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Research Article

The Determination of the Retrofitting Strategies on Thermal Comfort and Energy Efficiency of Mosques: The Case of Yasamkent Mosque

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Keywords

Mosque,
Thermal comfort,
Energy performance,
Retrofitting strategies.

Abstract

This study aims to address the issue of reducing heating loads in buildings located in cold climates, particularly in buildings of worship, by investigating the effects of various proposals for improvement. These proposals include insulation thickness, transparency ratio, glazing type, and green roof, on the thermal comfort and energy performance of a building situated in a cold-semi-arid climate region. In this research, the Yasamkent Mosque in Ankara, Turkey, was selected as a contemporary architectural example and case study. The effects of retrofitting scenarios on the thermal comfort and energy consumption of the building were evaluated using a simulation program. The results of the study suggest that the optimal retrofitting scenario for the building envelope involves the installation of a green roof and 30% transparency ratio with Low-E glazing, as well as an insulation thickness of 15 cm on the external walls and roof, and 7.5 cm thermal insulation for the floor. These improvements led to a 6% increase in indoor thermal comfort and a 23% decrease in annual energy consumption. This study is expected to contribute to guiding improvements in the energy performance and thermal comfort of existing buildings of worship in colder climate regions.

1. Introduction

The building sector, both directly and indirectly, accounts for 30% of global final energy consumption, or around 3,100 Mtoe, including nearly 55% of global electricity consumption. Furthermore, building operations, such as heating and cooling systems, account for approximately 28% of global CO_2 emissions, making decarbonization a top priority in the fight against global warming [1]. To minimize the demand for fossil fuel burning, new buildings must be responsible and respect the environment. They should decrease the amount of energy required to operate and prioritize using energy from sustainable sources [2]. Unfortunately, most building designers and builders around the world neglect the thermal performance of their structures.

Existing knowledge about design solutions that create thermal comfort conditions in a building is hesitantly applied. Architects must recognize that they need to design buildings with low heating and cooling loads while providing thermal comfort to their occupants. Architects have no choice but to use techniques that help reduce excessive energy consumption in buildings while ensuring an adequate degree of comfort for users. Therefore, architects seek inspiration and incorporate advances from other sectors, including engineering, sophisticated computers, and building science. Building performance is gaining relevance in the architectural industry as an integrated design approach that simultaneously addresses environmental issues and comfort [3].

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Mosque buildings hold a special place among other types of buildings due to their unique functional and operational use. While there have been studies aimed at improving indoor thermal comfort in mosques, the qibla orientation - which differs according to the geography where the building is located - affects mosque architecture and prevents a standardized approach to providing thermal comfort using passive methods. The reason for this lies in the fact that mosque buildings have a unique value and function, and therefore require specific considerations for their design and operation. Furthermore, mosque buildings typically experience intermittent occupancy during the five daily prayers - Fajr (dawn), Dhuhr (after midday), Asr (afternoon), Maghrib (after sunset), and Isha (nighttime) - with full occupancy occurring only during Friday daytime prayers [4][5]. These factors make studies on mosque building energy performance particularly challenging, especially for mosques that are operated using active systems.

In the literature, there are several studies on increasing thermal comfort and energy performance in mosques [6,7]. Al-Homoud et al. (2009) found that thermal insulation significantly affects energy consumption and thermal comfort in mosques located in hot and humid climates [8]. Ibrahim et al. (2014) determined that adding thermal insulation to the roof can sustain suitable thermal comfort conditions [9]. Results on thermal comfort in mosques differ according to climatic regions, and can be improved by approximately 18-21% in hot humid and hot dry climates with thermal insulation, low transparency rates, shading elements, and airtight jackets [10]. In their study, Al Anzi and Al-Shammeri (2010) concluded that improving the building envelope and efficient operation of HVAC systems can save up to 72% in energy consumption in a mosque in a hot and dry climate. They also determined that up to 42% energy savings can be achieved by using thermal insulation on the roof [11]. Another study in a hot and dry climate proved that using thermal insulation for walls and roofs and reducing air infiltration can reduce cooling loads by 26%. Additionally, using retrofit strategies and air conditioning systems can result in a reduction of up to 48% [12]. Alabdullatief et al. (2016) conducted a study to investigate the effect of sustainable techniques on energy consumption in a mosque situated in a hot and dry climate. The study demonstrated that cooling loads could be reduced by up to 10% by implementing green roofs and shading devices for windows [13]. In the same context, Alabdullatief and Omer (2017) examined six different scenarios for a mosque roof in a hot arid climate, including non-insulated roof, insulated roof, insulated roof with chipped stone finishing, insulated roof with a green roof, shaded insulated roof with chipped stone finishing, and shaded insulated roof with a green roof. The results indicated that the insulated roof with a green roof performed the best in terms of reducing annual cooling loads [14]. As demonstrated by these studies, passive design strategies are crucial in sustaining thermal comfort conditions in various climate regions. Implementing passive design strategies can improve the building's thermal performance and reduce energy consumption by 10% [15].

In Turkey, most of the literature focuses on studying the energy performance and thermal comfort of mosque buildings located in moderately humid and Mediterranean climates. Bughrara et al. (2017) found that most discomfort occurs during the winter period in a mosque located in a Mediterranean climate. The researchers suggested adding an underfloor heating system to improve thermal comfort, resulting in a 55% reduction in discomfort time [16]. Although some studies have used active systems [17] and a combination of active and passive design strategies [18], there is a clear lack of studies on mosque buildings in terms of thermal comfort and energy consumption in Turkey, particularly in cold climates. This study will be one of the first to shed light on this field.

