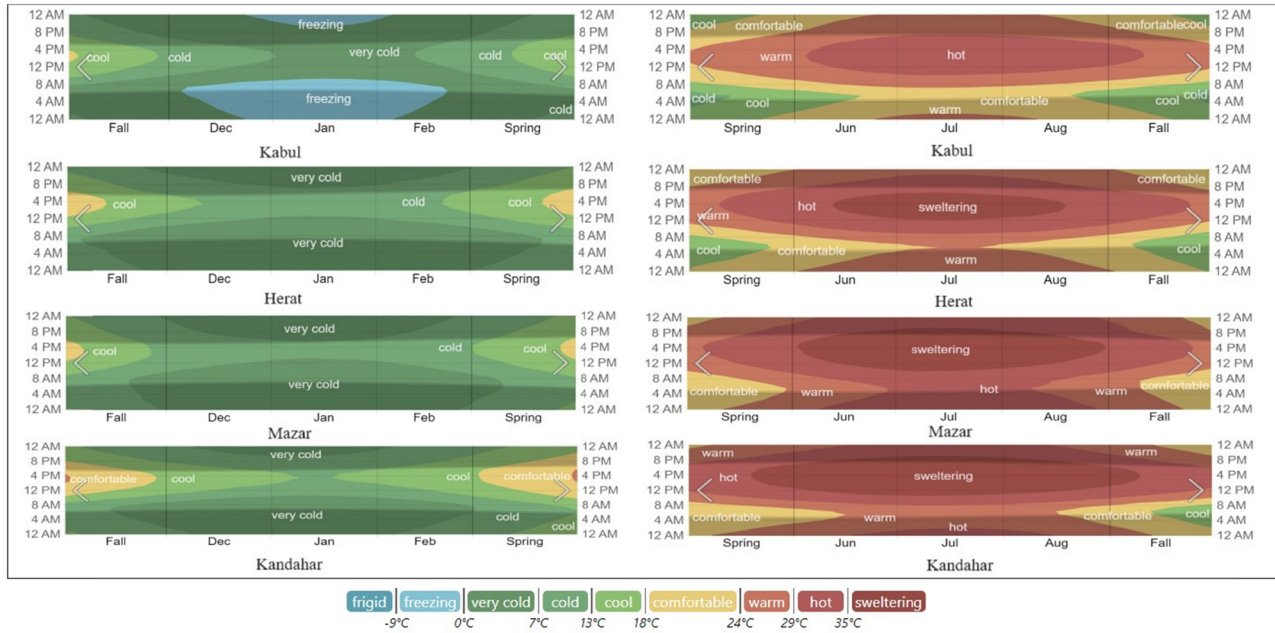


Figure 3: The hourly average temperature is divided into color-coded bands for summer and winter seasons [30].

and construction specifications. Additionally, historical weather data for four distinct climate zones, namely, Kabul, Herat, Mazar, and Kandahar cities, were collected to represent a spectrum of environmental conditions. Data on existing energy usage patterns and insulation levels within the selected building were also recorded. Simulations were conducted using a high-rise commercial building spanning 300 m² in floor area. This structure featured 4 vertical walls, 120 windows, and an insulated foundation. The walls were constructed with two layers of common brick, each measuring 150 mm in thickness, and they were plastered on the inside while being finished with 20 mm thick mortar on the outside. Table 1 lists the specifications of the

building. This assembly resulted in an effective R -value of 0.49 m² K/W for the entire wall system. The roof, on the other hand, consisted of six layers: a 20 mm plaster layer, a 150 mm concrete slab, a 150 mm batt insulation layer, a 30 mm plain cement concrete layer, a 3 mm asphalt roll layer, and a 70 mm reinforced cement concrete layer, providing an overall R -value of 5.01 m² K/W and being waterproofed with an asphalt roll. Figure 4 shows the architectural 2D plan for the building under the case study.

Table 2 provides information on various building materials, including common brick, plaster, concrete, wall insulation, and roof insulation, specifying their thickness, thermal resistance, density, and weight.

