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Assessment of Double-Glazing Performance on HVAC Energy Demand Using the HAP Simulation

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Abstract

Windows are a major source of heat loss and a significant contributor to solar heat gain in residential buildings, particularly in cold-dominated climates. In Kabul, Afghanistan, where winter heating demand is high, improving window thermal performance can significantly reduce HVAC energy consumption. This study evaluates the impact of double-glazed windows on heating and cooling loads in a typical mid-rise residential building using the Hourly Analysis Program (HAP). Two scenarios were simulated: single-glazed windows as the baseline and double-glazed windows (3 mm glass + 6 mm air gap) as the improved case, with all other building and operational parameters held constant. Results indicate that double glazing reduces the peak heating load by 14.9% and the cooling load by 6.2%, demonstrating improved thermal resistance, lower U-value, and reduced solar heat gain. These findings highlight double glazing as an effective and practical strategy for enhancing energy efficiency and indoor comfort in residential buildings in Kabul and similar cold and semi-cold climates.

Keywords: Double glazing, Window thermal performance, Building energy simulation

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Introduction

The building sector is one of the largest consumers of energy worldwide, with residential buildings accounting for a significant share of total energy use. A substantial portion of this energy is consumed by Heating, Ventilation, and Air-Conditioning (HVAC**)** systems to maintain indoor thermal comfort conditions (IEA, 2021; IEA, 2022). In cold and semi-cold climates, space heating accounts for the dominant share of building energy demand, making energy-efficient building design a critical priority (Ürge-Vorsatz et al., 2015).

Among building envelope components, windows play a crucial role in heat transfer due to their relatively high thermal transmittance compared with walls and roofs. Previous studies indicate that windows can account for 30–40% of total heat loss in residential buildings (Bjorn Petter

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et al., 2012). Particularly when single glazing is used (Gustavsen et al., 2011). In addition to conductive heat loss, windows also affect solar heat gain, which in turn affects both heating and cooling energy demand.

Double-glazed windows, consisting of two glass panes separated by an air- or gas-filled cavity, have been widely adopted as an effective means of improving window thermal performance. The additional pane and air gap reduce the overall thermal transmittance (U-value) and improve insulation performance, resulting in lower heating demand during winter and reduced solar heat gain during summer (Karlsson & Roos, 2015). Comprehensive review studies have confirmed that advanced glazing systems significantly improve thermal performance and reduce building energy consumption (Francesco Asdrubali, 2015). Previous studies have reported substantial reductions in heating energy consumption when replacing single-glazed windows with double-glazed windows in residential buildings in cold climates (Cuce & Cuce, 2016). Experimental studies have demonstrated that double-glazed systems significantly improve thermal insulation and reduce heating energy demand in cold climates (Wenjun Hee, 2015). In addition, improved glazing systems can reduce peak cooling loads by limiting solar radiation entering indoor spaces, potentially leading to smaller HVAC systems and lower operational costs (Troup et al., 2019).

Simulation-based approaches have been widely used to evaluate the energy performance of glazing systems under different climatic conditions. Building energy modelling tools such as EnergyPlus, TRNSYS, and the Hourly Analysis Program (HAP) enable detailed analysis of heating and cooling loads by incorporating climate data, building envelope characteristics, and internal heat gains (Crawley et al., 2001). Building energy simulation tools are widely recognized as reliable methods for evaluating HVAC energy performance (S. Attia, 2013). Among these tools, HAP is widely used for HVAC load estimation and system analysis in residential and commercial buildings (Carrier, 2023).

Kabul, the capital city of Afghanistan, experiences cold winters with outdoor temperatures frequently falling below 0 °C and relatively moderate summers. As a result, residential buildings in Kabul have significant heating requirements during the winter season. However, many existing buildings still use single-glazed windows due to economic limitations and the absence of strict energy-efficiency regulations. This situation contributes to increased heat loss through windows and higher HVAC energy demand.

Although several studies have investigated the impact of glazing systems on building energy performance in different climatic regions, limited research has focused on the specific climatic conditions and construction practices of Kabul. Furthermore, previous studies often evaluate glazing performance as part of broader building envelope optimization studies, making it difficult to clearly quantify the isolated impact of window glazing on HVAC loads.