The main objective of this research is to investigate the extent to which passive solar design strategies can reduce heating loads in cold semi-arid climates and achieve user comfort. The study also aims to analyze the design approach used in the construction of the Yasamkent Mosque and its effect on users' thermal comfort and energy consumption. This research is expected to provide insights into energy-efficient renovations of mosques in the cold semi-arid climate region.

2. Case Study

To achieve the aims of this study, a case study was conducted in one of the mosques in Ankara, Turkey. The Yasamkent Mosque was selected as the focus of this research. The mosque is situated in a newly developed residential area on the western axis of the Çankaya district in Ankara (see Figure 1). To select a case study that aligns with the study's objectives, certain criteria were established, including:

- The mosque must have passive solar design features.
- The mosque should be simple in design and devoid of any complexity that may negatively impact the measurement and modeling process.

Figure 1. Location of Yasamkent mosque

Apart from being an iconic example of modern mosque architecture, the Yasamkent Mosque incorporates passive solar design strategies within its 40 cm thick concrete walls. The almost south-facing qibla wall is utilized to capture direct solar gain (see Figure 2). Information about the building materials used in the construction of the Yasamkent Mosque was obtained through communication with the designer, and their passive solar design approach is evident from the thick concrete walls (providing thermal mass) and the southern facade with a 95% glazing ratio (acting as a solar collector). Table 1 shows the properties of the building materials. Field measurements of the mosque were taken using the SNDWAY SW-T60 Laser distance meter, and the mosque was modeled using Revit 2020.

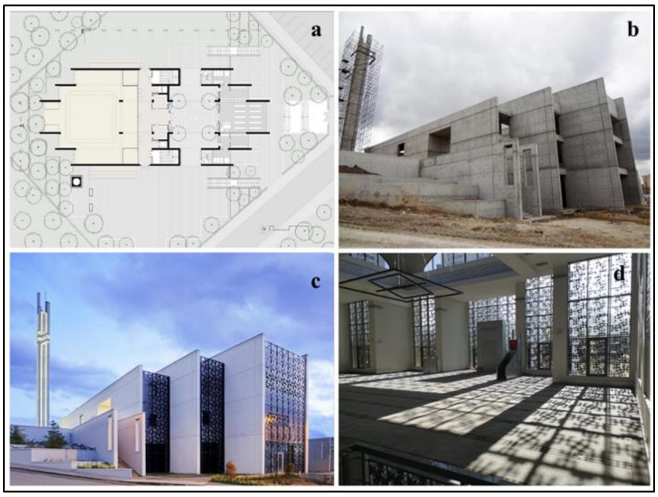

Figure 2. (a) The ground floor of the mosque, (b) The mosque during construction, (c) Outdoor view of the mosque, and (d) Qibla wall [19]

Table 1. Properties of construction materials in Yasamkent Mosque

	Materials	Thickness (mm)	Density (kg/m^3)	Specific Heat (J/kg.K)	Thermal Conductivity (W/m.K)
Wall	Precast concr.	400	2300	657	1.046
	Thermal insul.	50	23	1470	0.035
	Plaster	20	1120	960	0.51
Roof	Gravel	30	1840	840	0.36
	Thermal insul.	35	23	1470	0.035
	Precast concr.	120	2300	657	1.046
	Plaster	20	1120	960	0.51
Floor	Seramic	5	2000	850	1.20
	Mortar	20	1120	960	0.51
	Thermal insul.	50	23	1470	0.035
	Precast concr.	120	2300	657	1.046

Table 2. Properties of the glass material used in Yasamkent Mosque

Material	Thickness	Solar Transmittance	Solar Reflectance	Visible Transmittance	Visible Reflectance	Front Emissivity	Back Emissivity	Conductivity
Glass	6 mm	0.75	0.14	0.80	0.14	0.95	0.50	2.7

2.1. Climate

Ankara is the capital of Turkey and is located at the center of the Anatolian plateau in 39.57 latitudes, and 32.53 longitudes, at an altitude of 894 m above sea level. Ankara has a cold semi-arid climate according to the Köppen classification (BSk) (Figure 3).

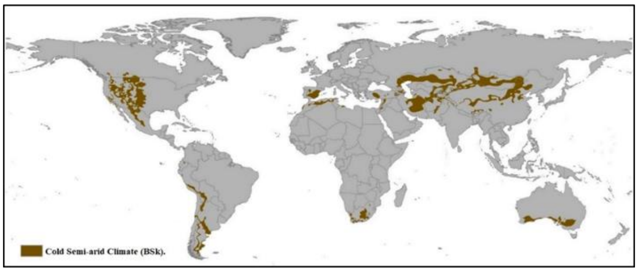

Figure 3. Cold semi-arid climate regions according to Köppen World Map [20]

Weather data for Ankara was obtained from weather maps provided by the Epwmap server at "https://www.ladybug.tools/epwmap/." The weather file data was obtained from Typical Meteorological Year (TMY) data used during the period from 2004 to 2018. Weather data was observed and collected through the Etimesgut Air Base station, located 15 km west of Ankara. The hourly temperature in Ankara ranges between -14 and 37 °C throughout the year. January is the coldest month, with a temperature range of -14 to 13 °C, while July is the hottest month of the year, with an average temperature range of 10.6 to 37 °C. Hourly relative humidity ranges between 13% to 100% throughout the year, with the highest relative humidity occurring in December with an average of 84.4%, and the lowest relative humidity occurring in August, where the average relative humidity was 48.9% (Figure 4).

