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# Assessment of Wall and Roof Insulation Thickness on HVAC Load Reduction Using HAP Simulation in a Mid-Rise Residential Building in Kabul

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## Abstract

*Kabul's semi-arid continental climate, residential buildings have high heating and cooling energy demands because of poor insulation and envelope performance. In this study, the HVAC load of a typical mid-rise residential building in Ahmad Shah Baba Mena, Kabul, is evaluated in relation to the thickness of the insulation on the roof and the exterior walls.*

*The Hourly Analysis Program (HAP) was used to simulate four different scenarios: a baseline model without insulation and three cases where Expanded Polystyrene (EPS) insulation was applied to the roof and external walls at thicknesses of 5 cm, 7.5 cm, and 10 cm. With four floors, three conditioned residential levels, and one unconditioned parking level, the case study building has a total conditioned area of 356.7 m².*

*According to simulation results, thermal insulation dramatically lowers energy use, particularly for heating. In comparison to the uninsulated baseline, heating loads were reduced by roughly 39%, 41%, and 43%, respectively, when 5 cm, 7.5 cm, and 10 cm of EPS insulation were applied to the envelope. Cooling load reductions were less pronounced.*

*This study provides useful, fact-based advice for maximizing passive envelope performance in Kabul's residential sector by assessing the effects of both wall and roof insulation. The results back up the use of moderate insulation thicknesses (7.5–10 cm) in local building design to strike a balance between cost and energy efficiency.*

**Keywords:** EPS (Expanded Polystyrene), HAP (Hourly Analysis Program), U-value (Thermal Conductivity Value).

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## 1. Introduction

One of the biggest energy consumers in the world is the building sector, where heating and cooling requirements account for a sizable amount of overall energy use, particularly in regions with harsh seasonal variations. Rapid urbanization and unregulated construction methods have resulted in the proliferation of residential buildings with subpar thermal performance in Afghanistan, especially in Kabul City. The majority of buildings have single-glazed windows, uninsulated roofs, uninsulated masonry walls, and high air infiltration, which raises operating costs, causes discomfort for occupants, and results in excessive HVAC energy loads.

Kabul experiences hot, dry summers (above 35°C) and cold winters (below -7°C) due to its semi-arid continental climate. For year-round thermal comfort, these climate conditions require both mechanical heating and cooling. However, many residents rely on inefficient heating methods like coal or wood stoves because of frequent power outages and limited access to modern HVAC technologies. This exacerbates environmental degradation and indoor air pollution.

Improving the thermal envelope, particularly by insulating the walls and roof, has been found to be one of the most effective and economical passive energy efficiency strategies for lowering heating and cooling loads. In particular, expanded polystyrene (EPS) insulation offers promising thermal resistance at a comparatively low cost, making it appropriate for Kabul's climate and economic situation. Despite this, Afghanistan continues to underuse insulation because of low awareness, limited funding, and lax enforcement of energy efficiency regulations.

For this study, expanded polystyrene (EPS) insulation was chosen because of its good thermal performance, affordability, and accessibility in Kabul's construction industry. Because EPS usually has a low thermal conductivity (about 0.035 W/m·K), heat transfer through building envelopes can be significantly reduced. Additionally, EPS is lightweight, simple to install, and compatible with traditional masonry construction, making it ideal for both new and retrofitted residential buildings in Kabul. Given Afghanistan's present financial and construction limitations, EPS is a practical choice because it is among the most reasonably priced insulation materials available locally.

This study examines the impact on HVAC energy demand of varying EPS insulation thicknesses (5 cm, 7.5 cm, and 10 cm) applied to the roof and external walls of a typical Kabul mid-rise residential building. The Hourly Analysis Program (HAP), a specialized HVAC design and load estimation tool, was used to run the simulations. According to preliminary findings, insulation thickness considerably lowers heating and cooling loads, with diminishing returns after 7.5 cm. These results offer compelling evidence to support whole-envelope insulation practices and guide the development of energy-efficient homes in Afghanistan.

This study is unique because it focuses on Kabul City, a place that has gotten very little attention in building energy research despite its harsh winters and fast, uncontrolled residential construction. This study uses the Hourly Analysis Program (HAP), a useful HVAC design tool that engineers frequently use in real-world applications, in contrast to the majority of earlier studies that concentrate on hot-arid or temperate climates and rely on sophisticated simulation tools like EnergyPlus or DesignBuilder. Additionally, the

study assesses several insulation thickness levels concurrently for both walls and roofs, offering locally relevant recommendations on the ideal insulation thickness that strikes a balance between energy efficiency and economic viability, given Kabul's unique building and climate conditions.
The structure of this paper is as follows. In Section 2, prior research on building envelope insulation and HVAC load reduction in comparable climates is reviewed. The methodology, which includes the case study building, climate data, insulation scenarios, and HAP simulation settings, is explained in Section 3. The simulation results for various insulation thicknesses are shown and examined in Section 4. The results are compared with previous research in Section 5, and the study's main recommendations for Kabul City's residential building design are presented in Section 6.

### 1.1 Objectives

This study's principal goal is to use simulation-based analysis using the Hourly Analysis Program (HAP) to assess how various external wall insulation thicknesses affect the HVAC energy load of a mid-rise residential building in Kabul City.
The study is directed by the following particular goals in order to accomplish this:

1. To use HAP software to model the baseline energy performance of a typical Kabul mid-rise residential building with uninsulated walls and roofs.
2. To model and examine HVAC load reductions for three different Expanded Polystyrene (EPS) wall insulation thickness scenarios: 5 cm, 7.5 cm, and 10 cm.
3. To assess each insulation level's potential for energy savings in relation to the baseline model for peak heating and cooling loads.
4. To ascertain the ideal insulation thickness for Kabul's semi-arid continental climate that strikes a balance between energy efficiency and usefulness.

## 2. Literature review

The substantial impact of wall and roof insulation on HVAC energy performance has been shown in numerous studies, especially in cold or mixed climates like Kabul's. Using EnergyPlus simulations, Rashid and Khan (2021) carried out a thorough investigation of residential buildings in cold climate zones. According to their research, depending on the initial state of the base building, adding 50 mm of wall insulation decreased the heating energy demand by 15% to 25%. They also underlined the significance of combining material and construction quality improvements, noting that air sealing around window frames and wall joints could help reduce heating energy demand by an additional 10% [1].
Similarly, Singh and Kumar (2023) assessed thermal insulation techniques using ANSYS and EnergyPlus tools. According to their research, adding 75 mm of wall insulation could lower yearly heating loads by as much as 30%, especially when using cutting-edge insulation materials like aerogel composites. Additionally, they emphasized how crucial it is to reduce thermal bridges in order to stop localized heat loss [2].