Although previous studies have shown that double-glazed windows reduce building energy demand, most were conducted in different climatic conditions. Since residential buildings in Kabul commonly use single-glazed windows and lack adequate insulation, it is necessary to evaluate double-glazing under local conditions. Therefore, this study uses the Hourly Analysis

Program (HAP) simulation to assess its impact on heating and cooling loads in a mid-rise residential building in Kabul.

Therefore, the primary objective of this study is to assess the effect of double-glazed windows on heating and cooling load reduction in a typical mid-rise residential building located in Kabul, Afghanistan. Using the Hourly Analysis Program (HAP) simulation tool, two glazing scenarios, single glazing and double glazing, are evaluated under identical building and operational conditions. The results aim to support engineers, designers, and policymakers in promoting energy-efficient window solutions suitable for cold and semi-cold climates.

Methods and Materials

This study follows a quantitative research approach based on building energy simulation. A comparative analysis was conducted to evaluate the impact of single-glazed and double-glazed windows on heating and cooling loads using simulation modeling.

The research design is a case study of a typical mid-rise residential building in Kabul. Two scenarios were developed under identical conditions: (1) single-glazed windows and (2) double-glazed windows. All other building parameters were kept constant to isolate the effect of glazing type.

The primary research tool used in this study is the Hourly Analysis Program (HAP) for HVAC load calculation and energy simulation. Additional tools include (Power BI) for data organization and graphical presentation.

Climatic data for Kabul were obtained from the HAP weather database. Building geometry, envelope properties, and system parameters were defined based on standard residential construction practices and literature values. Window thermal properties were selected based on manufacturer data and previous research.

Case Study Building Description

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: one unconditioned ground floor used for parking and three fully conditioned residential floors. Each residential floor has an approximate floor area of 118.9 m², resulting in a total conditioned area of 356.7 m².

The building is assumed to have a rectangular plan, with its main façades oriented along the north–south axis, a common feature 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 Figure 1.

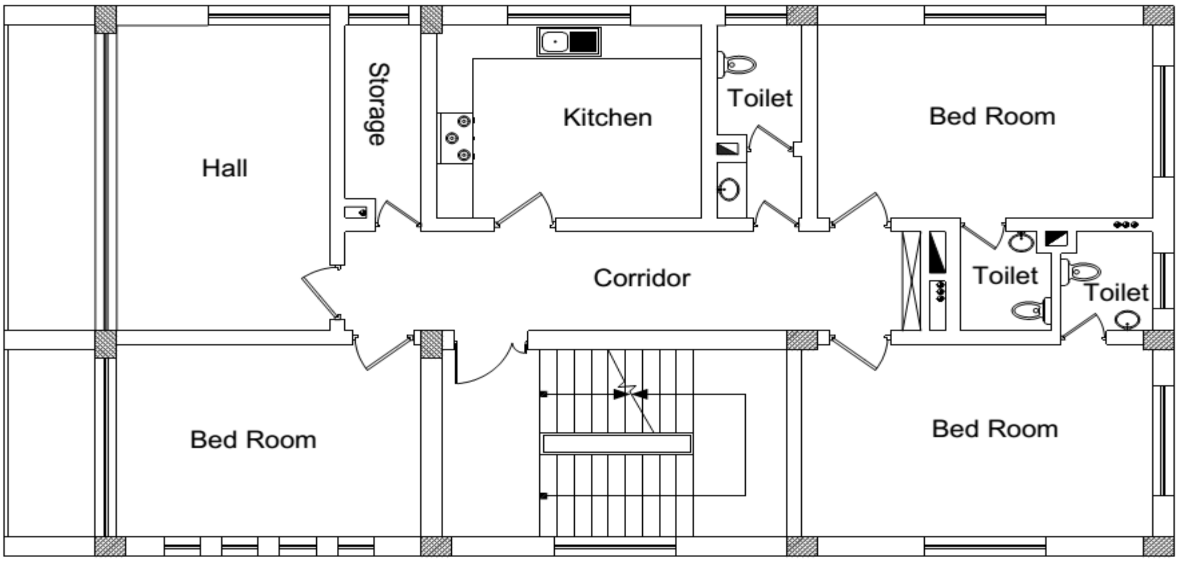

***Figure 1**. Typical Building Floor Plan* (Construction, 2025)

Climate Data and Design Conditions

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

The climate data used in the simulation was prepared by the Department of Mechanical Codes of the Ministry of Urban Development and Housing (MUDH) (Housing, 2015).