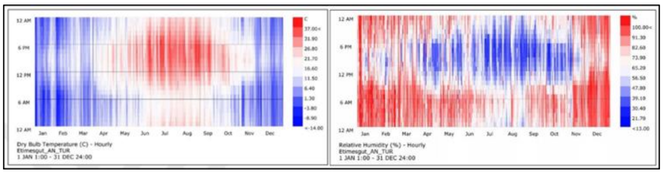

Figure 4. Annual dry bulb temperatures and relative humidity in Ankara by LadyBug Tools

The International Energy Agency (IEA) proposes a model consisting of six climate zones and uses the heating and cooling degree-days method. The suggested base temperature in this model is 18°C (Table 3).

Table 3. Heating and cooling degree-day limits [21]

Climatic Zones	Heating Cooling	Cooling
Cold Climate	2000 ≤ HDD 18 °C	CDD 18 °C < 500
Heating Based Climate	2000 ≤ HDD 18 °C	500 ≤ CDD 18 °C < 1000
Combined Climate	2000 ≤ HDD 18 °C	1000 ≤ CDD 18 °C
Moderate Climate	HDD 18 °C < 2000	CDD 18 °C < 1000
Cooling Based Climate	1000 ≤ HDD 18 °C < 2000	1000 ≤ CDD 18 °C
Hot climate	HDD 18 °C < 1000	1000 ≤ CDD 18 °C

2.2. Simulation Program

Computer simulation software is an essential tool for verifying the performance of buildings, and its potential for further development is limitless. Building performance simulation provides numerous benefits for building stakeholders and the environment [22]. The software enables effective improvement and development of building form, user needs, mechanical equipment and systems, environmental elements, and dynamic interactions of the building with its components and the surrounding environment. As a result, simulation software has become a crucial tool in supporting decision-making in the early design stages to determine the impacts on building performance [23].

Grasshopper has recently been considered one of the most significant building performance simulation (BPS) software tools. It is an open-source tool that only works within the Rhino environment and is primarily used to create generative algorithms for various applications such as creative art, parametric modeling for architecture and structural engineering, digital fabrication, optimization and automation, jewelry design, evolutionary design, and biomimicry [24].Several open-source plugins are available for Grasshopper that deal with BPS. These plugins act as interfaces for preparing the energy model of the building and performing simulations using external simulation engines such as Energyplus, OpenStudio, Radiance, etc. [23]. They can run a wide range of simulation and optimization operations. Ladybug tools and Honeybee tools are the most popular and widely used BPS tools in Grasshopper. Ladybug and Honeybee tools can exchange data with the most distinguished simulation engine EnergyPlus, in addition to other well-known and validated engines such as OpenStudio and Radiance.

Ladybug (LB) is a plugin that works inside Grasshopper. This tool imports weather data in EPW format and analyzes it to understand the site and its climatic conditions. Honeybee (HB) is used to create the energy model and connects it to EnergyPlus and OpenStudio engines to analyze the building performance.

In this study, the mosque was modeled using Revit 2020 and then exported to Rhino 7 for the simulation process using LadyBug and HoneyBee Tools through the Grasshopper plugin, which is developed to work with Rhino software exclusively. The construction materials of the building envelope were established according to their physical and thermal properties using HoneyBee tools. Figure 5 illustrates the preparation of the energy model using the tools utilized in this study.

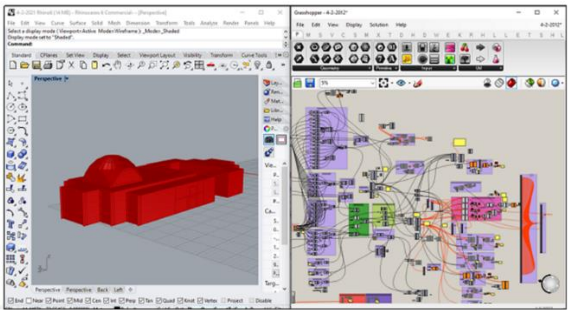

Figure 5. Preparing energy model for the case study

2.3. Data Collection and Calibration

The main objective of this research is to investigate indoor thermal comfort in a cold semi-arid climate. To achieve this, data was collected for six consecutive days during winter, from November 28th to December 3rd, 2020. The indoor temperature data was obtained by placing an Elitech RC-51H data logger (Figure 6) inside the mosque prayer hall. The data logger had a recording interval of one minute. To eliminate external influences and obtain accurate data, the mosque officials were requested not to operate the HVAC system during the data collection period.

Figure 6. RC-51H data logger

The indoor temperature data was collected during the same period as the data recorded by the data logger. The observed data was then compared to the simulation results to validate the accuracy of the study.

To verify the accuracy of both the observed and simulated data, several methodologies have been developed by various organizations. The most well-known calibration models include ASHRAE Guideline 14-2014, the International Performance Measurement and Verification Protocol (IPMVP), and the Federal Energy Management Program (FEMP). Simulation programs and tools have become increasingly important due to their ability to simulate reality and predict results. Simulation tools are considered reliable when their results fall within the margins of error allowed by the criteria set by the aforementioned organizations [25].

In this study, two indicators were used to measure uncertainty, which are compatible with the three protocols:

1) Normalized Mean Bias Error (NMBE). It is the normalization of the MBE indicator, which is used to extend the range of the MBE indicator results to make them comparable. It can be calculated by Eq. (1).

$$NMBE = \frac{1}{\bar{m}} \frac{\sum_{i=1}^{n}(m_i - s_i)}{n-p} \times 100\ (\%) \qquad (1)$$

in where:

$(\bar{m})$ is the mean of observed values,
(m_i) is the observed data,
(s_i) is the simulated data,
(n) is the number of observed points,
(p) is the number of adjustable model parameters that are recommended to be zero (0).