Table 1: Building specifications

Parameters	Value
Floor area	300 m ²
Number of floors	10
Length	20 m
Width	15 m
Height	37 m
Window area	28.32 m ²
Wall area	216.68 m ²
Wall U -value	2.049 W/m ² K
Window U -value	2.719 W/m ² K
Roof U -value	0.199 W/m ² K
Polystyrene insulation R -value (50 mm thick)	2.41 m ² K/W
Lighting load	5 W/m ²
Occupants density	25 People/floor
Infiltration rate	0.5 ACH
Electrical equipment loads	2,000 W/floor

3.2 Simulation modeling

To enable a detailed analysis of energy dynamics within the commercial building, The HAP, an advanced building energy simulation software, was employed for the analysis. The simulation model encompassed intricate details of the building, including geometry, construction materials, HVAC systems, and occupant behavior. A dynamic thermal simulation component was incorporated to provide real-time insight into heat transfer through insulation.

“HAP” is a widely used software tool for simulating energy consumption and HVAC system performance in buildings. This software uses the American Society of Heating, Refrigerating, and Air-Conditioning Engineers-



Figure 4: Architectural 2D plan for the examined building.

recommended transfer function method [31] for heating and cooling loads calculations and building energy analysis. The software allows for detailed modeling of building components, system configurations, and operational parameters, enabling accurate predictions of energy usage under various scenarios. By inputting building characteristics, climate data, occupancy schedules, and insulation specifications, we simulated the energy performance of the studied buildings before and after insulation improvements.

This involved estimating the energy savings achieved through insulation measures within the HAP software and determining the corresponding CO₂ emission reduction. The emission factor used in the calculations was specific to the energy source used in the building, which in this study was city electricity (0.39 kg/kWh). Simulation input data for this study are shown in Table 3.

4 Results and discussion

4.1 Cooling and heating loads

To perform the energy, cost, and CO₂ emissions analysis, the first step is defining the heating and cooling loads in four different climate zones for the entire building. Figure 5 depicts the cooling load for the four cities. In Kabul, with no insulation, the cooling load is about 37.68 W/m². As insulation thickness increases to 100 mm, the cooling load decreases by approximately 1.90%, indicating that insulation has a limited effect on the cooling load in Kabul. In Herat, the cooling load starts at 73.74 W/m² with no insulation and decreases to 67.91 W/m² with 100 mm insulation, representing a reduction of approximately 7.90%. Mazar, with no insulation, has a

Table 2: Characteristics of building materials

Material	Thickness (mm)	Thermal Conductivity (W/m K)	Density (kg/m ³)	Weight (kg/m ²)
Common brick	300	0.727	1922.2	576.7
Plaster	20	0.723	1858.1	37.2
Concrete	180	1.731	2242.6	403.7
Wall insulation	50	0.021	32	1.6
Roof insulation	100	0.045	8	0.8