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

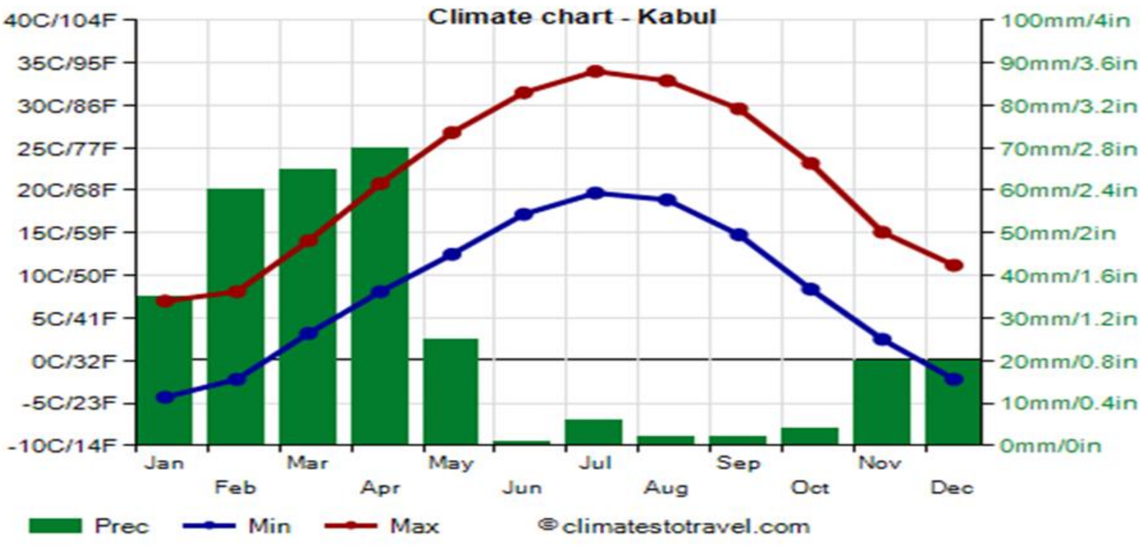

Figure 2*. Kabul city Climatic Chart* (ClimatesToTravel.com, 2025)

Scenario Description

Figure 3 shows the HAP simulation interface for the baseline model using single-glazed windows, including the higher thermal transmittance (U-value) associated with single glazing.

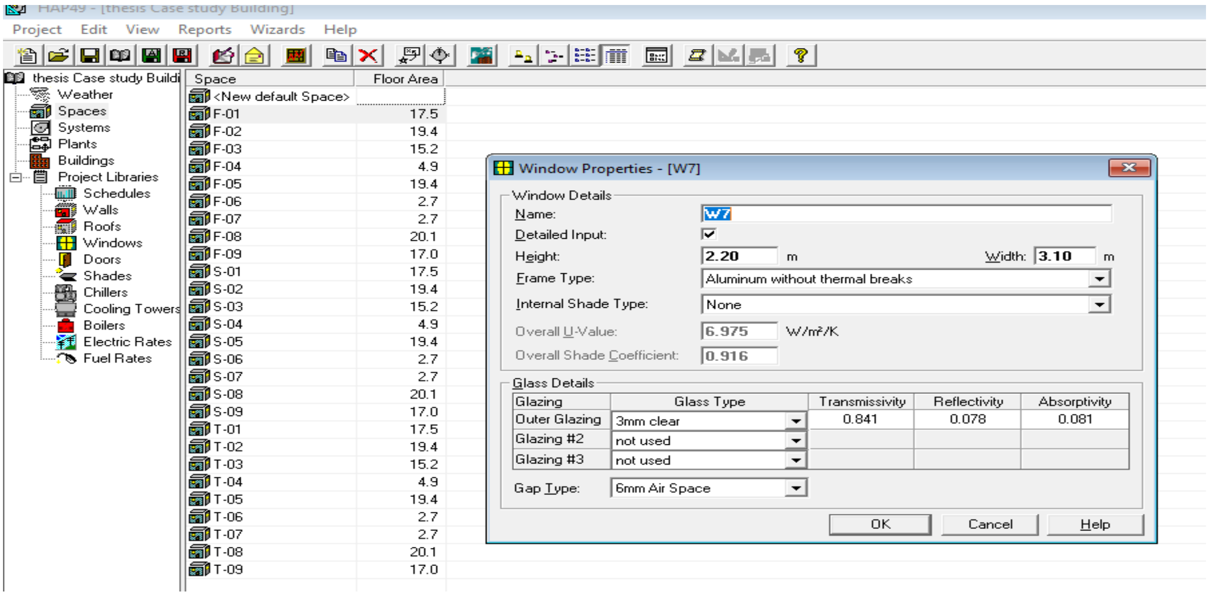

Figure 3*. HAP Single Glass Scenario Model*

Figure 3 illustrates the HAP simulation model used in this study, showing the defined building spaces for the three conditioned floors as well as the double-glazed window properties, including the thermal transmittance (U-value) applied in the simulation.