2) Coefficient of Variation of the Root Mean Square Error CV(RMSE). It calculates the variation of errors among observed and simulated data. Also, it demonstrates the capacity of the model to determine the shape of the total load that is reflected in the data. CV(RMSE) can be calculated by Eq. (2).

$$CV(RMSE) = \frac{1}{\bar{m}} \sqrt{\frac{\sum_{i=1}^{n}(m_i - s_i)^2}{n-p}} \times 100\ (\%) \qquad (2)$$

in where:

$(\bar{m})$ is the mean of observed values,
(m_i) is the observed data,
(s_i) is the simulated data,
(n) is the number of observed points,
(p) is recommended to be one (1).

Table 4 presents the acceptable deviation limit values for CV (RMSE) and NMBE. The calibration results of this study revealed an increase in the NMBE value on the first day, reaching -21.17%, and 16.69% on the sixth day. However, it remained within the tolerances set by the three protocols on the second, third, fourth, and fifth days. The average NMBE value over the entire six-day period was 9%. All CV(RMSE) values were within the permissible limits set by the IPMVP, FEMP, and ASHRAE protocols (see Table 5 and Figure 7).

Table 4. Calibration criteria of IPMVP, FEMP, and ASHRAE Guideline 14 [26]

Calibration Type	Index	Acceptable Value		
		IPMVP	FEMP	ASHRAE Guideline 14
Hourly data	NMBE	± 5%	± 10%	± 10%
	CV(RMSE)	20%	30%	30%

Table 5. Calibration data of the case study

Index (Hourly)	Date					
	11/28 /2020	11/29 /2020	11/30 /2020	12/01 /2020	12/02 /2020	12/03 /2020
NMBE %	-21.1	-3.85	-2.11	-9.98	0.26	16.69
CV(RMSE)%	22	14	13	16	7	17

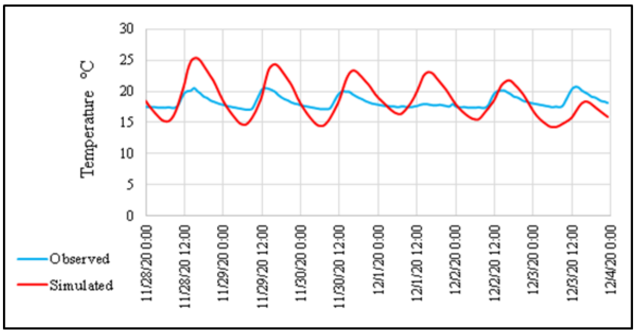

Figure 7. Hourly observed and simulated temperature data

2.4. Retrofitting Scenarios

The main objective of this study is to evaluate the performance of passive solar design systems in providing thermal comfort for users in cold climates. Therefore, the main criterion for evaluating the model's efficiency is how effective it is in reducing heating loads. In this study, five retrofitting scenarios were examined.

Scenario 1: In this scenario, the thicknesses of thermal insulation for the external walls, ground floor, and roof were examined. Four different values of thermal insulation thickness for the external walls, two values for the floor, and one value for the roof were examined, as shown in Table 6.

Table 6. U-value of the building envelope with different thermal insulation thicknesses

	Scenario	Insulation thickness (mm)	U-value (W/m^2-K)
Wall	S_{1a}	80	0.36
	S_{1b}	100	0.30
	S_{1c}	150	0.21
	S_{1d}	200	0.16
Floor	S_{1e}	75	0.43
	S_{1f}	100	0.33
Roof	S_{1g}	150	0.22

Scenario 2: Glazing is a significant element in passive solar design systems as it collects direct sunlight and transmits it inside the building. To ensure the efficient performance of passive solar systems, it is crucial to identify the location and size of the glazing in the building. To achieve this, three different window to wall ratio (WWR) values were examined in this study: WWR 75%, WWR 50%, and WWR 30% (Table 7).

Table 7. Glazing ratio scenarios

Subscenarios	WWR%
S_{2a}	75
S_{2b}	50
S_{2c}	30

Scenario 3: The appropriate type of glazing is crucial for the performance of buildings in cold climates. In this research, various types of glazing were taken into account (Table 8).

Table 8. Properties of glazing types in the Scenario 3

Subscenarios	Glazing type	Thickness (mm)	Air thickness (mm)	U-value (W/m^2-K)
S_{3a}	Triple glazing	6	6	1.19
S_{3b}	Triple glazing	6	10	1.19
S_{3c}	Double glazing low-E	6	12	0.70

Scenario 4: A green roof is a specialized roofing system that meets the requirements of sustainable architecture. Its use has positive effects on the environment, such as reducing energy consumption and minimizing the impact of heat islands on the urban environment. Additionally, it offers the possibility of benefiting from rainwater or recycled wastewater. This study discusses the use of green roofs in general. Specifically, the study examines the extensive green roof as a replacement for the thermal insulation layer and as a supporting layer for the thermal insulation layer. Table 9 provides details about a roof with a green roof system.

