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Determination of Optimum Envelope of Religious Buildings in Terms of Thermal Comfort and Energy Consumption: Mosque Cases

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Abstract: Mosques are quite different from other building types in terms of occupant type and usage schedule. For this reason, they should be evaluated differently from other building types in terms of thermal comfort and energy consumption. It is difficult and probably not even necessary to create homogeneous thermal comfort in mosques' entire usage area, which has large volumes and various areas for different activities. Nevertheless, energy consumption should be at a minimum level. In order to ensure that mosques are minimally affected by outdoor climatic changes, the improvement of the properties of the building envelope should have the highest priority. These optimal properties of the building envelope have to be in line with thermal comfort in mosques. The proposed method will be a guide for designers and occupants in the design process of new mosques or the use of existing mosques. The effect of the thermal properties of the building envelope on energy consumption was investigated to ensure optimum energy consumption together with an acceptable thermal comfort level. For this purpose, a parametric simulation study of the mosques was conducted by varying optical and thermal properties of the building envelope for a temperature humid climate zone. The simulation results were analyzed and evaluated according to current standards, and an appropriate envelope was determined. The results show that thermal insulation improvements in the roof dome of buildings with a large volume contributed more to energy savings than in walls and foundations. The use of double or triple glazing in transparent areas is an issue that should be considered together with the solar energy gain factor. Additionally, an increasing thickness of thermal insulation in the building envelope contributed positively to energy savings. However, the energy savings rate decreased after a certain thickness. The proposed building envelope achieved a 33% energy savings compared to the base scenario.

Keywords: religious buildings; thermal comfort; energy consumption; building envelope

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1. Introduction

Mosques are religious buildings used at different times of the day, with varying user densities and types and where many people can worship at the same time. The formal and physical properties of the mosques vary according to parameters such as culture, geography, and topography. However, the orientation of mosques should always be towards Mecca (Kaaba). The buildings are used for various activities such as worshipping, reading the Qur'an, chatting, and visiting for touristic purposes.

One of the important things that should be considered in building design would be the comfort of the occupants. Thermal comfort is the state of being satisfied with the thermal environment [1]. In order to increase the thermal comfort level of the users in buildings, many studies have been carried out with various methods such as experiments, measurements, and surveys since 1897 [2]. There are many studies to determine the thermal comfort of different building types such as schools, hospitals, offices, and residential buildings in the literature [3–8]. There are various studies to reduce the energy consumption of buildings too [9,10]. An effort has been made to reduce the energy consumption load of buildings with active design parameters and by developing technological facilities [11,12].

The usage density and hours of religious buildings are quite different from building types such as offices, schools, shopping malls, and hospital. There are limited studies on determining the thermal comfort level in religious buildings. The studies generally aim to determine the indoor thermal comfort level [13,14]. The thermal sensations of the users were determined by the survey method in the studies. At the same time, the indoor comfort parameters and the survey results were compared. The results were controlled according to the standards [15,16]. There are studies to reduce energy consumption in the design and usage stages of mosques [17,18]. The suggestions of the studies are presented to improve the current situation. In addition, the improvements are made in terms of energy consumption with active design parameters [19–22].

The acceptable thermal comfort and efficient use of energy in the buildings is an issue that should be considered at the design stage of the buildings. First of all, the building envelope should be improved in order for the buildings to be minimally affected by outdoor climatic changes. There are many studies on the improvement of the building envelope and the effect on energy consumption [23,24]. Tong et al. investigated the indoor temperature relationship of scenarios such as the transparency ratio of the building envelope, the open-closed state of the windows, and the glass solar heat gain coefficient (SHGC) in residential buildings [25]. Additionally, the issues of different materials and new application proposals related to the improvement of the building envelope have been studied [26,27].

There are very few studies on optimum design and building envelope characteristics to ensure the minimum energy consumption of religious buildings. Al-Homoud conducted an optimization study on the design of physical and thermal properties of medium-sized mosques (300 m^2) in the hot-dry and hot-humid climates of Saudi Arabia [28]. Budaiwi et al. studied envelope retrofit and usage schedule alternatives of heating, ventilation, and air conditioning (HVAC) systems to reduce the energy consumption of mosques in hot climates. They presented recommendations about the use of insulation in roof and wall, air infiltration, and air conditioning (AC) operational strategies [29]. Ibrahim et al. proposed improvements in the materials of the roof of a mosque in Sarawak, a hot-humid climate zone. The thermal comfort level was examined according to the Corrected Effective Temperature (CET) index [30]. Majid et al. investigated the effects of orientation and volume differences on thermal comfort and energy consumption in the design of mosques in a hot-humid climate zone [31]. In the literature, there are many studies examining buildings in different climate types in terms of thermal comfort, energy consumption, and building envelope. However, there are a very limited number of the studies examining the building envelope parameters in terms of both thermal comfort and energy consumption of buildings with a specific character such as mosques. In addition, the climate types in which the mosques will be designed are important. The climate type directly affects the envelope organizations of buildings. In conclusion, it is necessary to determine the optimum building envelope properties in terms of energy savings and thermal comfort at the same time. In this sense, this study provides guidelines for designers and users for new mosques or mosques that will be repaired in a temperate humid climate.

The aim of the study was to improve the building envelope properties of mosques to minimize energy consumption while providing an acceptable thermal comfort level. For this purpose, a parametric simulation study of the mosques was conducted by varying optical and thermal properties of the building envelope for a temperature humid climate zone. The simulation results were analyzed and evaluated, and a building envelope proposal was made.

2. Materials and Methods

The most basic type of worship in mosques is "prayer" (salaat). The prayer in the buildings can be done collectively, simultaneously, or individually. The occupants gradually fill the worship place according to the prayer time. However, they leave the building at the same time at the end of the worship. Prayer times vary according to the movement of the sun throughout the year. The occupants pray together at 5 different meals of the day. They can also pray individually at any time of the day. It is necessary to keep the building at a certain level of thermal comfort for individual prayers during worship hours. This situation requires energy consumption. In order to ensure that the mosques are minimally affected by outdoor thermal changes, it is important that the building envelope should be properly designed.

The aim of this study was to improve the building envelope properties of mosques that allow individual and collective worship. Figure 1 shows the stages of the developed method in the study. First of all, a base scenario was created in order to have a reference for other stages and a comparison model. In the second stage, the recommended heat transfer coefficient value of the insulation material to be used in the building envelope and 20 different layer intervals were analyzed. In addition, the recommended heat transfer coefficient for glazed areas and five improvement suggestions were examined. The building envelope scenarios created in the third stage were examined with regard to the overall heat transfer coefficient, the transparent ratio (window-to-wall ratio), the shading element condition, and the thickness of the thermal insulation material. The stages of this study were created in order to determine the amount of saved energy without harming thermal comfort. In this context, the sample mosque models were drawn in the Sketchup program [32]. The building envelope scenarios of the mosques were created through the OpenStudio and EnergPlus programs [33,34]. The scenario results were analyzed on a daily, monthly, and annual basis through the DataViewer program [35].