Because of its reasonable thermal resistance and affordability, EPS has gained recognition as a useful insulating material. Applying 50 mm of EPS insulation to residential building walls reduced annual cooling energy consumption by roughly 18%, according to a study conducted in the United Arab Emirates (UAE) (Ali, 2023). The results are applicable to Kabul's hot summers and support the role of EPS in lowering HVAC loads all year round, despite the UAE's hot and dry climate [3].

In a parametric simulation in a Mediterranean climate, Martinez and Lopez (2022) found that a 100 mm increase in wall insulation thickness resulted in notable summer and winter energy savings. Beyond 75 mm, they did observe diminishing returns, though, as insulation gains grew only slightly in comparison to earlier thickness increase stages. This is directly related to the study's simulation results, which showed that EPS insulation longer than 7.5 cm resulted in smaller marginal gains [4].

Dynamic thermal simulation tools have been used in a number of studies to model envelope upgrades. Aljabri and Al-Sallal (2024) assessed five passive strategies, such as wall insulation, in residential buildings in a hot, arid climate using EnergyPlus and DesignBuilder. Their results demonstrated that just 50 mm of wall insulation lowered cooling demand by 25% and served as the foundation for a comprehensive energy-saving plan [5].

After synthesizing more than 70 full-text articles, Sohani et al. (2022) came to the conclusion that bundled envelope retrofits (airtightness, glazing, and insulation) offered the greatest energy savings, ranging from 20% to 50% depending on the climate. The most economical solutions for colder climates were found to be infiltration control and wall insulation [6].

### 2.1. Research Gap

There is a dearth of region-specific research on Afghanistan, especially Kabul City, despite the fact that many international studies have shown how effective thermal insulation is in lowering building energy consumption. Previous research focuses on hot-arid, Mediterranean, or temperate regions and frequently uses sophisticated simulation tools that might not be easily available in low-resource settings. Furthermore, only a small amount of research has used useful HVAC design software to investigate the combined effects of different wall and roof insulation thicknesses on both heating and cooling loads. Furthermore, previous research frequently looks at individual envelope components without evaluating varying insulation thicknesses or how they affect heating and cooling loads in combination. Additionally, there is insufficient data regarding the economic application of Expanded Polystyrene (EPS) insulation in light of Kabul's building methods and energy-related issues.

By testing three EPS insulation levels (5 cm, 7.5 cm, and 10 cm), modeling HVAC performance in a realistic residential case study using HAP, and offering useful information to Afghan architects, engineers, and policymakers, this study fills these gaps.

### 2.2. Problem Statement

The majority of Kabul's residential buildings have single-glazed windows, uninsulated brick walls, and inadequate airtightness, which causes high heating loads in the winter

and high cooling demands in the summer. Poor indoor comfort, higher expenses, and high HVAC energy consumption result from this. Many homes rely on coal or wood stoves because of frequent power outages and limited access to efficient systems, which harms the environment and pollutes indoor air.

There is a lack of region-specific research to determine the ideal insulation thickness for Kabul's climate, despite the obvious potential of passive measures like insulation. In order to close the gap, this study uses HAP software to assess how various EPS insulation thicknesses affect HVAC load reduction.

## 3. Methodology

This study uses a simulation-based methodology to measure the effect of various insulation thicknesses on HVAC heating and cooling loads in a typical residential building in Kabul City, filling the research gap mentioned in the previous section.

This study evaluates the impact of varying wall insulation thicknesses on HVAC load reduction using a quantitative, simulation-based methodology. The Hourly Analysis Program (HAP), created by Carrier and renowned for its precision in dynamic thermal analysis and HVAC system design, has been chosen as the simulation tool [7].

The technical assessment of building envelope performance and its effect on HVAC heating and cooling loads is the sole focus of this study. The main goal is to measure how different wall and roof insulation thicknesses affect the reduction of thermal load in Kabul's climate. The scope of this study purposefully excludes economic and cost analyses, such as life-cycle cost assessment, energy tariffs, and material costs. This method provides a clear understanding of the thermal efficacy of envelope insulation strategies by enabling the insulation performance to be assessed independently of market swings and economic uncertainties.

Four scenarios are used in the study to model a mid-rise residential building in Kabul's climate: an uninsulated baseline and three insulated cases with thicknesses of 5 cm, 7.5 cm, and 10 cm for Expanded Polystyrene (EPS). The goal is to ascertain the ideal degree of insulation to lower heating and cooling loads while taking Kabul's semi-arid continental climate into account.

In all of the simulated situations, EPS insulation was put on the outside of the walls and roof. The chosen EPS material has a thermal conductivity of 0.035 W/m·K, which is the same as most commercial EPS products used in Afghanistan. We used 5 cm, 7.5 cm, and 10 cm of insulation because these are the most common thicknesses used in local residential projects and because international studies have suggested these thicknesses for cold and mixed climates. These thickness levels allow an evaluation of both initial energy savings and diminishing thermal returns at higher insulation levels.

### 3.1. Case Study Building

The case study building is a typical mid-rise residential structure located in Ahmad Shah Baba Mena, Arzan Qemat, Kabul City. The building consists of four floors, including one unconditioned ground floor used for parking and three upper floors that are fully conditioned residential spaces. Each residential floor has an approximate floor area of 118.9 $m^2$, resulting in a total conditioned area of 356.7 $m^2$.

The building is assumed to have a rectangular plan with its main façades oriented along the north–south axis, which is common in local residential developments. External walls are constructed using conventional brick masonry with cement plaster, while the floors and roof are reinforced concrete slabs. No insulation is applied in the baseline model.
Windows are single-glazed aluminum-framed units with an overall U-value of 6.975 W/m²·K. The window-to-wall ratio (WWR) is 25%, reflecting typical residential construction practices in Kabul. All external doors are wooden, which is consistent with common local building materials.
Occupancy is modeled as full-time residential use with a 24-hour occupancy schedule. Internal heat gains from occupants, lighting, and equipment are defined according to standard residential assumptions and remain constant across all simulation scenarios. Table .1 shows the Building Information.