Table 9. U-values of green roofs examined

Subscenarios	Roof system	U-value (W/m^2-K)
S_{4a}	Roof with green roof	1.68
S_{4b}	Roof with a green roof and 100mm thermal insulation	0.28
S_{4c}	Roof with a green roof and 150mm thermal insulation	0.20

Scenario 5: In this scenario, a proposed modification to the building envelope was examined. The best variable from each of the previous four scenarios was selected based on the building's performance in reducing heating and cooling loads and improving the thermal comfort level of the indoor environment, while also ensuring the U-values were compatible with the Turkish Standard [27], as shown in Table 10.

Table 10. U-value of building envelope in the retrofitted model

Scenario 5	U-value (W/m^2-K)	TS825 U-value
Wall with 150 mm insulation	0.21	0.50
Floor with 75 mm insulation	0.43	0.45
Roof with a green roof and 150 mm thermal insulation	0.20	0.30
Double glazing low-E	0.70	2.40

3. Results

Existing model: To evaluate the existing building's performance, an energy model was developed using information gathered with Ladybug and Honeybee tools and analyzed through Energy Plus. As shown in Table 11 and Figure 8, the heating load was 76.20 kilowatt-hours per square meter. Despite the building envelope's high thermal mass, the thermal insulation layer with a thickness of 5 cm for the external walls was insufficient to meet the acceptable value in the Turkish standard (TS 825), as were the roof with 10 cm of insulation and the floor with 5 cm of insulation. Moreover, despite Ankara's temperate summer climate, the cooling loads amounted to 65.75 kilowatt-hours per square meter. The glazing facade facing south with a glazing ratio of 90% was the primary factor increasing the indoor temperature during the summer. This transparent surface leads to increased solar gains during the summer because of the extended daylight hours and sunlight exposure.

Table 11. Annual heating and cooling loads for the existing model by floor area (kWh/m^2)

Loads	Energy use intensive (EUI) kWh/m^2	Total
Heating	76.20	141.95
Cooling	65.75	

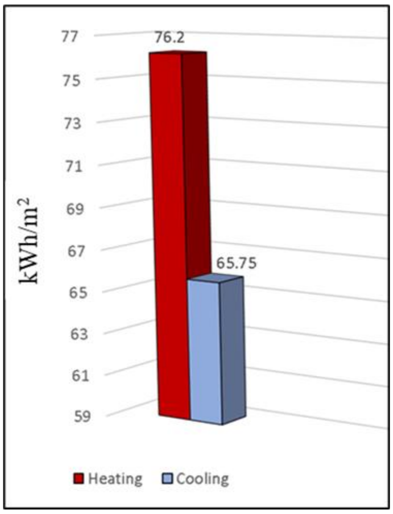

Figure 8. Annual heating and cooling loads for the existing model by floor area (kWh/m^2)

The thermal comfort of the existing envelope was evaluated during the field measurement period according to the ASHRAE 55 standard. The results showed that the users were dissatisfied most of the time (Figure 9).

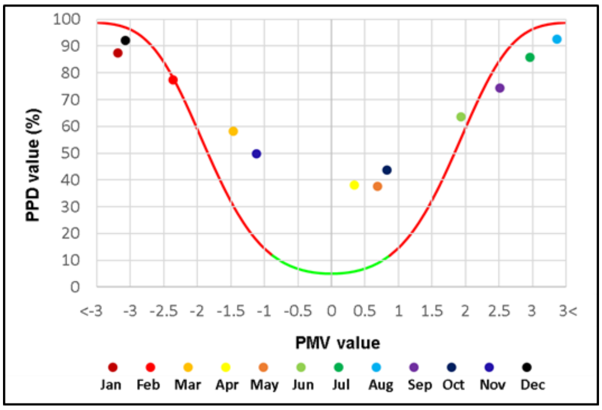

Figure 9. The monthly average of PMV and PPD values for the existing building

Scenario 1: According to the results, increasing the thickness of the thermal insulation of the external walls has a positive role in reducing energy consumption, which is consistent with the conclusions in the literature. In this study, increasing the external wall insulation thickness reduced the annual energy consumption by 3% (Table 12). Moreover, increasing the thickness of the thermal insulation of the floor was also examined, but it did not lead to significant results in reducing energy consumption. On the contrary, increasing the insulation thickness of the floor raised cooling loads. Additionally, increasing the thermal insulation thickness for the floor raised the total energy consumption. The results showed that increasing the thermal insulation of the roof reduced heating loads by 3% and cooling loads by 0.40%. Moreover, increasing the thickness of the roof thermal insulation reduced total energy use by 2%.

Table 12. Annual heating and cooling loads for each thickness of thermal insulation by floor area (kWh/m^2)

	Subscenarios	Thermal insul. thickness (mm)	Energy use intensive (EUI) kWh/m^2		Total
			Heating	Cooling	
Wall	S_{1a}	80	73.84	65.96	139.80
	S_{1b}	100	72.91	66	138.91
	S_{1c}	150	71.50	66.12	137.62
	S_{1d}	200	70.71	66.14	136.85
Floor	S_{1e}	75	76	67.13	143.13
	S_{1f}	100	75.95	68.51	144.46
Roof	S_{1g}	150	73.83	65.46	139.29

The results of the thermal comfort analysis showed that increasing the thickness of the thermal insulation of the exterior walls, floor, and roof did not have a significant effect on the indoor environment. The findings suggest that while increasing insulation for the external walls contributes to improving indoor thermal comfort during the heating season, it is not sufficient. Conversely, increasing insulation contributed to a further deterioration in the level of thermal comfort during the cooling season. Additionally, the results indicate that increasing the thickness of the floor's thermal insulation correlates with a decrease in indoor thermal comfort during the cooling season.