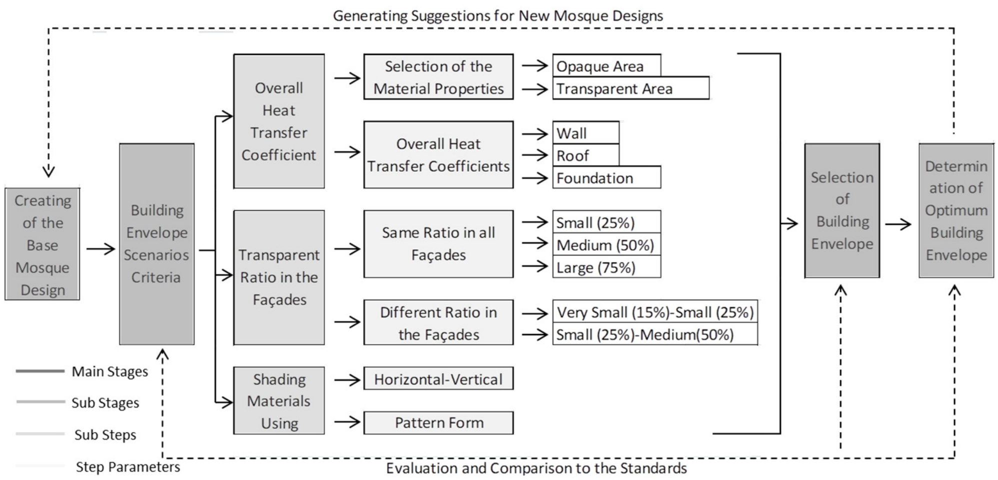


Figure 1. Stages of determining the optimum envelope properties of the mosques.

The thermal comfort analysis of the base mosque and other scenarios were made according to the Predicted Mean Vote-Predicted Percentage Dissatisfied (PMV-PPD) thermal comfort scale in the International Organization for Standardization (ISO) 7730 and the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) 55 standards [36,37]. PMV—PPD thermal comfort scale was recommended as $+0.5 > \text{PMV} > -0.5$ and $10\% > \text{PPD}$ to the acceptable comfort range for newly constructed or used buildings in the standards. For this reason, the acceptable thermal comfort ranges of the scenarios in the mosque usage hours were accepted as the values specified in the standard.

2.1. Introduction of Physical Characteristics and Determination of Base Scenario Properties

Istanbul was chosen as the location of the mosque used in the simulations. It is located in the temperate humid climate zone. The outdoor mean air temperature in Istanbul is 8 °C in winter, 15.9 °C in spring, and 25.0 °C in summer. The yearly mean number of rainy days is 125.1 days [38]. The yearly mean relative humidity is 72.5% [39]. The mosques in Istanbul should be oriented towards the qibla (Mecca) at an angle of 146.7°. This situation directs the design of mosques in the southeast–northwest direction. The climate data introduced to the simulation program were taken from the weather data of the Energyplus program [40].

Determination of Base Scenario Properties

The transparent ratio of the base mosque was 50%, being the same on all façades. A single dome was added to the square base as a planning scheme of the mosque. The total floor area of the mosque was 900 m^2, and its volume was 11,094 m^3. The dimensions and the plan scheme of the base scenario were determined according to the classifications obtained from the literature [41,42]. The heating and cooling system was a fan coil system. The heating of the indoor environment was provided by the boiler water system. In summer, the cooling is done by the chiller water system. The nominal thermal efficiency value of the boiler system was 0.8, and the coefficient of performance (CoP) value of the chiller system was 5.5. The shading element was not used in front of the transparent areas in the base mosque scenario. Double glazing was used in transparent areas. Figure 2 shows the cross-sectional properties of the building envelope components.

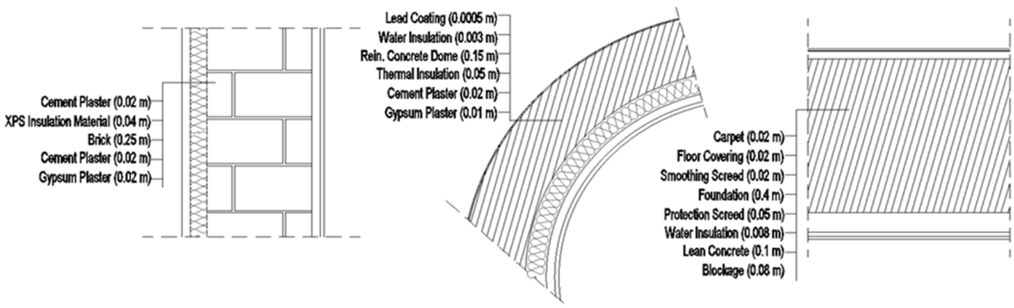


Figure 2. The section properties the building envelope of base mosque scenario.

The properties such as the form and mass organization for the base scenario were kept constant in other scenarios. The optical and thermophysical properties of the building envelope were investigated in terms of energy consumption and thermal comfort. Figure 3 shows the dome and façade organization of the base mosque design.

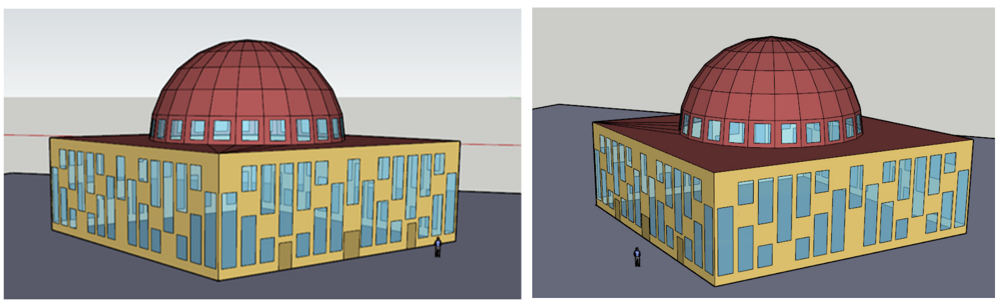


Figure 3. Outdoor façades of the base mosque scenario.

The usage schedule of the mosque was determined according to the usage density of mosques in the literature and the research works of the authors [17,19]. Time, the type of worship, and seasonal changes were taken into account in the creation of usage schedules. Figure 4 shows the usage density on Friday and other days of the base scenario. The occupants' density was determined according to the data obtained from the literature and real conditions [17].