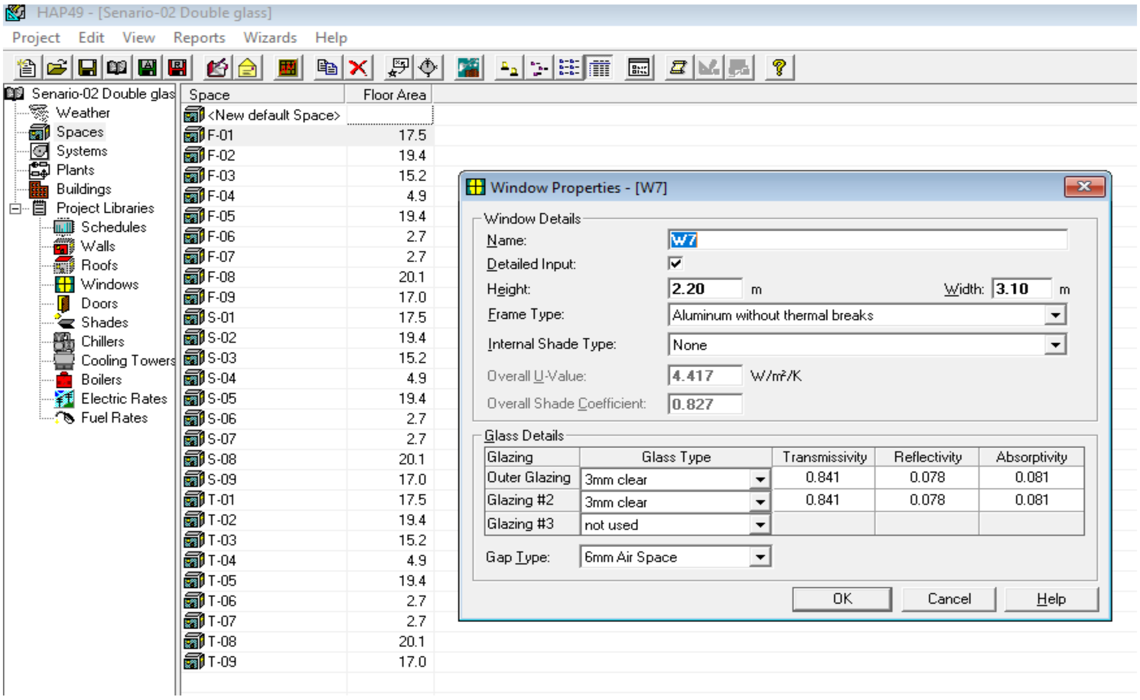

Figure 4. *HAP double glass Scenario Model*

The study examines how improvements in window glazing affect HVAC energy performance, after evaluating wall and roof insulation. One of the main causes of heat gain in the summer and thermal loss in the winter is poorly insulated windows. In order to solve this, double-glazed windows with a 6 mm air gap are installed in place of the standard single-glazed windows. A comparison of the main features of the baseline and optimized window glazing scenarios used in the simulation is given in Table 2.

Table 2: *Thermal Properties of Window Glazing Systems*

Parameter	Baseline Window	Optimized Window
Glass Type	Single Glazed	Double Glazed (3 mm + 6 mm gap)
U-Value (W/m²·K)	6.975	4.469
Frame Type	Aluminum	Aluminum (unchanged)
Air Gap	—	6 mm

By lowering the U-value from 6.975 W/m²·K to 4.469 W/m²·K, the optimized double-glazed windows dramatically improve thermal performance, as shown in Table 9. This improved glazing system ensures compatibility with current architectural designs by reducing conductive heat transfer while preserving the same frame type and window area. As further examined in the following figures and load summaries, it is anticipated that the ensuing insulation improvement will reduce both heating and cooling demand.