Table 3: Input data for building insulation analysis for four climate zones

Zone name	Kabul	Herat	Mazar	Kandahar
Climate zone	Cool temperate steppe [29]	Warm temperate thorn steppe [29]	Arid with cold winters and hot summers [29]	Warm temperate desert scrub [29]
Climate data	- Highest temperature (36°C) - Lowest temperature (−10°C) - Average annual relative humidity (51.6%) [32]	- Highest temperature (46°C) - Lowest temperature (−15°C) - Average annual relative humidity (49.7%) [32]	- Highest temperature (45°C) - Lowest temperature (−10°C) - Average annual relative humidity (51.5%) [32]	- Highest temperature (46.5°C) - Lowest temperature (−5°C) - Average annual relative humidity (38%) [32]
Building details	- Type of building (commercial) - Total floor area (3,000 m²) - Building orientation (South) - Wall insulation level (0 mm) - Window type (Double glass with aluminum frame)	- Type of building (commercial) - Total floor area (3,000 m²) - Building orientation (South) - Wall insulation level (0 mm) - Window type (Double glass with aluminum frame)	- Type of building (commercial) - Total floor area (3,000 m²) - Building orientation (South) - Wall insulation level (0 mm) - Window type (Double glass with aluminum frame)	- Type of building (commercial) - Total floor area (3,000 m²) - Building orientation (South) - Wall insulation level (0 mm) - Window type (Double glass with aluminum frame)
Insulation details	- Roof insulation (R-30) - HVAC system type (package rooftop unit VAV)	- Roof insulation (R-30) - HVAC system type (Package rooftop unit VAV)	- Roof insulation (R-30) - HVAC system type (Package rooftop unit VAV)	- Roof insulation (R-30) - HVAC system type (Package rooftop unit VAV)
HVAC System details	- Set point temperature for cooling (23.9°C) - Set point temperature for heating (21.1°C)	- Set point temperature for cooling (23.9°C) - Set point temperature for heating (21.1°C)	- Set point temperature for cooling (23.9°C) - Set point temperature for heating (21.1°C)	- Set point temperature for cooling (23.9°C) - Set point temperature for heating (21.1°C)
Lighting and internal loads	- Ventilation rate (3,440 L/s) [33] - Infiltration rate [0.5 ACH] [34] - Lighting power density (5 W/m²) [35] - Electrical equipment load (2,000 W/floor) [35]	- Ventilation rate (3,440 L/s) [33] - Infiltration rate [0.5 ACH] [34] - Lighting power density (5 W/m²) [35] - Electrical equipment load (2,000 W/floor) [35]	- Ventilation rate (3,440 L/s) [33] - Infiltration rate [0.5 ACH] [34] - Lighting power density (5 W/m²) [35] - Electrical equipment load (2,000 W/floor) [35]	- Ventilation rate (3,440 L/s) [33] - Infiltration rate [0.5 ACH] [34] - Lighting power density (5 W/m²) [35] - Electrical equipment load (2,000 W/floor) [35]
Energy price and utility tariff	- Number of occupants (25/floor) - Occupancy load (102.6 W/person) [36] - Electricity price (0.17\$/kWh) [37]	- Number of occupants (25/floor) - Occupancy load (102.6 W/person) [36] - Electricity price (0.17\$/kWh) [37]	- Number of occupants (25/floor) - Occupancy load (102.6 W/person) [36] - Electricity price (0.17\$/kWh) [37]	- Number of occupants (25/floor) - Occupancy load (102.6 W/person) [36] - Electricity price (0.17\$/kWh) [37]
Simulation settings	- Simulation period (January to December) - HVAC system schedule (08:00–22:00 every day)	- Simulation period (January to December) - HVAC system schedule (08:00–22:00 every day)	- Simulation period (January to December) - HVAC system schedule (08:00–22:00 every day)	- Simulation period (January to December) - HVAC system schedule (08:00–22:00 every day)
Sensitivity parameters	Impact of wall insulation on energy consumption	Impact of wall insulation on energy consumption	Impact of wall insulation on energy consumption	Impact of wall insulation on energy consumption

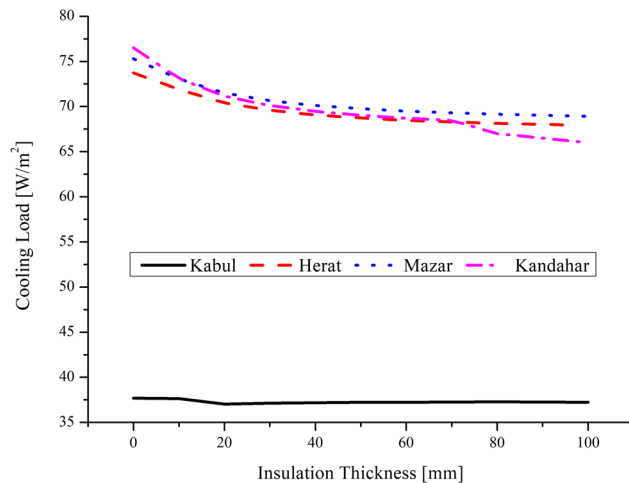


Figure 5: Cooling load for the building at different outdoor temperatures.

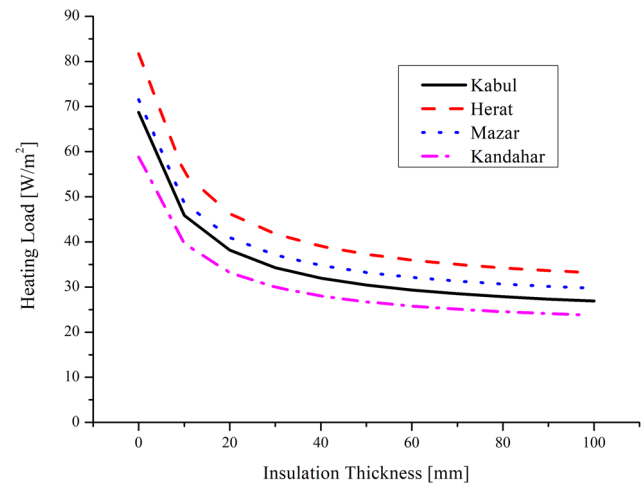


Figure 6: Heating load for the building in different outdoor temperatures.

cooling load of 75.30 W/m^2 , which decreases to 68.92 W/m^2 with 100 mm insulation, reflecting a reduction of approximately 8.50%. Kandahar follows a similar pattern, with the cooling load dropping from 76.50 W/m^2 at no insulation to 65.11 W/m^2 at 100 mm insulation, which represents a reduction of approximately 14.88%. Like Herat and Mazar, Kandahar also benefits from insulation to reduce cooling loads by a limited percentage. In summary, we can say that the insulation has less effect on the cooling load of any of the climate zones, but does not have a considerable effect on the cooling load of Kabul city, this is because, in regions with mild climates or where cooling demand is relatively low compared to heating demand, the potential for insulation to significantly reduce the cooling load may be limited [38].