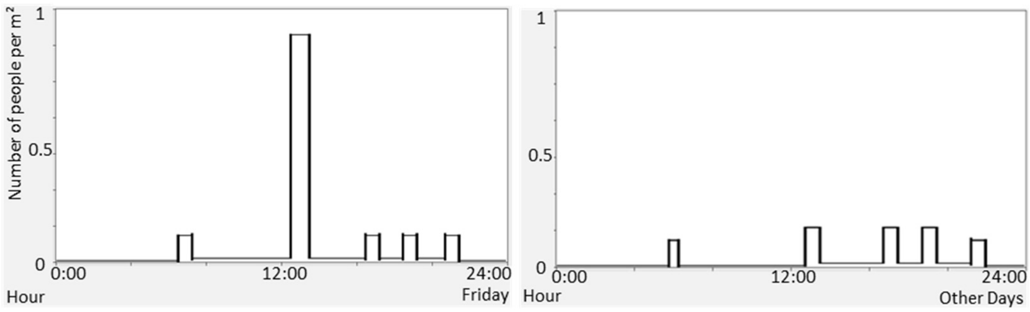


Figure 4. The usage density schedules on Friday and other days (except for Friday) of the base scenario.

Figure 5 shows the heating and cooling system schedule used as a reference in other scenarios. In all scenarios, HVAC system operation was adjusted according to prayer times to ensure thermal comfort. The indoor environment of the mosque scenarios was kept at a certain temperature, except during prayer times. During the heating period, the indoor temperature was maintained at 25 °C in prayer times, at 23 °C during usage hours out of the collective prayer time, and at 15 °C during the hours when the mosque was closed. During the cooling period, the indoor temperature was at 20–22 °C in prayer times, 23–25 °C during usage hours out of the collective prayer time, and it was turned off during the hours when the mosque was closed. In addition, indoor temperature level schedules were introduced to the program in detail according to situations such as Friday prayers, Ramadan tarawih prayers, and seasonal prayer times. The air temperatures at the floor differ from the average temperatures in the mosque, which are usually calculated by simulation programs. This is especially true in high indoor spaces. The real thermal comfort of prayers in a mosque will most likely differ from the calculated one. The mean radiant temperature (MRT) and the relative humidity level were taken from the Istanbul climate file in EnergyPlus weather data. The mean radiant temperature of the scenarios was determined by the zone-averaged MRT calculation type in the program.

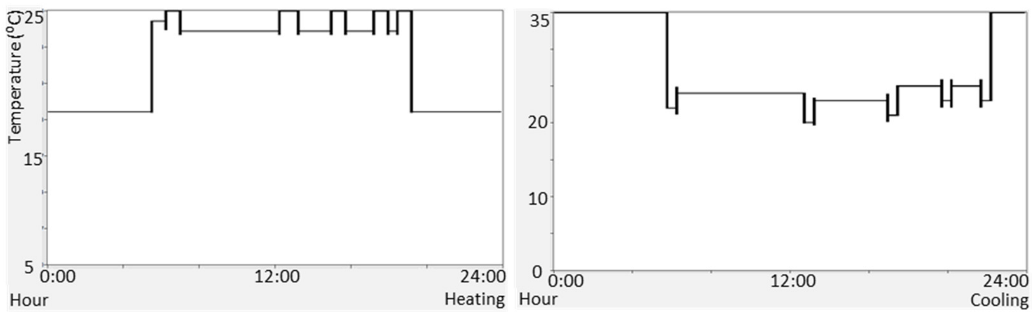


Figure 5. The heating and cooling system schedules of the base scenario.

In all scenarios, the schedules of the mosque such as lighting, the electrical load of the interior equipment, and the airtightness level were processed in detail in the input part of the simulation program. The values in Table 1 were determined according to the values specified in Turkish Standard (TS) 825, taking into account the seasonal changes, the type of worship, and the intensity of the prayer time [43]. The effect of the changed features in the scenarios on the energy consumption will be determined. There are recommended values for thermal comfort parameters in the standards [36,37,44]. The values taken into account in the simulations were determined by benefiting from the studies conducted by the authors for Istanbul through survey, measurement, and observation methods and through the standards [17,19,45]. Table 2 shows the thermal comfort parameters in the scenarios.

Table 1. The physical properties and HVAC system data of the base mosque scenario.

Properties of Base Mosque Scenario			
Transparent ratio	%50—All Façades	Plan Schema	Square
Overall heat transfer Coefficient (W/m^{2}K)	Wall—0.57 Ground—0.36 Roof—0.53 Window—1.8	Dome roofing Plan area Total volume Air exchange rate	Single r = 10 m 900 m^2 (30-30-10) 11,094 m^3 0.5 ach (1/h)
HVAC system type	Fan coil system (natural gas + electricity)	Shading materials (vertical-horizontal or pattern form)	None

Table 2. Thermal comfort level analysis inputs of mosque scenarios.

Parameters/Season	**Winter**	**Spring**	**Summer**
Relative air velocity (m/s)	0.15	0.15	0.15
Clothing insulation (clo)	1.1	0.9	0.5
Metabolic rate (met)	1.3	1.3	1.3

2.2. Other Scenarios Depended on Building Envelope Parameter Change

Other scenarios were created based on the change in the *U*-value, the transparent ratio, and the shading elements. Within the scope of the study, the improved values and limit values specified in the TS 825 standard were examined in terms of the effect on thermal comfort and energy consumption in the scenarios. Table 3 indicates the overall heat transfer coefficients of the building envelope to be considered in the scenarios. The reduction in energy consumption due to changing only the thickness of the thermal insulation material (1 cm intervals) used in the building envelope was also investigated. For this reason, it was analyzed by increasing the thermal insulation material from 0 to 0.2 m on the wall, roof, and foundation.

Table 3. Heat transfer coefficients and thickness range of thermal insulation material in the scenarios.

Building Component	**Improved U Value (W/m^{2}K)**	**The Standard U Value (W/m^{2}K)**	**Insulation Material Location**	**Thermal Conductivity (W/mK)**	**Specific Heat (J/kgK)**	**Density (kg/m^3)**	**Thickness Range (m)**
Wall	0.34	0.57	Wall	0.03	1400	35	0–0.2
Roof	0.25	0.53	Floor	0.03	1400	35	0–0.2
Foundation	0.26	0.37	Foundation	0.03	1400	35	0–0.19
Window	0.92	1.81	Window	Variables: Gas type, U value, SHGC			

Table 4 shows the transparent ratios of the building envelope according to directions. The changes in the transparent ratios on the façades were designed over four levels, taking into account the existing applications. These were very small (15%), small (25%), medium (50%), and large (75%).