**Table 1.** Building Information

| Parameter | Value |
|---|---|
| **Building Type** | Mid-rise residential |
| **Floors** | G + 3 |
| **Conditioned Area** | 356.7 m² |
| **Orientation** | North–South |
| **WWR** | ~25% |
| **Wall Type** | Brick masonry |
| **Roof** | Reinforced concrete |
| **Glazing** | Single glazing |
| **Occupancy** | 24/7 residential |

The case study building, a four-story residential building in Ahmad Shah Baba Mena, ArzanQemat, Kabul City, has a typical floor plan layout, as shown in Fig. 1. The energy simulation model's zoning and internal gain assumptions were based on this arrangement.

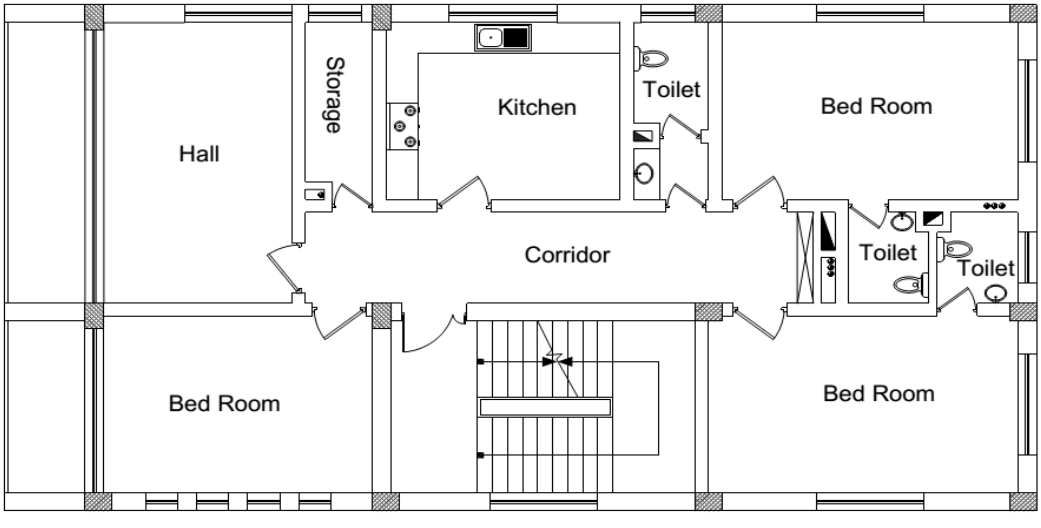



**Fig.1.** Typical building floor plan [8]

### 3.2. Climate Conditions

Kabul experiences cold winters below -7°C and hot summers above 35°C due to its semi-arid continental climate (Kakar, Safi, & Hossaini, 2022).

Climate data used in the simulation was prepared by the Department of Mechanical codes of the Ministry of Urban Development and Housing (MUDH) [9].

Fig. 2 shows Kabul's climate, with hot summers and cold winters, highlighting the seasonal variations that drive heating and cooling demands in residential buildings.

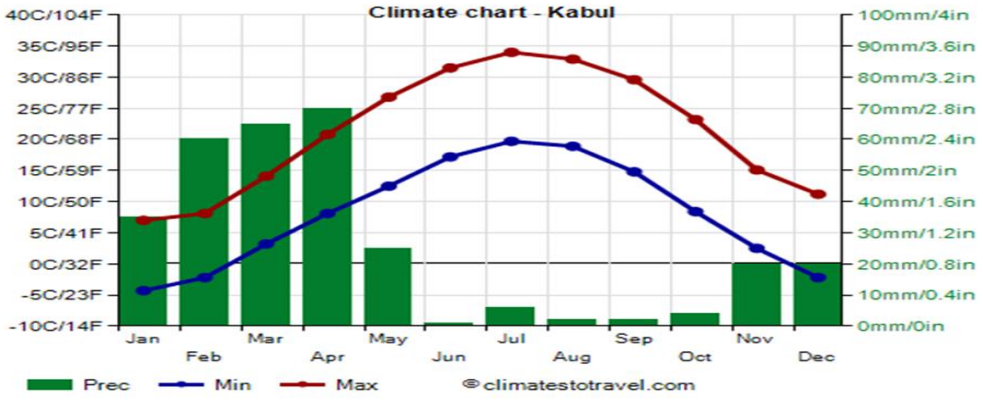



**Fig. 2.** Kabul City Climatic Chart [10]

### 3.3. Simulation Tool

Hourly Analysis Program (HAP) v4.9, which computes HVAC loads hourly using local weather files, occupancy schedules, zoning, and envelope characteristics, was used to run the simulations. [7].

#### 3.3.1 HAP Simulation Setup and Assumptions:

All energy simulations were performed using the Hourly Analysis Program (HAP) version 4.9 developed by Carrier. The software calculates hourly heating and cooling loads based on local climate data, building envelope characteristics, internal heat gains, occupancy schedules, and ventilation assumptions.

The climate data used in the simulation corresponds to Kabul City and was obtained from the Ministry of Urban Development and Housing (MUDH). The same weather file was applied to all simulation scenarios to ensure consistency and comparability.

Indoor thermal comfort set points were fixed at 22°C for heating and 26°C for cooling, reflecting typical residential comfort conditions and ASHRAE-based recommendations. Occupancy was modeled as full-time residential use (24 hours per day), consistent with local living patterns. Internal heat gains from occupants, lighting, and equipment were kept constant across all cases.

Natural ventilation was not explicitly modeled; instead, infiltration was assumed at a constant rate of 1.0 air changes per hour (ACH) for the baseline model, representing typical construction quality in Kabul. This infiltration rate was maintained for all insulation scenarios to isolate the impact of insulation thickness on HVAC loads.

The HVAC system was modeled using an idealized load calculation approach within HAP, focusing on peak heating and cooling demand rather than detailed system operation.

This approach allows a direct comparison of envelope performance across different insulation thicknesses.

### 3.3.2 HVAC System Modeling Approach:

The purpose of this study is to evaluate the impact of building envelope insulation on peak heating and cooling loads rather than to assess the operational energy consumption of a specific HVAC system. Therefore, an idealized HVAC load calculation approach available in HAP was used.

The HVAC system was assumed to be capable of maintaining the defined indoor set points (22°C for heating and 26°C for cooling) under all simulated conditions. System efficiency, equipment type, and control strategies were kept constant and were not explicitly modeled, as the focus of the analysis is on envelope-driven load reduction. This approach ensures that variations in heating and cooling loads are solely attributed to changes in insulation thickness.

Such an approach is commonly adopted in early-stage HVAC design and envelope optimization studies, where peak load estimation is the primary objective.

## 3.4. Building Input Parameters

The HVAC load simulation's primary input parameters, such as comfort set points, internal gains, and space characteristics that are crucial for estimating energy performance, are shown in Table 2.