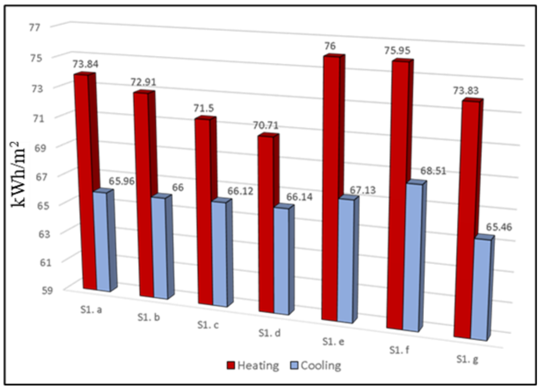

Figure 10. Annual heating and cooling loads for scenario 1

Scenario 2: The results of examining three different glazing ratios on the south facade indicate that higher glazing ratios relative to wall area result in lower heating loads inside the building. Conversely, reducing the glazing ratio increases the heating loads. As shown in Table 13 and Figure 11, reducing the glazing ratio on the south facade has a positive influence on the annual total energy use. According to the results, reducing the glazing ratio achieved an energy saving of 7%.

S_{2a} examined a window-to-wall ratio (WWR) of 75%, which resulted in an increase in heating loads of 0.70%. However, it led to a decrease in cooling loads of 6%. The 75% glazing ratio reduced total energy consumption by 2%, and indoor thermal comfort was slightly improved in summer.the window-to-wall ratio (WWR) of 75%. The results indicated an increase in heating loads of 0.70%. On the contrary, it led to a decrease in the cooling loads of 6%. The glazing ratio of 75% reduced the total energy consumption by 2%. In addition, indoor thermal comfort was slightly improved in summer.

S_{2b} examined a window-to-wall ratio (WWR) of 50%. According to the findings, the heating demand increased by 4%. On the contrary, it resulted in a 16% decrease in cooling loads. The 50% glazing ratio reduced total energy use by 5%. Furthermore, in summer, indoor thermal comfort improved further compared to scenario S_{2a}.

S_{2c} evaluated a window-to-wall ratio (WWR) of 30%. According to the findings, the heating demand climbed by 8%. On the contrary, it resulted in a 24% decrease in cooling loads. Therefore, indoor thermal comfort increased in the summer compared to scenarios (S_{2a}) and (S_{2b}), whereas it significantly decreased in the winter. The 30% glazing ratio saved total energy use by 7%.

Table 13. Annual heating and cooling loads for each supposed glazing ratio by floor area (kWh/m^2)

Scenario	Glazing ratio (%)	Energy use intensive (EUI) kWh/m^2		Total
		Heating	Cooling	
S_{2a}	75	76.75	61.84	138.59
S_{2b}	50	79.51	55.34	134.85
S_{2c}	30	82.76	49.89	132.65

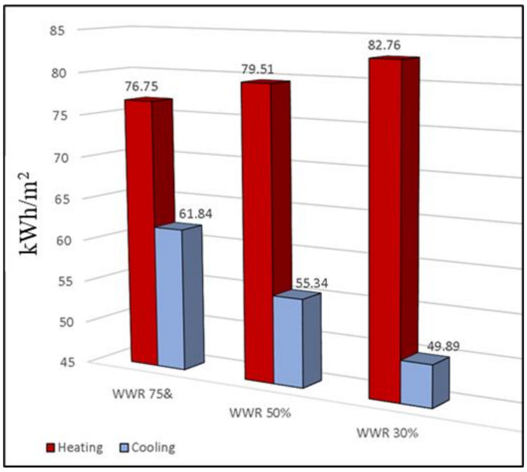

Figure 11. Annual heating and cooling loads for each supposed glazing ratio by floor area within Scenario 2 (kWh/m^2)

Scenario 3: Through the simulation process, it was observed that increasing the thickness of the air gap between the glass panels in the triple glazing system had no effect on energy consumption. Moreover, the research confirmed that using low emissivity glass panels (Low-E) can save 16% of energy consumption, as shown in Table 14 and Figure 12.

Table 14. Annual heating and cooling loads for each glazing type within Scenario 3 (kWh/m^2)

Sub scenario	Glazing type	Energy use intensive (EUI) kWh/m^2		Total
		Heating	Cooling	
S_{3a}	Triple glazing with 6 mm cavity	71.05	60.19	131.24
S_{3b}	Triple glazing with 10 mm cavity	71.05	60.19	131.24
S_{3c}	Double glazing with Low-E panels	55.33	63.73	119.06

S_{3a} evaluated the use of a triple glazing system with an air cavity that has a 6 mm thickness. The results revealed a 7% improvement in decreasing heating loads. Moreover, it resulted in an 8% decrease in cooling loads. By using this glazing system, the total energy consumption was decreased by 8%. In terms of indoor thermal comfort, there was no noticeable effect.

S_{3b} examined the installation of a triple glazing system with a 10 mm thick air cavity. The results were the same as in scenario (S_{3a}), indicating that increasing the thickness of the air cavity in the triple glazing system had no influence on its performance.

S_{3c} examined the use of a double-glazing system with Low-E panels and a 12 mm thick air cavity. The results showed a 27% reduction in heating loads. Furthermore, it resulted in a 3% reduction in cooling loads. The total energy usage was reduced by 16% by employing this glazing system. In terms of indoor thermal comfort, there was a slight reduction in winter.