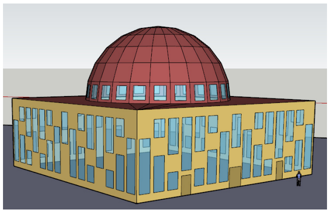
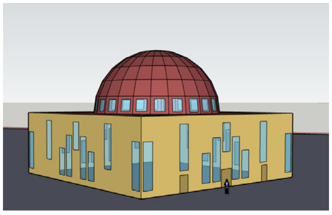
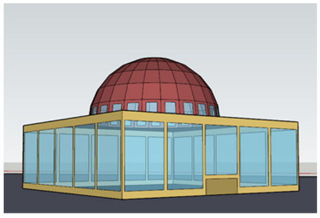
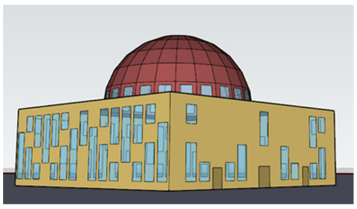
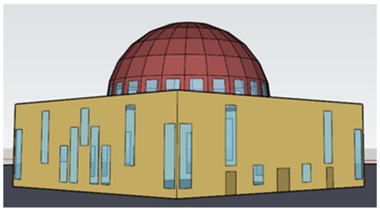
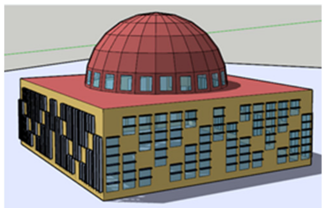
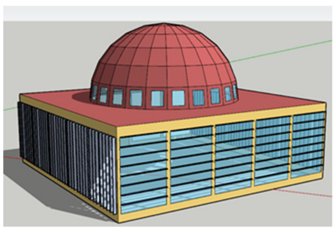
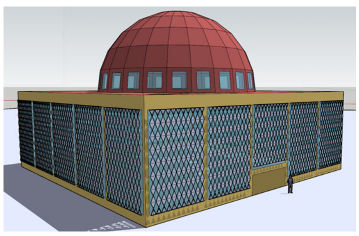
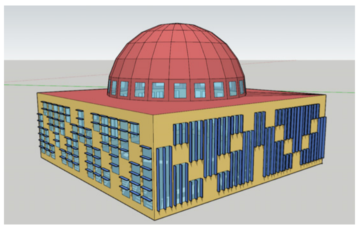
- Scenarios where the same transparent ratios were applied on all façades were 25%, 50%, and 75%.
- The very small rate on the northern façade was kept constant at 15%, while the other façades were scenarios as 25% (small) and 50% (medium).

In cases where the transparent ratio was 50% and 75%, it was tried to reduce the cooling loads by using shading elements in the building envelope. The shading elements were applied as a horizontal–vertical and pattern-decorative form on the envelopes depending on the directions. Calculations regarding the shading elements were made on 21 June at 9:00 on the northeast side of the building, at 12:00 on the southeast side, and at 15:00 on the southwest side. Accordingly, the width of the horizontal shading elements was 0.32 m, and the width of the vertical shading elements was 0.4 m. The pattern shading elements were designed to create 50% transparency on the façades. The unit of the patterns consisting of rhombuses was 0.25 m^2. The building envelope and mosque design properties were used in common with their general properties in the scenario stages. Table 5 shows the façade views of the other scenarios created for comparison according to the base scenario. It is also stated in the parameters changed in the scenarios.

Table 4. Transparent ratios of building envelope according to directions in scenario types.

Directions	Transparent Ratio (%) in the Scenario Types				
North	15	15	25	50	75
South	50	25	25	50	75
East	50	25	25	50	75
West	50	25	25	50	75

Table 5. The changed properties of the building envelope according to Sample A in the other scenarios.

		
All façades transparency: 50%	All façades transparency: 25%	All façades transparency: 75%
Samples A–D	**Sample E**	**Sample F**
		
Variable transparency: 50%–15%	Variable transparency: 25%–15%	All façades transparency 50% with H-V shading elements
Sample G	**Sample H**	**Sample I**
		
All façades transparency 75% with H-V shading elements	All façades transparency 75% with pattern shading elements	All façades transparency 50% with H-V shading elements
Sample J,K	**Sample L,M**	**Sample Optimum Envelope**

Variables/Sample Scenarios		A	B	C	D	E	F	G	H	I	J	K	L	M	O.E.
Transparent area	Same on all façades	-	-	-	-	√	√	-	-	-	√	√	√	√	-
	Variable façade	-	-	-	-	-	-	√	√	-	-	-	-	-	-
Heat transfer coefficient	Opaque areas	-	-	√	√	-	-	-	-	-	-	-	-	-	√
	Transparent A	-	√	-	√	-	-	-	-			√	-	√	√
Shading materials	Horizontal–vertical	-	-	-	-	-	-	-	-	√	√	√	-	-	√
	Pattern form	-	-	-	-	-	-	-	-	-	-	-	√	√	-

3. Results and Discussion

3.1. Effect of Material Properties Change in Base Scenario

The usage amount and type of materials in the building envelope should be considered at the beginning of the design process of the buildings. Material selection and amounts should be at the optimum level based on the climate type and the intended use of the buildings. In order to improve the thermal properties of the building envelope while being provided with the thermal comfort of the indoor environment, the common application is the use of a double-triple glazing window and a thermal insulation material. At the same time, the improvement in the thermal properties of transparent areas is made. However, the optimum use of these materials is important in terms of both the initial investment cost and the reduction in the use of raw materials.

The energy consumption change was investigated by reducing the heat transfer coefficient of the transparent areas. The effect of the improvements made in the glass areas of the base scenario with a 50% transparent ratio was examined on the energy consumption. Table 6 shows the thermal properties of transparent area alternatives. In creating the scenarios, the thermal insulation material was not used on the opaque areas of the mosque building envelope. In this way, only the effect of transparent area improvements was examined. The air and argon gas used in the gaps between the glasses and double-triple glass alternatives were tried. In the simulations, it was noted that the thermal comfort level was within acceptable ranges.

Table 6. The alternative scenarios to transparent area of the mosque envelope.

Scenario's Name	Type	Filling	Glass Layer Types (mm)	Visible Transmittance (%)	Solar Heat Gain Coefficient	U Value (W/m^2K)
W1	Double	Air	4 + 16 + 4	83	0.82	2.7
W2	Double	Air	4 + 16 + 4	73	0.54	1.81
W3	Double	Argon	4 + 16 + 4	73	0.54	1.51
W4	Double	Argon	4 + 12 + 4	73	0.54	1.46
W5	Triple	Air	4 + 12 + 4 + 12 + 4	62	0.46	0.92
W6	Triple	Argon	4 + 12 + 4 + 12 + 4	62	0.46	0.78

Figure 6 shows the energy consumption of different glass alternative scenarios. In comparing W1 and W2 scenarios, there was an increase in energy consumption despite the improvement in the *U*-value due to the decrease in solar energy gain of the transparent areas. This situation shows the benefit of solar energy gain for the heating period. In addition, the reduction in solar energy gain could not balance the increase in the total, although it is beneficial during the cooling period. The contribution of the quality of the gas used and the improvement in the *U*-value were investigated to energy saving. The *U*-value improved with the gas used in the W2 and W3 scenarios. It was same for the SHGC and glass-layer values in the W2 and W3 scenarios. This situation was reflected in the energy consumption. Although triple glass provides benefits in terms of *U*-value, it had a negative effect in terms of solar energy gain. This affected the amount of reduction in total energy consumption. Thermal improvements in transparent areas did not have a large positive effect during the cooling period.