Reduced convective and conductive heat transfer through the window assembly is reflected in the optimized case's higher U-value. To isolate the impact of glazing type, neither the window area nor orientation was altered.

Simulation Tool and Assumptions

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. (Carrier, 2023).

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 for Kabul City 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.

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 not explicitly modeled, as the analysis focuses 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.

Building Input Parameters

The primary input parameters for the HVAC load simulation, including comfort set points, internal gains, and space characteristics, are shown in Table 3.

Table 3: *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
Internal Heat Gains	120 W sensible / 60 W latent per person
Ventilation Type	Natural (modelled as infiltration)

Findings

This section presents the results of the HAP simulation evaluating the impact of double-glazed windows on the heating and cooling loads of a mid-rise residential building in Kabul. Two glazing scenarios, single glazing (base case) and double glazing (improved case), were analyzed under identical building, occupancy, and climatic conditions.

To establish a reference for evaluating the impact of window glazing on HVAC loads, the baseline case was first simulated using single-glazed windows. This scenario represents the prevailing glazing condition in residential buildings in Kabul. The baseline simulation was performed using HAP with all building envelope properties, internal gains, occupancy schedules, and climatic conditions kept constant. The resulting cooling and heating loads obtained from this baseline case serve as a benchmark against which the performance of the double-glazed window scenario is compared.

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	

As shown in Table 4, the baseline simulation results indicate relatively high heating and cooling loads across all building floors, with heating demand exceeding cooling demand. This trend reflects the cold-dominated climate in Kabul, where heat loss through building envelope components, particularly windows, significantly increases heating requirements. The heating load intensity of 205.8 W/m² highlights the poor thermal performance of the single-glazed windows used in the baseline case, emphasizing the need for improved glazing systems to reduce heat loss and HVAC energy demand.

A simulation used double-glazed windows with a 3 mm glass layer and a 6 mm air gap to measure the effect of improved window glazing on HVAC energy demand. The resulting heating and cooling loads are contrasted with the standard single-glazed situation in this section. The simulation results are summarized in Table 5, which also shows the peak heating and cooling loads for each floor of the residential building with the optimal window configuration.

Table 5: *Load Summary of Baseline Model*

Zone Name	Maximum Cooling Sensible (kW)	Maximum Heating Load (kW)	Zone Floor Area (m²)
First Floor	16.3	22.2	118.9
Second Floor	13	15.3	118.9
Third Floor	19.4	25	118.9
Total load	48.7	62.5	356.7
W/m²	136.5	175.2	

Table 5 shows that all three conditioned floors experience a discernible decrease in heating and cooling loads when double-glazed windows are used. The cooling load dropped from 51.9 kW to 48.7 kW, and the overall heating load decreased from 73.4 kW in the baseline to 62.5 kW. These findings demonstrate how double glazing reduces heat transfer and enhances indoor comfort. Upgrading window glazing remains a useful and realistic way to improve energy performance in Kabul's residential buildings, even though the improvement is not as significant as with wall insulation.

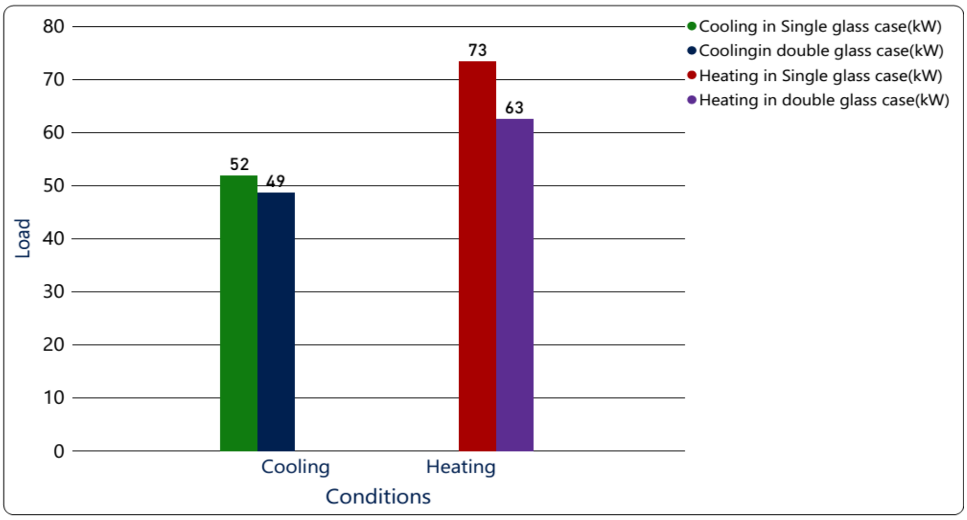

Figure 5: *HVAC load Reduction for double glass vs single glass by (KW)*

Figure 5 above compares the total heating and cooling loads (in kilowatts) between the optimized double-glazed configuration and the baseline single-glazed window scenario to illustrate the impact of window glazing improvements on HVAC energy demand. The absolute energy savings attained through improved glazing performance are depicted in this graphical representation.