**Table 2.** Building Input Parameter

| Parameter | Value / Source |
|---|---|
| **Total conditioned area** | 356.7 m² (3 floors) |
| **Set points** | Heating: 22°C, Cooling: 26°C |
| **Occupancy** | Full-time residential (24/7) |
| **Lighting Load** | 10 W/m² |
| **Equipment Load** | 8 W/m² |
| **Infiltration** | 1.0 ACH (baseline) |
| **Internal Heat Gains** | 120 W sensible / 60 W latent per person |
| **Ventilation Type** | Natural (modeled as infiltration) |

## 3.5. EPS Insulation Scenarios

The computed U-values for external walls and roofs with varying Expanded Polystyrene (EPS) insulation thicknesses of 5 cm, 7.5 cm, and 10 cm are displayed in Table 3. These figures are used to evaluate how the building envelope's thermal resistance is enhanced by thicker insulation.

**Table 3.** Scenarios vs U-Value

| Insulation Thickness | Wall U-Value (W/m²·K) | Roof U-Value (W/m²·K) |
|---|---|---|
| **0 cm (Baseline)** | 2.4 | 2.9 |
| **5 cm EPS** | 0.555 | 0.578 |
| **7.5 cm EPS** | 0.401 | 0.413 |
| **10 cm EPS** | 0.314 | 0.321 |

To clearly illustrate the construction differences between the baseline and insulated scenarios, typical wall and roof section assemblies used in the HAP simulations are presented. These sections show the material layers and insulation thicknesses applied in each case, including the uninsulated baseline condition and the three EPS-insulated configurations (5 cm, 7.5 cm, and 10 cm). The figures provide a visual representation of how increasing insulation thickness improves the thermal resistance of the building envelope and supports the U-value calculations used in the simulation model.

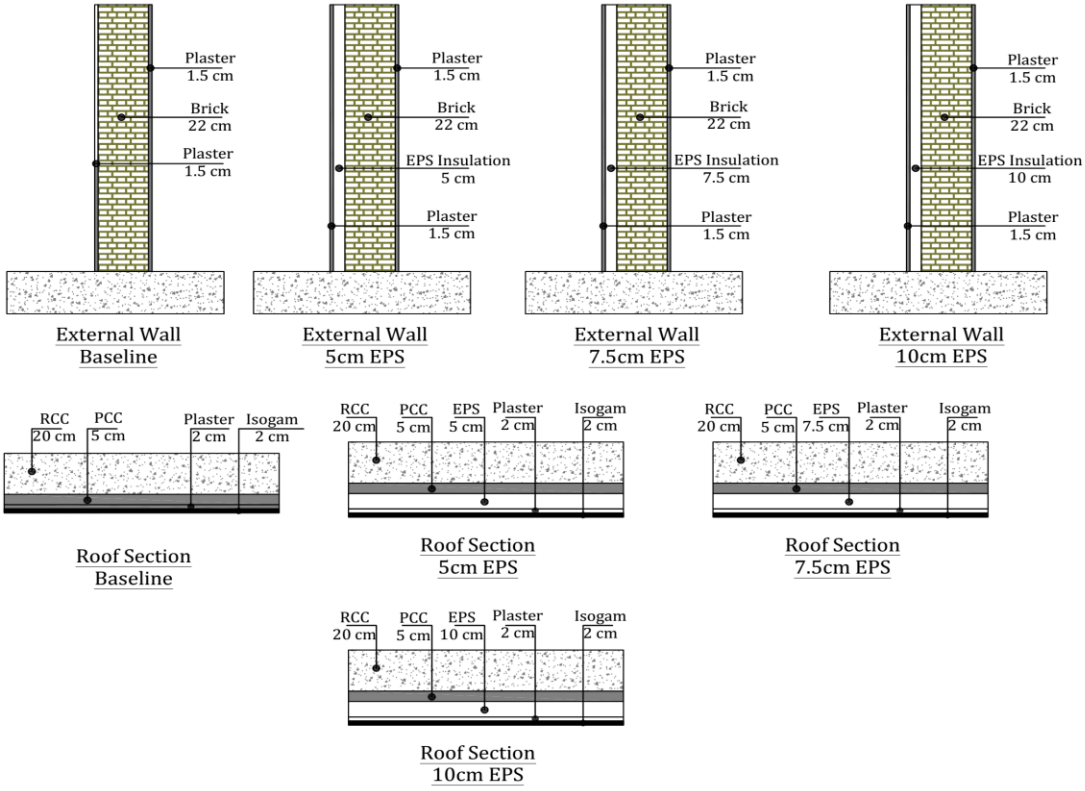



**Fig. 3.** Roof and Wall Sections for different Scenarios

As shown in Fig. 3, the baseline configuration consists of conventional brick masonry walls and reinforced concrete roof slabs without thermal insulation. In the insulated cases, Expanded Polystyrene (EPS) is applied externally to both walls and roofs with increasing thickness. This external insulation approach reduces conductive heat transfer, minimizes thermal bridging, and significantly lowers the overall U-values of the envelope components. These construction assemblies were consistently modeled across all simulation scenarios to isolate the effect of insulation thickness on HVAC load reduction. The selected insulation thicknesses of 5 cm, 7.5 cm, and 10 cm were chosen based on a combination of practical construction practices in Kabul, recommendations from international literature, and economic considerations. In local residential projects, insulation thicknesses rarely exceed 10 cm due to cost constraints and construction limitations. A thickness of 5 cm represents a minimum practical insulation level that is

affordable and commonly available in the local market. The 7.5 cm thickness represents a moderate level of insulation that aligns with optimal ranges suggested in previous studies for cold and mixed climates, while 10 cm represents a high-performance envelope option used to evaluate the upper limit of energy savings and the effect of diminishing thermal returns.

Similar insulation thickness ranges have been reported as cost-effective in cold and mixed climates in previous studies [4], [1].