The air or argon gases in the spaces between the glasses did not cause a large difference in terms of energy consumption. Within the scope of this study, when considering the current cost and access conditions of argon gas, it can be thought that the use of air gas in windows is more effective. Improving the *U*-value and solar energy gain in transparent areas greatly affects the total energy consumption. It was seen in the simulation results that the use of double glazing or triple glazing in transparent areas is an issue that should be considered together with the solar heat gain coefficient. The glass type was selected according to the analysis in base and other scenarios.

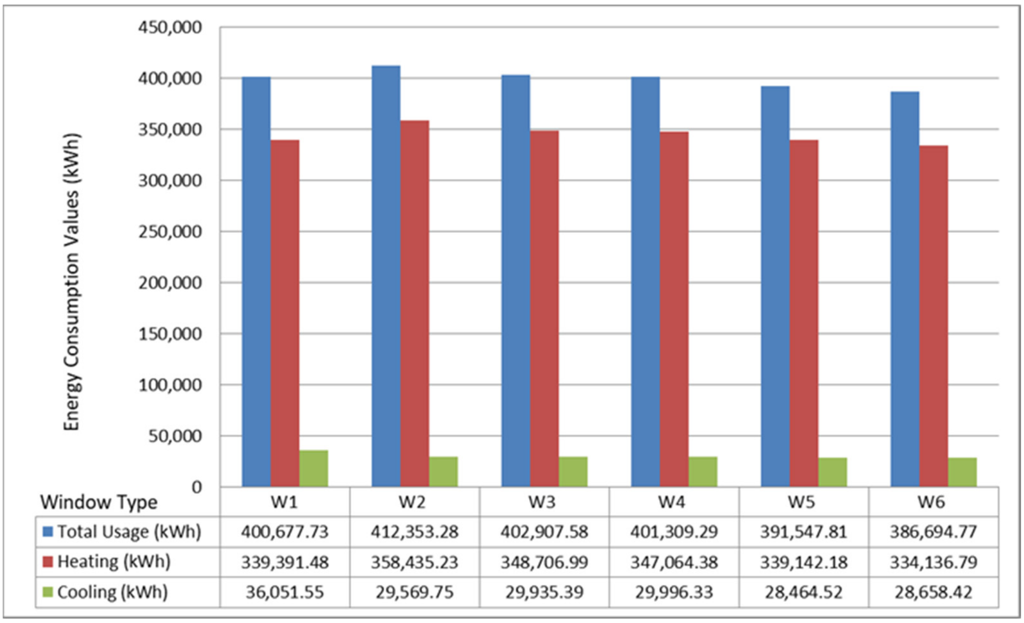


Figure 6. Energy consumption amounts due to improving the thermal properties of the transparent areas.

In this section, while being provided with indoor thermal comfort, the effect of the thickness of the thermal insulation material used in the mosques' building envelope was examined in terms of energy consumption. Table 7 shows energy saving values in terms of insulation material thickness in the building envelope. The analyses were made according to the changed features so that the features of the base scenario (Sample A) remained the same. Energy saving refers to the amount of reduction in energy consumption with the effect of the added thermal feature compared to the absence of any thermal insulation material. The light grey line shows the thickness used in the base scenario, while the dark grey line shows the optimum thickness. After the dark grey line's values, increasing the thickness of the insulation material did not make a significant contribution to energy saving. The determined insulation material thickness and *U*-values were used by crossing each other with different parameters in other scenarios.

Table 7. Energy saving via thermal insulation material thicknesses in the building envelope.

Thickness Ranges (cm)	U Value (W/m^{2}K)	Energy-Saving in Wall (kWh)			U Value (W/m^{2}K)	Energy-Saving in Roof (kWh)			U Value (W/m^{2}K)	Energy-Saving in Ground (kWh)		
		Total Wall	Heating	Cooling		Total Roof	Heating	Cooling		Total Ground	Heating	Cooling
0	1.69	0	0	0	2.49	0	0	0	0.83	0	0	0
1	1.13	20,329	20,603	493	1.44	65,527	65,774	1039	0.67	1227	2463	1105
2	0.85	31,833	32,309	809	1.01	93,435	93,997	1698	0.56	2030	4089	1859
3	0.68	37,858	38,406	958	0.78	109,307	110,127	2169	0.48	2357	5069	2443
4	0.57	42,461	43,112	1114	0.63	119,008	119,960	2429	0.42	2648	5814	2848
5	0.49	45,253	45,965	1210	0.53	125,957	126,985	2598	0.37	2969	326,298	36,877
6	0.42	46,932	47,622	1216	0.46	131,902	133,068	2812	0.34	3033	326,071	37,040
7	0.38	48,577	49,312	1277	0.41	135,658	136,877	2914	0.31	3562	7570	3615
8	0.34	49,946	50,702	1316	0.36	138,863	140,126	3003	0.28	3385	7493	3703
9	0.31	50,965	51,746	1352	0.33	141,281	142,605	3089	0.26	3559	7798	3825
10	0.28	52,397	53,250	1438	0.30	142,364	143,649	3072	0.24	3706	8077	3944
11	0.26	53,098	53,973	1468	0.28	145,093	146,483	3202	0.23	1961	6629	4191
12	0.24	53,763	54,652	1490	0.25	146,624	148,029	3244	0.21	2108	6859	4269
13	0.23	54,392	55,309	1529	0.24	147,910	149,342	3282	0.20	2210	7047	4346

Table 7. *Cont.*

Thickness Ranges (cm)	U Value (W/m^{2}K)	Energy-Saving in Wall (kWh)			U Value (W/m^{2}K)	Energy-Saving in Roof (kWh)			U Value (W/m^{2}K)	Energy-Saving in Ground (kWh)		
		Total Wall	Heating	Cooling		Total Roof	Heating	Cooling		Total Ground	Heating	Cooling
14	0.21	55,009	55,929	1535	0.22	149,104	150,555	3321	0.19	2246	7163	4418
15	0.20	55,422	56,353	1551	0.21	150,131	151,610	3357	0.18	4737	9557	4352
16	0.19	55,810	56,749	1565	0.20	151,043	152,538	3388	0.17	4792	9673	4407
17	0.18	56,151	57,095	1576	0.19	151,882	153,394	3415	0.16	4828	9767	4460
18	0.17	56,472	57,425	1587	0.18	151,616	153,062	3354	0.15	4881	9870	4504
19	0.16	56,802	57,757	1593	0.17	152,223	153,680	3374	0.15	4438	9501	4573
20	0.15	57,029	57,987	1601	0.16	152,724	154,198	3393				

Another parameter that prevents the indoor environment from being affected by outdoor environment changes is the thermal inertia of the building envelope. It prevents and absorbs the transfer of heat to the indoor environment, especially in summer. The building envelope cools down at night. In the winter season, it prevents heat from transferring from the indoor environment to the outdoor environment. It is requested that the phase difference is high and that the thermal amplitude factor is low. However, within the scope of this study, the issue of thermal inertia was left to be examined in future studies.