Double-glazed windows significantly lower heating and cooling loads, as seen in Figure 5. The air gap and extra glass layer provide better insulation, as evidenced by the notable decrease in heating load. Even though it is less noticeable, the reduction in cooling load still improves HVAC efficiency. These findings lend credence to the use of double glazing as a practical energy-saving strategy, particularly in regions like Kabul where both summer cooling and winter heating are required.

Figure 6 shows the percentage decrease in HVAC load relative to the baseline single-glazed scenario, further elucidating the efficacy of the double-glazed window upgrade. This figure provides a clearer understanding of the efficiency gains from glazing enhancement by highlighting proportional improvements in both heating and cooling energy performance.

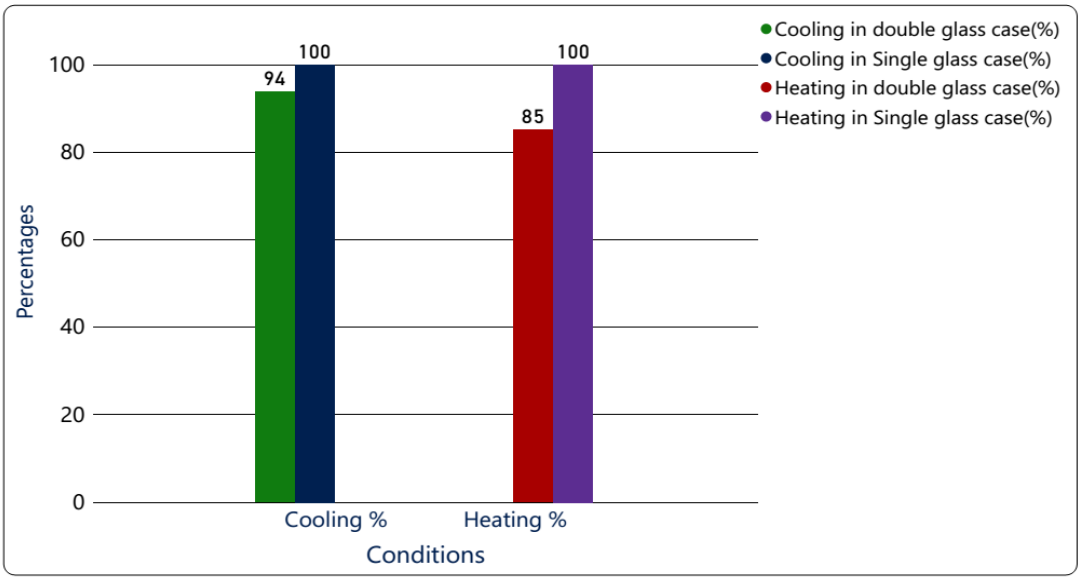

Figure 6. *HVAC load Reduction for double glass vs single glass by (%)*

Compared with the single-glazed baseline, the optimized double-glazed window system reduces the heating load by about 15% and the cooling load by about 6%, as shown in Figure 6. In line with Kabul's higher demand for winter heating, the improvement in heating performance is substantial even though the relative gain in cooling efficiency is small. According to this analysis, installing double glazing in residential buildings is an affordable way to improve thermal performance and reduce energy use.

Upgrading to double-glazed windows results in a significant drop in U-value, from 6.975 to 4.469 $W/m^2 \cdot K$, thereby enhancing thermal resistance and reducing unwanted heat transfer.

- The peak heating load is reduced by 14.9%, indicating better insulation performance during winter nights and early mornings.

- The peak cooling load is reduced by 6.2%, attributed to reduced solar and conductive heat gain.

Window upgrades alone have a moderate impact compared to insulation upgrades, but they are especially crucial for reducing glare and condensation and improving occupant comfort in window zones.