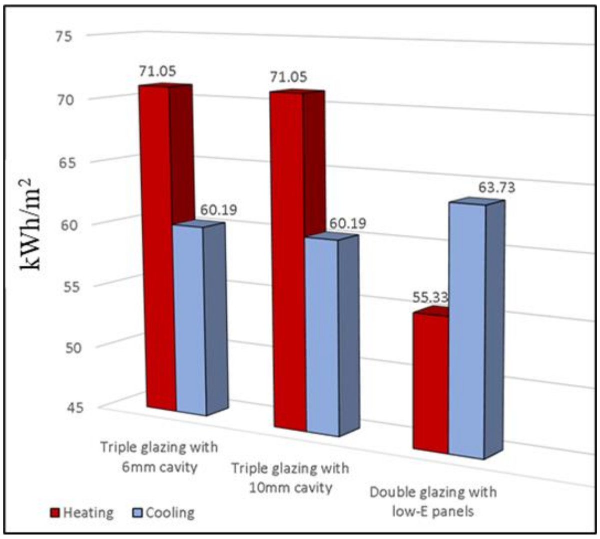

Figure 12. Heating and cooling loads for WWR values by floor area within Scenario 3 (kWh/m^2)

Scenario 4: To assess the effect of using a green roof in cold climates, three scenarios were conducted: the roof was examined with an extensive green roof and a thermal insulation layer of 100 mm thickness, the roof with an extensive green roof and a thermal insulation layer of 150 mm thickness, and the roof with an extensive green roof without thermal insulation. The findings are presented in Table 15 and Figure 13.

Table 15. Annual heating and cooling loads for the green roof within Scenario 4 (kWh/m^2)

Sub scenario	Green roof	Energy use intensive (EUI) kWh/m^2 Heating	Cooling	Total
S_{4a}	Green roof with 100 mm insulation	73.28	66.79	140.07
S_{4b}	Green roof with 150 mm insulation	71.95	66.31	138.26
S_{4c}	Green roof without insulation	88.96	71.25	160.21

S_{4a} examined the performance of the roof with a green roof and a thermal insulation layer of 100 mm thickness. The results showed a 4% reduction in heating loads. However, it resulted in a 1.5% increase in cooling loads. The total energy usage was slightly reduced by 1%. In terms of indoor thermal comfort, there was no noticeable effect.

S_{4b} evaluated the influence of the roof with a green roof and a 150-mm-thick thermal insulation layer. Heating loads were reduced by 6% as a result of the findings. However, it resulted in about a 1% increase in cooling loads. The total energy consumption was reduced by 2%. There was no obvious influence on indoor thermal comfort.

S_{4c} assessed the impact of a green roof without a thermal insulation layer on the roof. The thermal loads increased significantly in this scenario, with the heating demands increasing by 14%. Furthermore, cooling loads increased by 8%. The total amount of energy consumed has increased by 11%. Moreover, indoor thermal comfort deteriorated.

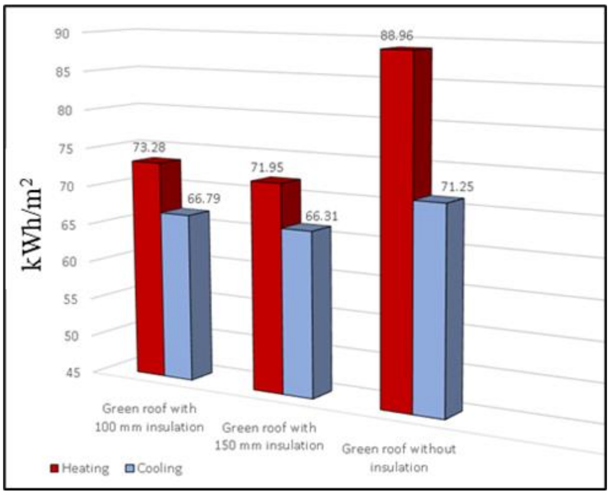

Figure 13. Heating and cooling loads for the green roof by floor area within Scenario 4 (kWh/m^2)

Scenario 5: The study examined external walls with a thermal insulation thickness of 150mm, a roof with a green roof and a thickness of 150mm, and a floor with 75mm thermal insulation to achieve the required level of U-value specified by the Turkish standard (TS825). Based on the results of Scenario 2, a glazing ratio of 30% was deemed the most appropriate for the case study and was used in combination with a double-glazing system that has Low-E panels.

The results of this scenario demonstrate the significant impact of retrofitting the existing building envelope on reducing thermal loads inside the building. With the proposed retrofit of the building envelope, heating loads were reduced by 25%. In addition, this scenario achieved a 22% reduction in cooling loads. Moreover, total energy consumption was reduced by 23% compared to the existing building, as shown in Table 16 and Figure 14.

Table 16. Annual heating and cooling loads the retrofitted model (S_5) by floor area (kWh/m^2)

Loads	Energy use intensive (EUI) kWh/m^2	Total
Heating	57.50	108.91
Cooling	51.41	

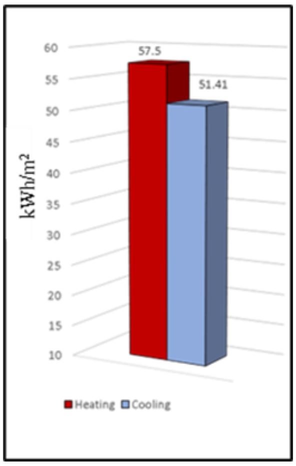

Figure 14. Heating and cooling loads for the retrofitted model (S_5) by floor area (kWh/m^2)

Additionally, with the proposed retrofit of the building envelope, indoor thermal comfort was improved, especially during the winter. However, this improvement did not reach the level suggested by the ASHRAE standard (as shown in Figure 15).