Figure 7 shows the curves of energy saved by increasing the thickness of the thermal insulation material. The scenarios were created by applying a thermal insulation material to a building envelope component and by not using it to other building components. It was seen that the slope of the curve decreases after a certain thickness in the curves of the thermal insulation material from 0 to 0.2 m on the wall and roof surface. On the other hand, the thermal insulation improvements made in the foundation proceeded linearly in a horizontal direction. The thickness of the thermal insulation of the floor had a minimal effect on energy savings. However, thermal improvements to be made in the roof dome organization of buildings with a large volume, such as mosques, contributed more to energy saving than to walls and foundations.

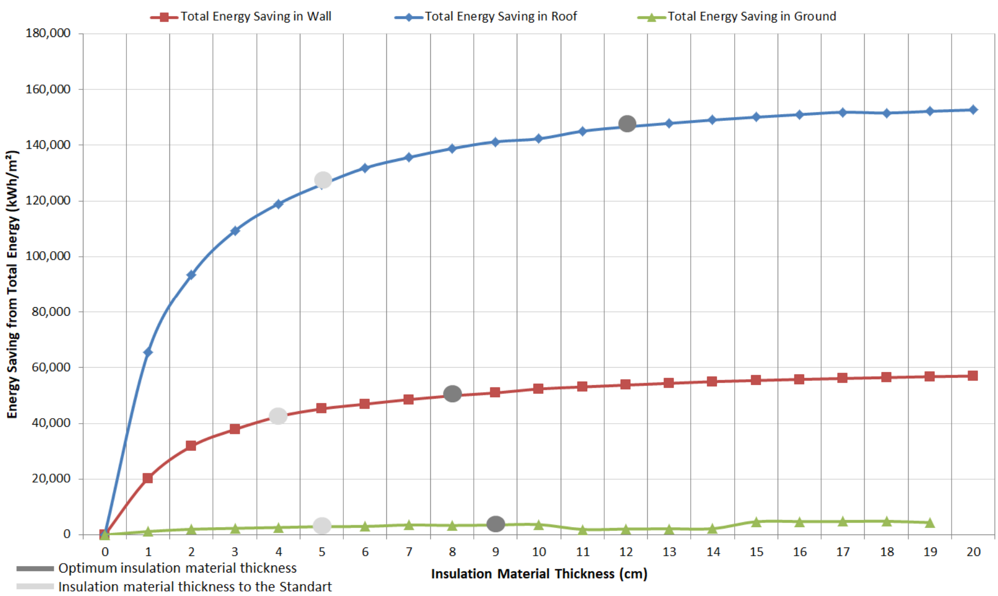


Figure 7. The curves of energy saved by increasing the thickness of the insulation material.

3.2. Thermal Comfort and Energy Consumption of Base Scenario

The thermal comfort level was arranged to be within acceptable ranges according to worship times in the base scenario. The heating and cooling system of the mosque was adjusted to remain at a certain performance, except for the collective prayer times. Figure 8 shows the PMV-PPD level results of the base mosque depending on the selected special days. The suitable conditions were created to achieve minimum energy consumption by being provided an acceptable level of thermal comfort in the mosque. In this scenario, the thermal comfort level remained within the acceptable limits during prayer times. The indoor environment, which was kept at a certain temperature during the night when the mosque is closed, was seen in the thermal comfort level range of +0.5 > PMV > −0.5 during partial usage times. The mosque was generally at the comfort levels indicated in Figure 8 on other days of the year.

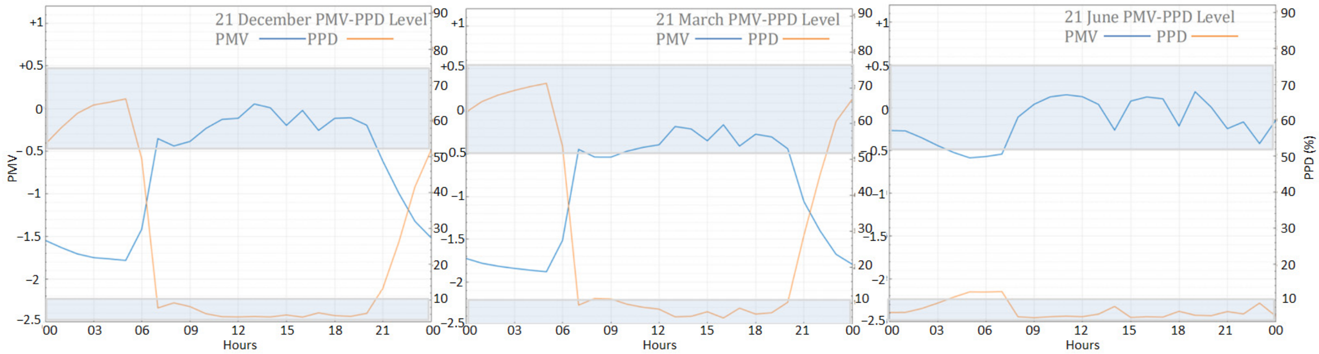


Figure 8. PMV-PPD results of the base mosque scenario on the selected days.

Table 8 shows the distribution of the energy consumption used to create the acceptable thermal comfort level in the mosque scenario. Natural gas energy constituted 61% of the total consumed energy for heating purposes. The electrical energy consumed for cooling was 26% of the total energy. There was energy consumption in the mosque for heating, cooling, lighting and for interior equipment, the pump, and the fan. The total energy consumption of the mosque was 195,700 kWh. The energy consumption per unit area of the mosque was 217.44 kWh/m^2. The amount of energy consumption per unit volume was 17.64 kWh/m^3. The obtained data were compared according to the results of other scenarios.

Table 8. The total energy consumption of the base mosque design.

Energy Usage	GJ	kWh	Energy Usage	GJ	kWh	Unit Area (W/m^{2}K)
Total side energy	704.5	195,700.0	Fan	29.7	8255.6	217.4
Heating	429.8	119,402.8	Lighting	29.8	8288.9	Unit Vol. (W/m^{3}K)
Cooling	184.7	51,322.2	Equipment	22.6	6280.6	17.6

3.3. Comparing to Energy Consumption Data of Other Design Scenarios

A base scenario refers to a set of basic assumptions that are expected to result in the most realistic outcome of a series of events. It allows an analyst to construct variant scenarios by changing key variables to determine the deviation between the variant outcome and the base scenario outcome.