U-values for both walls and roofs are considerably decreased by increasing insulation thickness, as the table shows. For instance, with 10 cm of EPS, the wall U-value decreases from 2.4 W/m²·K (baseline) to 0.314 W/m²·K. It is anticipated that this enhanced thermal performance will lead to a significant decrease in the energy needed for heating and cooling, especially in Kabul's frigid winter climate. The same was used to simulate each scenario:

- Climate data
- Internal load assumptions
- Building orientation
- HVAC systems

### 3.6. Procedure Summary

1. Base Model Development: Uninsulated model built using HAP, with Kabul climate data and occupancy profile.
2. Scenario Testing: EPS insulation added to walls at 5 cm, 7.5 cm, and 10 cm thickness.
3. Simulation Execution: Hourly HVAC load simulations run for all cases.
4. Results Comparison: Each scenario compared to baseline in terms of:
    - Heating load (kW)
    - Cooling load (kW)
    - % load reduction

## 4. Results and Discussion

This section presents the results obtained from the HAP simulations and discusses the impact of varying EPS insulation thicknesses on the heating and cooling loads of the case study building under Kabul’s climatic conditions. It should be noted that the reported heating and cooling loads represent peak design loads calculated by HAP and are independent of HVAC system efficiency.

The HAP simulation results for four wall and roof insulation scenarios are shown in this section. There is a baseline uninsulated case as well as three cases with EPS insulation thicknesses of 5 cm, 7.5 cm, and 10 cm. The objective is to ascertain how insulation thickness affects the reduction of heating and cooling loads in a typical residential building in the semi-arid continental climate of Kabul.

The results demonstrate that while increasing insulation thickness improves thermal performance, the rate of energy savings decreases beyond 7.5 cm. This confirms that the

selected thickness range is appropriate for identifying an optimal balance between energy efficiency and material cost in Kabul's residential buildings.

Baseline Energy Performance

Table 4 shows that the outcome of the building without any insulation is represented by the baseline simulation. For the entire conditioned area of 356.7 m², the peak heating load was 73.4 kW, and the peak cooling load was 51.9 kW. High per-area loads of 205.8 W/m² for heating and 145.5 W/m² for cooling are the result of this.

**Table 4.** Load Summary of Baseline Model

| Zone Name | Maximum Cooling Sensible (kW) | Maximum Heating Load (kW) | Zone Floor Area (m²) |
|---|---|---|---|
| **First Floor** | 17.6 | 25.8 | 118.9 |
| **Second Floor** | 14.3 | 19 | 118.9 |
| **Third Floor** | 20 | 28.6 | 118.9 |
| **Total load** | 51.9 | 73.4 | 356.7 |
| **W/m²** | 145.5 | 205.8 | |

## 4.1. Impact of 5 cm EPS Insulation

Both heating and cooling loads were significantly decreased when 5 cm thick EPS insulation was applied, lowering the U-value of the walls to 0.555 W/m²·K and the roofs to 0.578 W/m²·K.

**Table 5.** HVAC Load for 5 cm EPS Insulation

| Zone Name | Maximum Cooling Sensible (kW) | Maximum Heating Load (kW) | Zone Floor Area (m²) |
|---|---|---|---|
| **First Floor** | 14.1 | 15 | 118.9 |
| **Second Floor** | 13.8 | 14.3 | 118.9 |
| **Third Floor** | 13.7 | 15.7 | 118.9 |
| **Total load** | 41.6 | 45 | 356.7 |
| **W/m²** | 116.6 | 126.2 | |

The addition of 5 cm EPS insulation considerably lowers the building's thermal load, as Table 5 illustrates. The demand for heating and cooling dropped to 126.2 and 116.6 W/m², respectively, in comparison to the baseline scenario.

Fig. 4 compares baseline and 5 cm EPS cases, showing heating and cooling load reductions (kW) across all floors, visually illustrating the energy benefits of moderate insulation.

When compared to the baseline case, Fig. 5 shows that the 5 cm EPS insulation reduces heating demand by about 39% and cooling demand by about 20%. Even in buildings with otherwise conventional construction, these proportionate reductions highlight the significant relative impact of adding basic insulation. The figure illustrates how well this retrofit measure has worked to increase energy efficiency in Kabul's residential sector.