This finding backs up the suggestion that Kabul's residential buildings should have at least double-glazed windows, especially when combined with airtightness and insulation upgrades for optimal effect.

Discussion

The simulation results demonstrate that installing double-glazed windows results in a measurable reduction in both heating and cooling loads for the studied residential building in Kabul. Compared to the baseline single-glazed scenario, the optimized double-glazed window system reduces the peak heating load by approximately 14.9% and the peak cooling load by about 6.2%. These findings highlight the effectiveness of double glazing as an envelope improvement strategy, particularly in cold-dominated climates where winter heat losses through windows are significant.

The reduction in heating load is primarily attributed to the improved thermal resistance of the double-glazed windows. Single-glazed windows have high thermal transmittance, leading to substantial heat loss during cold winter conditions. In contrast, the double-glazed units, consisting of two glass panes separated by an air-filled cavity, lower the overall U-value of the window system, effectively reducing conductive heat transfer. Although previous studies have reported heating energy savings of 25–35% with high-performance double glazing, the 14.9% reduction in this study reflects the relatively high U-value of commercially available double-glazed windows in Kabul. Nevertheless, this improvement represents a meaningful enhancement in energy efficiency and indoor thermal comfort.

Even though Kabul has a predominantly heating-dominated climate, double-glazed windows also help reduce the cooling load. The 6.2% decrease in cooling demand is mainly due to the lower solar heat gain coefficient (SHGC) of the double-glazed windows, which limits the transmission of solar radiation into indoor spaces during summer months. This modest reduction in cooling load is consistent with Kabul's moderate summer conditions but still provides benefits by reducing peak cooling demand, improving HVAC system efficiency, and lowering operational energy use.

The results indicate that upgrading to double-glazed windows improves the building's thermal performance, reduces unwanted heat transfer, and enhances occupant comfort. While window upgrades alone have a moderate impact compared to insulation improvements, they are especially important for reducing glare, condensation, and thermal discomfort near window zones. Given the widespread use of single-glazed windows in Kabul's residential buildings, installing double-glazed windows is a practical and cost-effective way to enhance energy efficiency, especially when combined with other envelope improvements, such as wall insulation and airtightness measures.

Overall, this study confirms that double-glazed windows are a suitable and recommended solution for residential buildings in cold and semi-cold climates, thereby reducing HVAC energy demand and supporting sustainable building practices in Kabul.

Conclusion

This study assessed the impact of double-glazed windows on HVAC energy demand in a typical mid-rise residential building in Kabul, Afghanistan, using HAP simulations. Two scenarios were evaluated: the baseline single-glazed windows and an improved double-glazed configuration with a 3 mm glass layer and 6 mm air gap. The results clearly demonstrate that upgrading to double glazing leads to a measurable reduction in both heating and cooling loads.

Specifically, the annual heating load was reduced by approximately 14.9% and the cooling load by 6.2%, highlighting the effectiveness of double glazing in cold-dominated climates like Kabul, where winter heating demands are dominant. The reduction in heating load is attributed to the improved thermal resistance and lower U-value of the double-glazed windows, which minimizes heat loss through the building envelope. The decrease in cooling load, although smaller, is linked to reduced solar heat gain, thereby improving occupant comfort during warmer months.

The findings confirm that double-glazed windows are a practical and cost-effective envelope improvement strategy for residential buildings in cold and semi-cold climates. In addition to reducing HVAC energy consumption, upgrading window glazing enhances indoor thermal comfort, reduces condensation and glare near windows, and can support downsizing HVAC equipment due to lower peak loads.

While window upgrades alone provide moderate energy savings compared to wall or roof insulation, they are particularly significant for existing buildings with poor thermal performance. Therefore, promoting the use of double-glazed windows in Kabul's residential buildings can improve energy efficiency, reduce operational costs, and support sustainable building design.

Future work should include economic analyses, evaluation of advanced glazing technologies (such as Low-E or triple glazing), and testing different window-to-wall ratios and orientations to further optimize residential building performance in Afghanistan.

Authors Contributions

- Abdul Rahman Erfan: Conceptualized the study, conducted the research, performed data analysis, and prepared the original draft of the manuscript.
- Mohammad Mustafa Akbari: Supervised the research, provided technical guidance, reviewed the methodology, and contributed to manuscript revision and improvement.
- All authors reviewed and approved the final version of the manuscript.

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