In the scenarios from Sample A to Sample M, the effect of the building envelope overall heat transfer coefficient, the transparent ratio, and the shading element were investigated in energy consumption. The thermal comfort level of each scenario was examined in detail for special days and other days of the year. The scenarios' heating and cooling system schedule was arranged so that the indoor environment remained at an acceptable thermal comfort level. Therefore, other usage schedules except for the HVAC system schedules were the same as the Sample A scenario. The changes in the created scenarios are indicated in the grey boxes in Table 9.

The dimensions of the horizontal shading elements in the south direction and the vertical shading elements in the east and west directions were calculated according to the solar rays' angle on 21 June. The shading elements created for decorative purposes were designed to create a 50% transparent ratio in the building envelope. On the other hand, the optimum envelope scenario was created through the data obtained from the energy consumption of the other scenarios in the study. The overall heat transfer coefficient was improved compared to the Sample A scenario, and the horizontal–vertical shading elements were used in this scenario.

Table 9. The changed properties of scenario types created according to sample A.

Variables	Sample A	Sample B	Sample C	Sample D	Sample E	Sample F	Sample G
Transparent Ratio	50%—all façades	50%—all façades	50%—all façades	50%—all façades	25%—all façades	75%—all façades	50%—3 faç. 15%—North
Overall Heat Transfer Coefficient (W/m^2K)	0.57—wall 0.36—found. 0.53—roof 1.8—win.	0.57—wall 0.36—found. 0.53—roof 0.9—win.	0.33—wall 0.25—found. 0.25—roof 1.8—win.	0.33—wall 0.25—found. 0.25—roof 0.9—win.	0.57—wall 0.36—found. 0.53—roof 1.8—win.	0.57—wall 0.36—found. 0.53—roof 1.8—win.	0.57—wall 0.36—found. 0.53—roof 1.8—win.
Shading Materials	None	None	None	None	None	None	None
Variables	**Sample H**	**Sample I**	**Sample J**	**Sample K**	**Sample L**	**Sample M**	**Opt. Env.**
Transparent ratio	25%—3 faç. 15%—North	50%—all façades	75%—all façades	75%—all façades	75%—all façades	75%—all façades	50%—all façades
Overall Heat Transfer Coefficient (W/m^2K)	0.57—wall 0.36—found. 0.53—roof 1.8—win.	0.57—wall 0.36—found. 0.53—roof 1.8—win.	0.57—wall 0.36—found. 0.53—roof 1.8—win.	0.57—wall 0.36—found. 0.53—roof 0.9—win.	0.57—wall 0.36—found. 0.53—roof 1.8—win.	0.57—wall 0.36—found. 0.53—roof 0.9—win.	0.33—wall 0.25—found. 0.25—roof 0.9—win.
Shading Materials	None	Horizontal–vertical	Horizontal–vertical	Horizontal–vertical	Pattern form	Pattern form	Horizontal–vertical

Figure 9 shows the energy consumption results of 14 scenarios created to determine the mosque's optimum building envelope. The figure also shows the percentage change in the consumption amount of other scenarios by accepting the Sample A scenario as 100%. For example, 25% energy savings were achieved compared to the Sample A scenario in the Sample D scenario. Most energy saving was with the improvement in terms of the overall heat transfer coefficient of the opaque and transparent areas of the building envelope. The highest loss in energy saving occurred when the transparent ratio was 75% and the shading element was in a pattern-decorative form (Sample L).

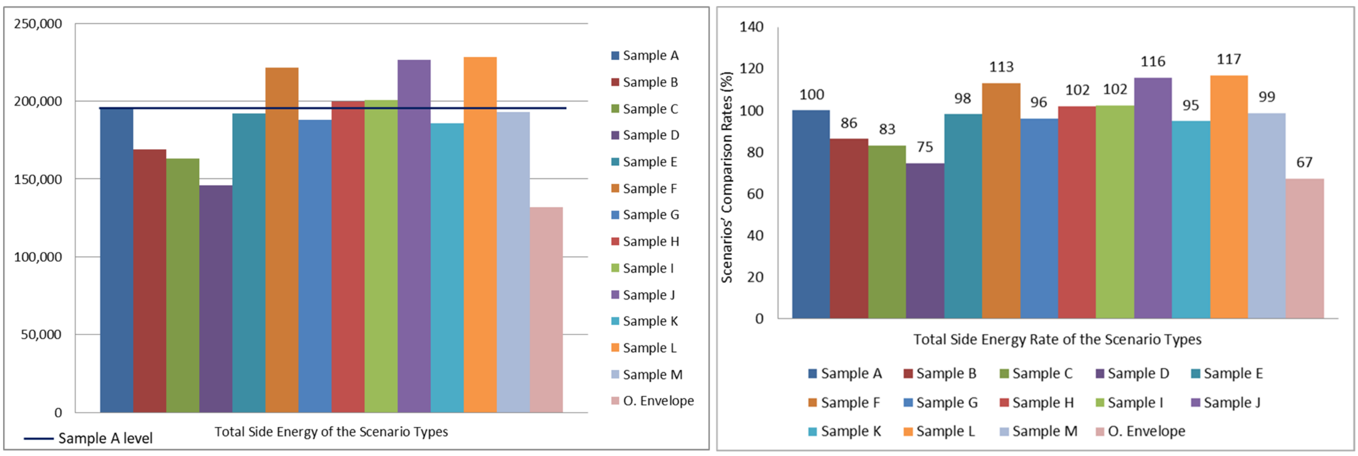


Figure 9. Total energy consumption amounts and rates of sample mosque scenarios.

The improvement in the heat transfer coefficient of only the windows of the building envelope with a 50% transparent ratio obtained a similar amount of energy saving with the improvement in the heat transfer coefficient of all opaque areas (Sample B,C). It is one of the best solutions to improve the heat transfer coefficient of opaque and transparent areas together (Sample D). Increasing the transparent ratio of the building envelope caused an increase in energy consumption (Sample F). As a result of reducing the transparent ratio, there was not a huge change in energy consumption compared to the base scenario (Sample E). However, reducing the transparent ratio reduced the gain of daylight. In addition, various transparent ratios depending on different directions were analyzed. According to the base scenario, there was no large difference in energy consumption (Sample G,H).

The use of shading elements in the building envelope of the base scenario, together with the improvement in the heat transfer coefficient of the transparent areas, made a huge positive contribution. There was no large difference in energy consumption between the horizontal–vertical shading element and the pattern shading element (Sample J,L). However, the horizontal–vertical shading element provided a greater positive contribution in terms of daylight saving and provided more effective visual contact with the outdoor environment.