Figure 6 illustrates the effect of insulation thickness on heating demand in Kabul, Herat, Mazar, and Kandahar cities. In the case of Kabul and Herat, there is a difference in their heating loads. However, both cities experience percentage reductions in heating load (60.83 and 59.39%) when using 100 mm insulation. This indicates that insulation is almost equally effective in both places. Herat initially has a higher heating load than the other selected zones. Similarly, by applying 100 mm polystyrene insulation, Mazar perceives a 58.44% reduction in the heating load. On the other hand, Mazar starts with a higher initial heating load than Kandahar. With the 100 mm insulation thickness, Kandahar shows a slightly greater percentage reduction of 59.64%. Regardless of the starting heating load in each city, it is evident that using insulation significantly improves energy efficiency and reduces heat loss across all four cities. The percentage reductions range from 58.44 to 60.83% highlighting the benefits of insulation across these diverse climates.

4.2 Energy analysis

Figure 7 shows the energy consumption for heating and cooling in four cities; Kabul, Herat, Mazar, and Kandahar. The focus is on insulation thickness and its impact on energy efficiency. When the insulation is applied to the building, there is a decrease in energy consumption. For example, in Kabul where the initial energy consumption is highest at 97.78 kWh/m^2 , it impressively drops to 33.20 kWh/m^2 – a reduction of 66.04%, while 100 mm polystyrene insulation is added. Similarly, Herat experiences a decrease from 88.63 to 43.03 kWh/m^2 with 100 mm insulation – representing a reduction of 51.45%. Mazar also witnesses a drop from 111.91 to 50.83 kWh/m^2 – a reduction of 54.58%. Finally, starting with an energy consumption of 82.33 kWh/m^2 Kandahar is reduced to 52.64 kWh/m^2 with a thickness of 100 mm – around a decrease of 36.06%. The findings reveal that once the insulation reaches a thickness of 50 mm, the rate at which energy consumption reduces stabilizes across all cities – indicating that there is a point where further increases in insulation thickness may not lead to benefits in terms of reducing energy consumption efficiently. This emphasizes the importance of finding the right balance, between insulation thickness and cost-effectiveness when aiming to improve building energy efficiency.

4.3 Economic analysis

By applying insulation, reductions in heating and cooling costs can be observed. In Mazar, where the initial combined cost is highest at $15.68 \text{ \$/m}^2$ it decreases substantially

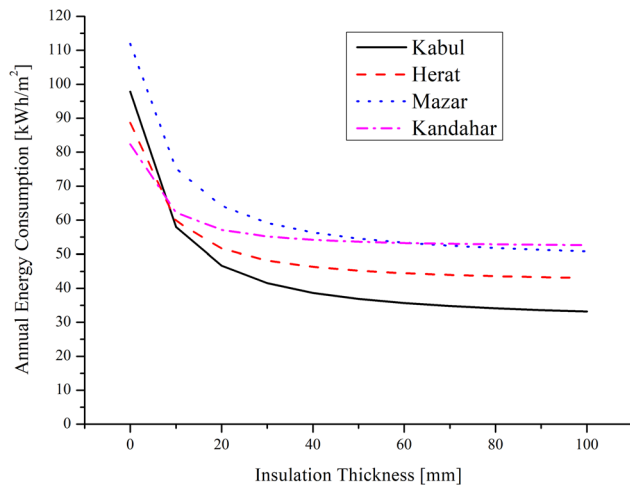


Figure 7: Annual electrical energy consumption for heating and cooling of the building.

to 7.12 $\$/\text{m}^2$ by adding 100 mm insulation which is an impressive cost reduction of 54.57%. Herat also experiences a decrease from 12.41 to 6.02 $\$/\text{m}^2$ representing a significant decrease of 51.46%. Kabul witnesses a reduction from 13.69 $\$/\text{m}^2$ to 4.65 $\$/\text{m}^2$, indicating a notable reduction of 66.06%.