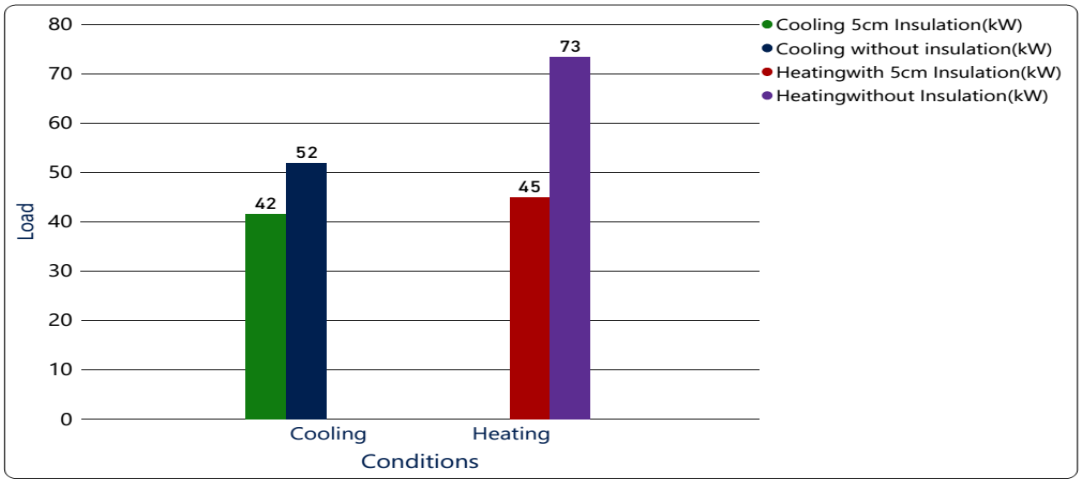



**Fig. 4.** HVAC Load Reduction for 5cm EPS Compared to Baseline by (kw)

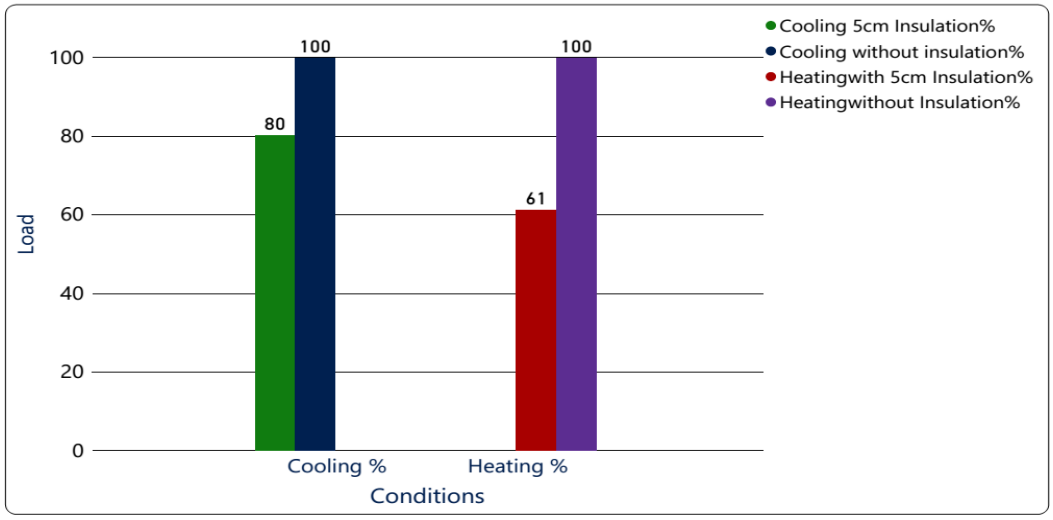



**Fig. 5.** HVAC Load Reduction for 5cm EPS Compared to Baseline by (%)

## 4.2. Impact of 7.5 cm EPS Insulation

Table 6 demonstrates that 7.5 cm EPS further lowers cooling to 115.8 W/m² and heating to 121.4 W/m².

**Table 6.** HVAC Load for 7.5 cm EPS Insulation

| Zone Name | Maximum Cooling Sensible (kW) | Maximum Heating Load (kW) | Zone Floor Area (m²) |
|---|---|---|---|
| **First Floor** | 13.9 | 14.4 | 118.9 |
| **Second Floor** | 13.8 | 14.1 | 118.9 |
| **Third Floor** | 13.6 | 14.8 | 118.9 |
| **Total load** | 41.3 | 43.3 | 356.7 |
| **W/m²** | 115.8 | 121.4 | |

Fig. 6 compares baseline and 7.5 cm EPS cases, showing heating and cooling load reductions (kW) across all floors, visually illustrating the energy benefits of moderate insulation.

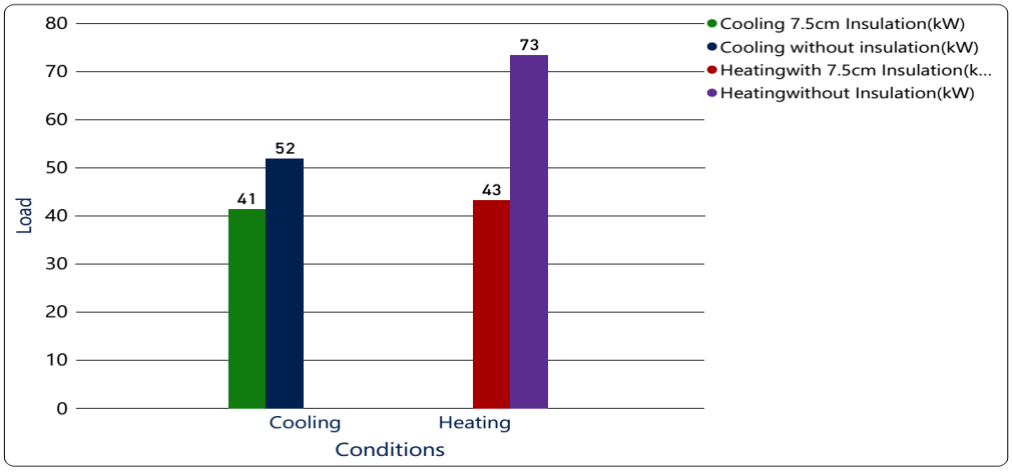



**Fig. 6.** HVAC Load Reduction for 7.5cm EPS Compared to Baseline by (kw)

When compared to the baseline case, Fig. 7 shows that the 5 cm EPS insulation reduces heating demand by about 41% and cooling demand by about 20%. Even in buildings with otherwise conventional construction, these proportionate reductions highlight the significant relative impact of adding basic insulation. The figure illustrates how well this retrofit measure has worked to increase energy efficiency in Kabul's residential sector.

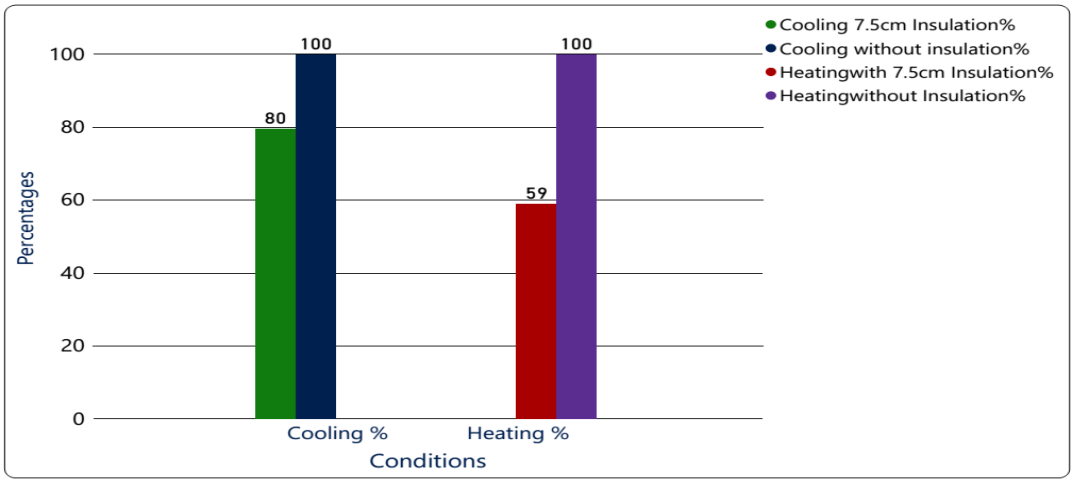



**Fig. 7.** HVAC Load Reduction for 7.5cm EPS Compared to Baseline by (%)

### 4.3. Impact of 10 cm EPS Insulation

A third simulation using 10 cm thick EPS insulation on the building's walls and roof was carried out in order to ascertain the maximum possible energy savings from insulation in this study. In order to compare the heating and cooling loads for each

residential floor under this high-performance insulation scenario with the baseline and previously tested thickness levels, Table 7 shows the results.

**Table 7.** HVAC Load for 10 cm EPS Insulation

| Zone Name | Maximum Cooling Sensible (kW) | Maximum Heating Load (kW) | Zone Floor Area ($m^2$) |
|---|---|---|---|
| **First Floor** | 13.7 | 13.8 | 118.9 |
| **Second Floor** | 13.7 | 13.7 | 118.9 |
| **Third Floor** | 13.5 | 14.1 | 118.9 |
| **Total load** | 40.9 | 41.6 | 356.7 |
| **W/m²** | 114.7 | 116.6 | |

According to Table 7, out of all the tested scenarios, 10 cm of EPS insulation results in the lowest HVAC loads, lowering the heating and cooling demands to 116.6 and 114.7 W/m², respectively. Despite offering the highest overall energy savings, this configuration only slightly improves performance over the 7.5 cm case.