Figure 10 shows the energy consumption amounts of the HVAC system for the scenarios created by changing the building envelope properties. Reducing the overall heat transfer coefficient contributed positively to the heating energy consumption while making a negative contribution in terms of cooling energy consumption. While the use of shading elements had a negative effect on the heating energy, it had a positive effect on the cooling energy. Reducing the transparent ratio according to base scenario increased the energy consumed for heating. However, it reduced the cooling load. Increasing the transparent ratio of the building envelope reduced the energy consumed for heating, while the energy consumed for cooling increased significantly. This situation was reflected in the total energy consumption of that scenario (Sample F). When the scenarios with a 75% transparent ratio were evaluated between themselves, the shading elements made a positive contribution in terms of the cooling load. However, it was seen that it increased the heating load depending on the glass feature. Reducing the transparent ratio of the building envelope by 15% and 25% decreased the cooling loads and increased the heating loads. This situation caused an increase in the heating consumption of the HVAC system.

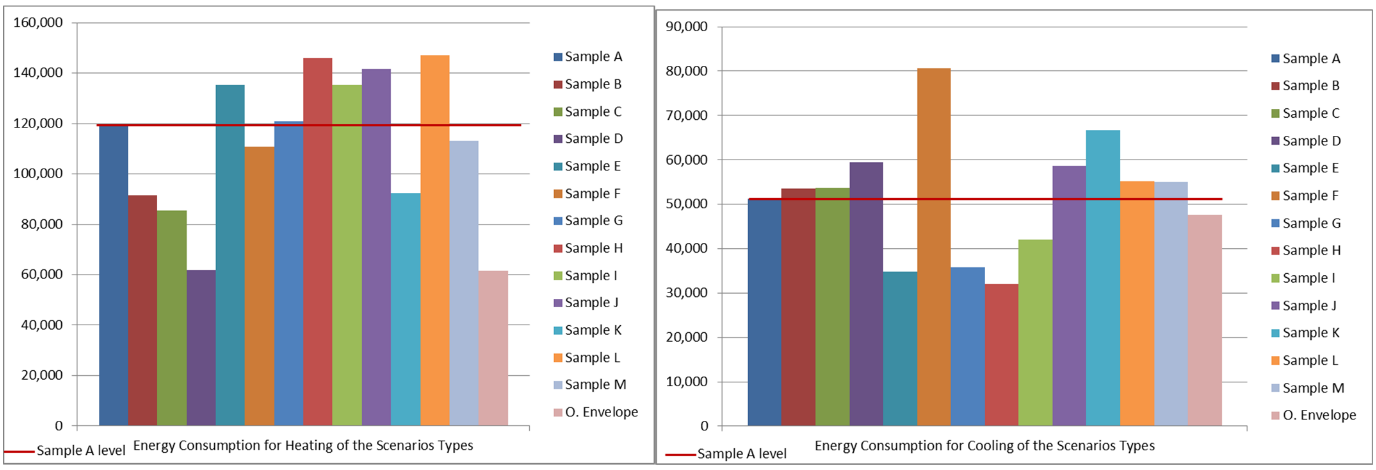


Figure 10. The HVAC system energy consumption amounts of sample mosque scenarios.

It is impossible to select a criterion in the properties of the building envelope in 14 different mosque scenarios. Therefore, there is a necessity for selection and optimization. As a result of the analyses made in the sample mosque scenarios, the improvement in the overall heat transfer coefficient should be applied to all building envelope components (opaque and transparent areas). The transparent ratio of the building envelope may be increased by decreasing the heat transfer coefficient of the transparent areas. In addition, the use of shading elements, when applied individually, increased the energy consumed for heating. In the optimum envelope scenario, the overall heat transfer coefficient of the building envelope components was improved by keeping the transparent ratio at 50%. In addition, horizontal and vertical shading elements were used depending on the directions on the envelopes. In the optimum envelope scenario, a 33% savings was achieved in total energy consumption compared to the base scenario. Further, the energy consumed for both heating and cooling was saved.

4. Conclusions

In this study, the building envelope's thermal properties were examined to minimize energy consumption while ensuring an acceptable level of thermal comfort in mosques. Within the scope of this purpose, the building envelope proposals of the mosques with different optical and thermal properties in the temperate humid climate were scripted through the simulation program. In the scenarios, the building envelope properties were diversified to ensure that the indoor thermal comfort level was minimally affected by the outdoor climatic changes. Consequently, the design suggestions of the building envelope were determined for the newly designed or used mosques.

- Thermal insulation improvements to be made in the roof dome organization of buildings with a large volume, such as mosques, contributed more to energy savings than to walls and foundations.
- The increasing thickness of the thermal insulation material used in the building envelope contributed positively to energy saving. However, the energy saving rate decreased after a certain thickness (wall *U*-value 50 mm-0.48 W/m^2K, roof *U*-value 90 mm-0.32 W/m^2K).
- The thickness of the thermal insulation of the floor had only a minimal effect on energy savings.
- Compared to the base scenario, energy consumption decreased by 33% in the optimum envelope scenario with the made improvements.
- While thermal comfort was provided in the 25%, 50%, and 75% options of the building envelope transparent ratio of the mosques, the minimum energy consumption was at a 25% and a 50% transparent ratio.
- Although the cooling energy load in the indoor environment was reduced, reducing the transparent ratio of the building envelope to 15% and 25% increased the heating load.
- The 75% transparent ratio of the building envelope caused 13% more energy consumption compared to the base scenario.
- Without improving the heat transfer coefficient, the use of shading elements with 75% transparency resulted in 16% more energy consumption.
- The use of a shading element in a temperate humid climate reduced the cooling energy load. However, there was an increase in the heating energy load.
- The shading element had the most positive effect in terms of energy consumption when used together with the improvement in the heat transfer coefficient of transparent areas.
- The use of horizontal–vertical or pattern shading elements (with a 50% transparent ratio) in the building envelope resulted in similar energy savings. When considered together with the daylight gain, horizontal and vertical shading elements depending on the directions were found more appropriate within the scope of the study.
- The thermal inertia of building envelope materials was very important in hot climates. In order to investigate it in future studies, the thermal inertia was excluded from the scope of this study.

The orientation of mosques, more variable transparency ratios, the thermal inertia of building envelope, and HVAC system types are important parameters affecting indoor thermal comfort and energy consumption. These parameters will be discussed more comprehensively in future studies.

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Nomenclature

Acronyms	
HVAC	Heating, ventilation, and air conditioning
AC	Air conditioning
CET	Corrected Effective Temperature
PMV	Predicted Mean Vote
PPD	Predicted Percentage Dissatisfied
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
ISO	International Organization for Standardization
TS	Turkish Standard
SHGC	Solar Heat Gain Coefficient
CoP	Coefficient of Performance
Meaning	
r	Radius
m	Meter
h	Hour
s	Second
ach	Air change per hour
Units	
clo	Clothing insulation
met	Metabolic rate
1/h	Air change per hour

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