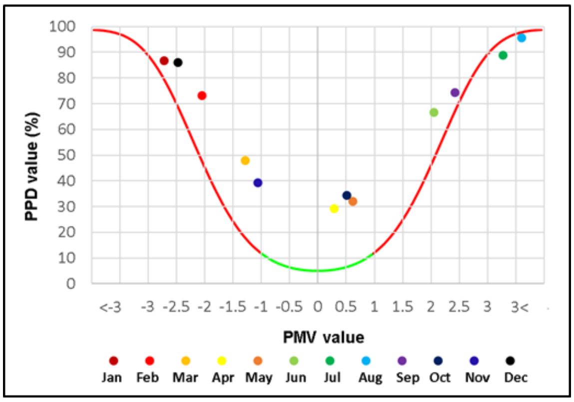

Figure 15. The monthly average of PMV and PPD values for the scenario 5

Through the proposed retrofitting in Scenario 5, a significant improvement was observed in the level of energy performance in the building. These improvements contributed to reducing the annual consumption rate by 23% compared to the existing building, as shown in Table 17.

Table 17. Comparing the annual consumption of retrofitting strategies with the existing model and Scenarios 1-5

Scenarios	Energy use intensive (EUI) kWh/m^2	(-)% decrease (+)% increase
Existing model	141.95	0
Walls with 80mm insulation (S_{1a})	139.80	-1.5%
Walls with 100 mm insulation (S_{1b})	138.91	-2%
Walls with 150 mm insulation (S_{1c})	137.62	-3%
Walls with 200 mm insulation (S_{1d})	136.85	-3.5%
Floor with 75 mm insulation (S_{1e})	143.13	+0.8%
Floor with 100 mm insulation (S_{1f})	144.46	+1.7%
Roof with 150 mm insulation (S_{1g})	139.29	-1.8%
WWR 75 % (S_{2a})	138.59	-2%
WWR 50 % (S_{2b})	134.85	-5%
WWR 30 % (S_{2c})	132.65	-6.5%
Triple glazing with 6mm cavity (S_{3a})	131.24	-7.5%
Triple glazing with 10mm cavity (S_{3b})	131.24	-7.5%
Double glazing with low-E panels (S_{3c})	119.06	-16%
Green roof with 100 mm insulation (S_{4a})	140.07	-1%
Green roof with 150 mm insulation (S_{4b})	138.26	-2.5%
Green roof without insulation (S_{4c})	160.21	+13%
Retrofitted model (S_5)	108.91	-23%

4. Conclusion and Suggestions

This study aimed to investigate the effectiveness of passive solar design strategies in cold and semi-arid climate areas, and was conducted in Ankara, Turkey, through the Yasamkent mosque. The methodology involved establishing retrofitting strategies in the case study, including thermal insulation for walls, floor, and roof, examining various values of glazing ratio and different types of glazing systems, and examining the effectiveness of green roofs.

According to the results, the glazing ratio has a significant impact on increasing and decreasing thermal loads, but the effect varies depending on the climate. In the winter, increasing the glazing ratio can significantly reduce heating loads, while a high glazing ratio will cause a significant increase in cooling loads in the summer. Therefore, more intensive studies are required to achieve satisfying results, especially in places with cold winters and hot summers. The results also reveal that the use of low-emissivity glass has an enormous effect on energy performance, especially heating energy, as it contributed to reducing heating loads by 27% compared to the existing building. In addition, establishing a green roof without thermal insulation has a negative effect on energy performance, as it increases energy consumption by 11% compared to the existing condition.

The fifth scenario was considered the best-performing scenario for the case study. Retrofitting the building envelope had a positive effect on reducing heating and cooling loads, except for a 4% increase in heating loads compared to the existing building when using low-emissivity glass. This was due to a lower transparency ratio (30%) on the south facade of the retrofitted building envelope, which decreased the amount of solar energy gained during the winter compared to the existing building with 90% transparency on the south facade.

While scenarios 1-4 did not result in an improvement in indoor thermal comfort, a weak improvement (up to 6% compared to the existing model) was observed in scenario 5. However, this improvement did not meet the ASHRAE standard's required level.

Based on the results of this study, it can be stated that the building envelope has a primary impact on indoor thermal comfort and the rate of energy consumption. Retrofitting and improving the building envelope will lead to both improving the level of indoor thermal comfort and reducing energy consumption.

The study's results indicate that retrofitting and improving the building envelope can significantly impact indoor thermal comfort and energy consumption. This study was an exploratory step in studying the performance of mosque buildings in a cold, semi-dry climate, highlighting the potential of retrofitting systems to enhance building performance using passive design strategies. However, further studies focusing on specific variables, such as:

- Examining the effect of different insulation materials and thicknesses
- Investigating the impact of shading devices on reducing cooling loads
- Studying the effect of incorporating renewable energy sources in mosque buildings

- Studying the effect of integrating the use of passive technique/s and active systems.
- Conducting a numerical study supported by measurements throughout the year.
- Conducting an optimization study to determine the optimum window-to-wall ratio (WWR) for the Qibla wall.
- Studying indoor thermal comfort supported by a questionnaire survey to compare actual and predicted mean votes.
- Study of different types of thermal insulation materials.
- Since passive solar design systems require air-tightened building envelopes, studies should be carried out on the effect of these systems on indoor air quality could provide more detailed insights into improving the energy performance and thermal comfort of mosque buildings in similar climatic regions.

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Conflict of Interest Statement

The authors declare no conflict of interest.

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