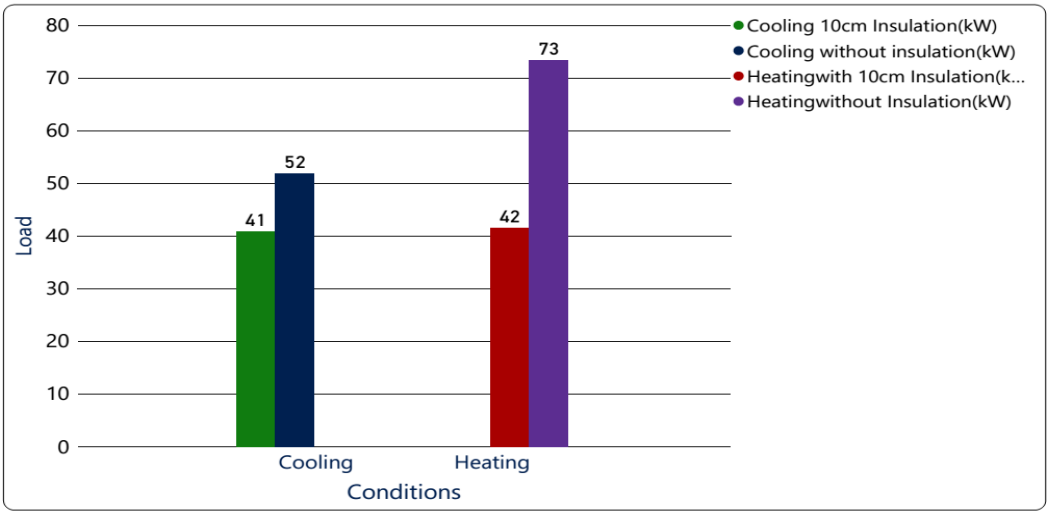



**Fig. 8.** HVAC Load Reduction for 10cm EPS Compared to Baseline by (kw)

As shown in Fig. 8, the use of 10 cm EPS insulation results in the most substantial reduction in both heating and cooling loads. However, the absolute difference in energy savings compared to the 7.5 cm insulation scenario is relatively small.

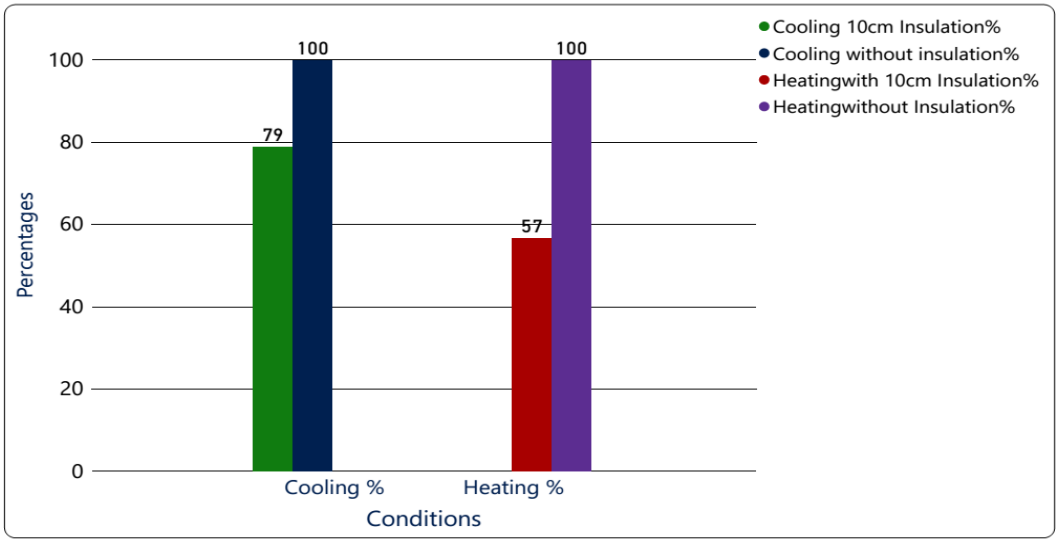



**Fig. 9.** HVAC Load Reduction for 10cm EPS Compared to Baseline by (%)

Fig. 9 shows 10 cm EPS cuts heating by 43% and cooling by 21% versus baseline, but gains over 7.5 cm are small, confirming diminishing returns and making 7.5 cm a cost-effective choice.

### 4.4. Insulation Performance Trends

Applying EPS insulation at 5 cm, 7.5 cm, and 10 cm reduces heating and cooling loads (in kilowatts) in comparison to the uninsulated baseline model. This helps visualize the absolute impact of varying insulation thicknesses on HVAC energy performance. The incremental improvement in thermal performance that comes with thicker insulation is evident in this graph.