Finally, for Kandahar, the cost for cooling and heating starts at 11.53 $\$/\text{m}^2$ without insulation and gradually drops to 7.37 $\$/\text{m}^2$ with 100 mm of insulation, resulting in about 34.89% annual energy cost reduction for both heating and cooling systems.

These percentages highlight the considerable cost savings achieved by adding insulation, particularly in heating expenses, while also underscoring the continued importance of insulation for both cooling and heating efficiency

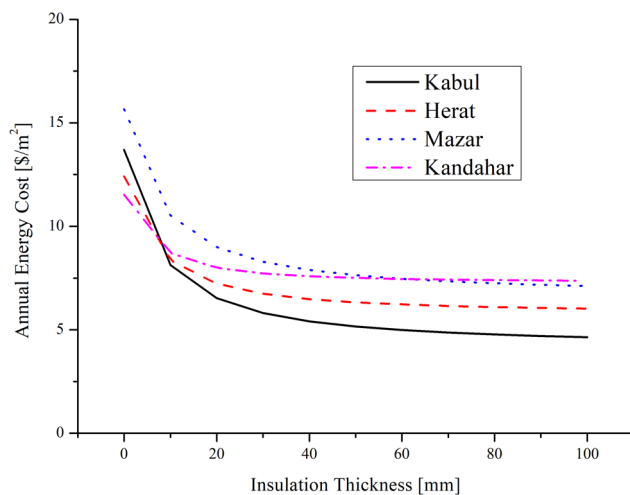


Figure 8: Annual energy cost for heating and cooling of the building.

in this specific climate context. Figure 8 shows that once the insulation thickness reaches 50 mm, the rate at which costs reduce stabilizes across all cities suggesting that there is a point where increasing insulation thickness has diminishing returns, in terms of benefits.

4.4 Environmental consequences

Figure 9 illustrates that insulation is a useful strategy for lowering CO_2 emissions in buildings in climatic zones like Kabul, Herat, Mazar, and Kandahar. Applying 100 mm thick insulation to the structure under the study in Kabul city resulted in a drop of 25.19 kg CO_2 equivalent/ m^2 emissions (38.20% reduction).

Similarly, in Herat 100 mm insulation results in a drop of 17.79 kg CO_2 equivalent/ m^2 representing a reduction of about 28.50%. Mazar experiences a decline of 23.82 kg CO_2 equivalent/ m^2 with the use of 100 mm insulation reflecting approximately a 33.33% reduction. In Kandahar, this level of insulation leads to a decrease of 11.58 kg CO_2 emissions/ m^2 accounting for around 19.32% reduction. However, it is important to mention that beyond the thickness of 50 mm for insulation, the additional reductions in CO_2 emissions are not as significant anymore.

4.5 Optimum condition

When it comes to cooling loads, the data reveal that in Kabul, increasing insulation thickness from 0 to 100 mm results only in a 1.90% reduction in cooling load. However, in Herat, Mazar, and Kandahar there are reductions in cooling loads ranging from approximately 7.90–14.88% indicating that insulation can effectively reduce cooling demands to some extent. When examining heating loads, there is a trend of percentage reductions across all four cities when applying 100 mm of insulation. These reductions range from 58.44–60.83% showing that insulation is equally effective across all these cities in terms of reducing heating demand. Regarding energy analysis, the data demonstrate a decrease in energy consumption for both heating and cooling as insulation thickness increases across all four cities. This emphasizes the potential for energy savings through insulation practices with impressive reductions ranging from 36.06 to 66.04%. It is worth mentioning that the rate at which energy consumption decreases stabilizes when insulation reaches a thickness of 50 mm. This suggests that further increases in insulation may not have a big impact. From this standpoint,

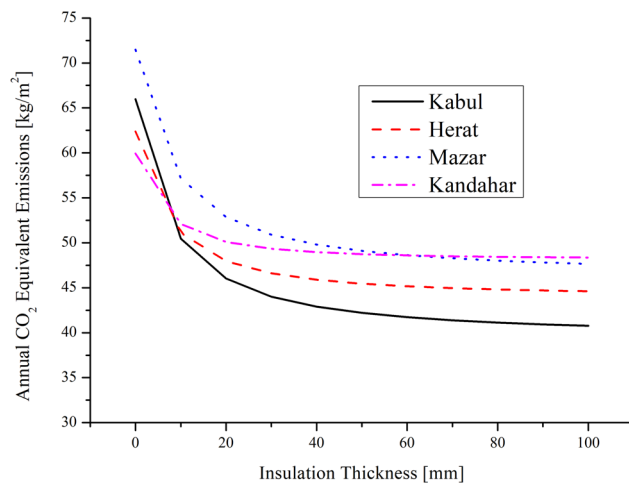


Figure 9: Annual CO₂ equivalent emissions at different insulation thicknesses.

the cost savings related to insulation are clear. Cooling and heating costs are significantly reduced in all four cities ranging from 36.06 to 66.06%. These findings highlight how insulation can help building owners save money on expenses. Insulation also plays a role in reducing CO₂ emissions from buildings. With 50 mm of insulation, CO₂ emissions decrease by around 18.68 to 36.02% for four cities. However, beyond the 50 mm thickness, the additional decrease in CO₂ emissions becomes less significant. The data provided strongly supports the idea that 50 mm thickness of insulation is the optimum choice. This strikes a balance between energy efficiency, cost effectiveness and environmental benefits, in climate zones. Table 4 shows the maximum reductions for the energy consumption, energy cost, CO₂ emissions, and payback period at 50 mm insulation thickness for four cities.

4.6 Summary

The results of this study are consistent with other studies that highlight how important insulation is to raising a building's energy efficiency. The findings highlight the

substantial energy savings that insulated buildings may accomplish, especially when it comes to lowering the need for heating and cooling. This is consistent with earlier research showing how insulating walls, floors, and ceilings may lower total energy use. Furthermore, the research indicates that insulation predominantly affects heating requirements, which is in line with basic building science concepts. Insulation results in considerable energy savings in regions where interior and outdoor temperatures range significantly. The ramifications of this discovery go beyond energy efficiency to include mitigation of climate change and sustainability. Reducing carbon emissions through effective insulation is in line with international climate goals. In Afghanistan, where issues with sustainability stem from growing urbanization and inadequate regulations, well-informed policies that encourage energy-efficient building methods are essential. These results are important for emerging countries that are trying to strike a balance between rising energy use and environmental issues. There are a number of directions this field might go in the future. The research first establishes the framework for evaluating the insulating solutions' cost-effectiveness. Subsequent studies can assess the economic feasibility of insulation techniques across different geographic areas and types of buildings, considering elements like energy and material pricing. Second, investigating the point of diminishing returns for insulation thickness would provide valuable insights into optimal insulation levels for different climatic zones and building types. Additionally, conducting environmental life cycle analyses of insulation materials and assessing their long-term durability would enhance construction practices. Finally, given the continuous evolution of the construction sector, future research should explore emerging insulation technologies and their impact on energy efficiency. Overall, this study reaffirms existing knowledge on the energy-saving benefits of insulation in high-rise buildings across diverse climates, emphasizing the importance of informed policy decisions and paving the way for a more energy-efficient and environmentally conscious construction industry.

Table 4: Optimum condition results for four cities

Location	Insulation thickness (mm)	Climate condition	CO ₂ emissions reduction (%)	Energy cost reduction (%)	Energy consumption reduction (%)	Payback period (years)
Kabul	50	Temperate	36.01	62.28	62.28	1.3
Herat	50	Arid	27.15	49.02	49.02	1.81
Mazar	50	Continental	31.29	51.26	51.26	1.37
Kandahar	50	Desert	18.68	34.86	34.89	2.73

5 Conclusion

In conclusion, our study significantly contributes to the understanding of how insulation impacts the energy efficiency and sustainability of commercial high-rise buildings, particularly in diverse climatic zones like those found in Afghanistan. By highlighting the substantial energy savings achievable through effective insulation techniques, our findings emphasize the practical implications for building design and construction practices. Furthermore, this research underscores the broader implications of insulation in reducing carbon emissions and promoting sustainability, especially for the existing challenges posed by rapid urbanization and climate change in Afghanistan. We acknowledge the limitations of our study including the need for further research to evaluate the economic viability of insulation strategies, determine optimal insulation thickness for different climates and building types, and conduct environmental life cycle assessments of insulation materials. Additionally, exploring new insulation technologies could advance energy efficiency in building practices. By addressing these future research directions, this study aims to enhance the scientific understanding and applicability of insulation techniques in high-rise buildings. And finally, ultimately contributing to more sustainable and energy-efficient building practices in the future.

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