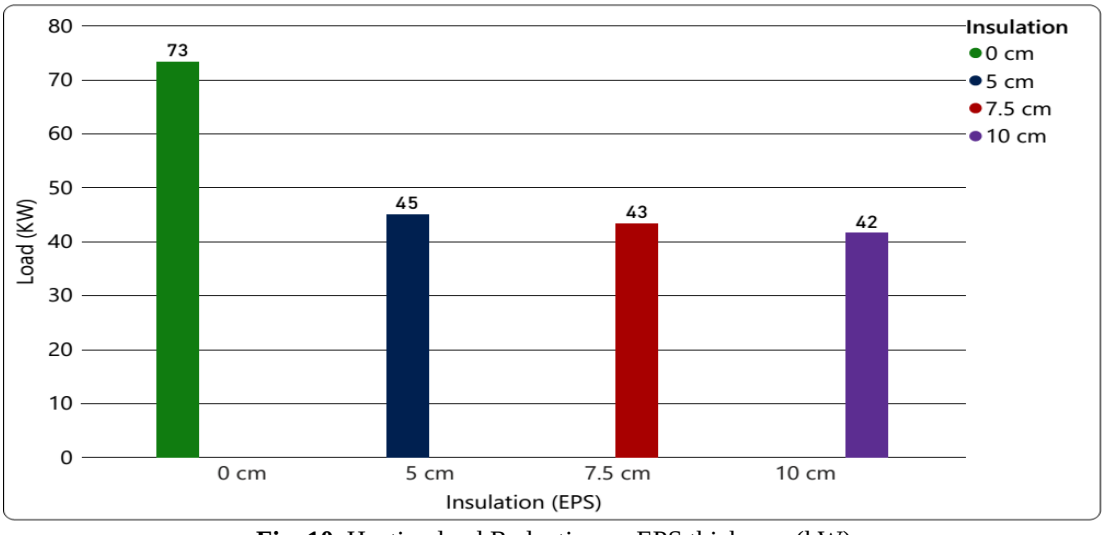



**Fig. 10.** Heating load Reduction vs EPS thickness (kW)

Fig. 10 illustrates how adding 5 cm of EPS insulation reduces the heating load by 28 kW and the cooling load by 10 kW. The overall heating load is reduced by 30 kW when the thickness is increased to 7.5 cm, but the cooling load reduction is essentially unchanged. The cooling load drops by 11 kW, and the heating load drops by 32 kW at 10 cm thickness. These figures support the idea of diminishing returns in insulation design by confirming that, although insulation thickness increases energy performance, the marginal gains diminish beyond 7.5 cm.

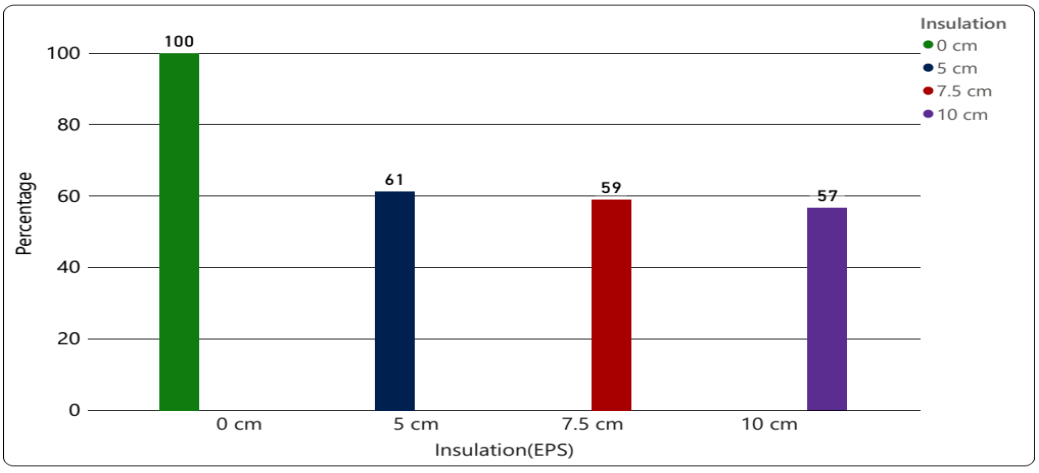



**Fig. 11.** Heating load Reduction vs EPS thickness (%)

Fig. 11 makes it abundantly evident that adding 5 cm of EPS insulation results in the biggest gains in thermal performance, with a 39% decrease in heating load and a 20% reduction in cooling load. A slight improvement is obtained by increasing the insulation to 7.5 cm; the reduction in heating load increases to 41%, while the reduction in cooling load changes slightly. An additional 10 cm of insulation reduces the heating load by 43% and the cooling load by 21%.

## 5. Discussion

The results confirm findings from international studies [1], [2], and [3], which show that insulation thickness significantly reduces HVAC energy demand in cold and mixed climates. In line with [4], the diminishing performance of insulation beyond 7.5 cm suggests that cost-benefit trade-offs should be considered when recommending insulation levels.

Additionally, the higher percentage decrease in heating load as opposed to cooling load highlights the fact that insulation works better in colder climates, which is in line with Kabul's winter-dominant thermal profile.

**Table 8.** Compare simulation Results

| Study | Climate / Building Type | Insulation Thickness | Heating / Cooling Reduction | Comparison to Your Study |
|---|---|---|---|---|
| **Rashid & Khan (2021)** | Cold climate | 50 mm | 15–25% heating | Your study shows higher heating reduction (39–43%) because Kabul buildings have poorer initial envelope performance. |
| **Singh & Kumar (2023)** | Cold climate | 75 mm (advanced materials) | 30% heating | EPS provides comparable results; slightly higher reduction due to lower baseline insulation and higher thermal contrast. |
| **Ali (2023, UAE)** | Hot-arid climate | 50 mm EPS | 18% cooling | Matches your cooling reduction (20–21%), Kabul summers are moderate, so cooling gains are slightly higher. |
| **Martinez & Lopez (2022)** | Mediterranean | 100 mm | Diminishing returns beyond 75 mm | Same trend in your study: 10 cm gives a small improvement over 7.5 cm, confirming diminishing returns. |

When comparing the simulation results with previous studies, the heating load reduction achieved through EPS insulation in Kabul's mid-rise residential buildings (39–43%) is notably higher than reported in other cold climate studies, likely due to the poor thermal performance of the baseline building. The cooling load reduction (20–21%) is slightly higher than that observed in hot-arid climates, which can be attributed to the moderate summer temperatures in Kabul and the building's relatively low window-to-wall ratio. Consistent with [4], diminishing returns are observed beyond 7.5 cm, suggesting that moderate insulation thickness provides the most cost-effective improvement in building envelope performance.

## 6. Conclusion

Based on the simulation results and comparative analysis presented in the previous sections, the following conclusions are drawn.

Using the Hourly Analysis Program (HAP) for simulation, this study assessed the effects of different Expanded Polystyrene (EPS) wall and insulation thicknesses, specifically 5 cm, 7.5 cm, and 10 cm, on the reduction of heating and cooling load in a typical mid-rise residential building in Kabul City.

The findings show that increasing wall insulation dramatically lowers HVAC loads; the biggest decrease is seen in heating demand, which is consistent with Kabul's frigid winter climate.

### 6.1. Key findings include:

- The uninsulated baseline model exhibited the highest HVAC loads: 73.4 kW (heating) and 51.9 kW (cooling).
- 5 cm EPS insulation reduced heating by 39% and cooling by 20%.

- 7.5 cm EPS insulation provided 41% heating and 20% cooling load reductions.
- 10 cm EPS insulation achieved 43% heating and 21% cooling load reductions.

### 6.2. Recommendations

- To optimize energy efficiency, install EPS insulation on exterior walls of all new residential buildings, extending at least 7.5 cm.
- 10 cm EPS can be used in colder climates or high-performance buildings, but cost and marginal energy savings should be weighed.
- To improve overall thermal performance, combine insulation with other envelope strategies like airtightness and window glazing upgrades.

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