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# Development of energy efficient design proposals for air conditioned mosques: Temperate humid climate case

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ABSTRACT

Mosques, which are types of religious buildings, are large buildings where many people pray at the same time. The diversity of the user type and density and the variability of the usage schedule make it difficult to establish the homogeneous thermal comfort of these large-volume public buildings. At the same time, the energy consumption in the buildings should be minimal in nowadays when the conventional energy sources decrease. The aim of this study is to evaluate created design strategies for designers and users in order to minimize energy consumption by determining the passive design criteria and choosing the type of air conditioning equipment while providing an acceptable thermal comfort level in mosques. According to the method created for the aim, the scenarios of mosques were compared in terms of thermal comfort and energy consumption in the temperate humid climate conditions. This method includes the analysis of scenarios created from the change of design parameters of mosques (plan, size, roof type of the mosques) with a simulation software which was validated with actual utility data. The suggestions were presented for the selection and design of the mechanical system as a result of the implementation of the created method. When the design scenarios of mosques are compared, the air conditioning of the indoor with radiant method consumed less energy than HVAC equipment with fan system. In accordance with the plan schemes (square, rectangle, circular), the least energy consumption per unit area was in the circular plan scheme and hemispherical design. Compared to the roof types (single dome, multi dome, pyramidal roof, flat roof), the most energy consumption per unit area was generally in the multi dome design. According to the average energy consumption values of the HVAC systems, there was 23 % less energy consumption in the flat plan type (105.06 kWh/m$^2$) compared to the rectangular plan type (129.2 kWh/m$^2$). In the intermittent use schedule of the HVAC system, 8 % more energy was consumed than in the continuous use schedule. According to the air changes per hour in the mosques, there was 5.93 % more energy consumption in 2 ach conditions compared to 0.5 ach conditions.

## 1. Introduction

There has been an increase of over 19 % in the energy use of buildings in the last 10 years due to global warming and climate change in the world, differentiation of building characteristics according to changing climatic conditions, increase in human population, diversification of building typologies for different needs, etc. [1,2]. Buildings account for approximately 36–40 % of global energy

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demand each year. This corresponds to about a quarter of carbon dioxide ($CO_2$) emissions [3,4]. The increase in energy consumption and demand in buildings affects global warming and climate change negatively. Therefore, passive and active design criteria for reducing energy consumption in the design process of buildings should be considered in detail during the design and usage stages. It is vital that energy is used effectively in buildings that are open to public use, non-residential, and generally use HVAC systems. While using energy effectively in buildings, comfort levels should not be compromised.

Thermal comfort is the state of being satisfied with the thermal environment [5,6]. Thermal comfort affects the health, working efficiency, psychological, physiological, and biological behaviors of building users. In addition, heating and cooling equipment are used for suitable thermal comfort conditions in buildings. When the thermal comfort level is outside of the acceptable ranges, it may cause either the users' discomfort or unnecessary consumption of energy.

Mosques, one of the religious building types, are large buildings that allow many people to pray at the same time. In mosques, people can worship individually or collectively, communicate, read books or use the buildings for religious activities [7]. The users can come together at least five times a day at different times to pray collectively or individually. Prayers are held collectively in important month (Ramadan) and nights (Kandil nights) of the year in the buildings. Mosques usually reach full occupancy at noon on Friday. As can be seen, the mosques have a unique usage schedule. Therefore, the indoor comfort conditions of mosques should be evaluated separately from other building typologies.

Nowadays, many studies are carried out on the thermal comfort and energy consumption of buildings [8–11]. In addition, there are studies on thermal comfort or energy consumption of mosques [12–14]. However, although there are studies on the design and renovation of mosques as well as on thermal comfort and saving energy consumption, they are insufficient [15]. Al-ajmi conducted thermal comfort measurements and surveys in the summer period in six air-conditioned mosques in Kuwait. The thermal sensations (AMV) of the users and Predicted Mean Vole (PMV) index results were different in terms of both temperature and thermal comfort level. PMV index found the environment is 2.8 °C lower [16]. Samiuddin and Budaiwi investigated the effect of HVAC system's air distribution type on thermal comfort of a mosque in Saudi Arabia through the simulation software. They found that ensuring the homogeneity of thermal comfort completely depends on the air diffusion performance index value [17]. Yüksel et al. conducted measurements to improve the thermal comfort and indoor air quality of a typical urban mosque. They made suggestions for the use of fans and air conditioning equipment for mosques with natural ventilation [18]. Mushtaha and Helmy evaluated six cases including shading elements, thermal insulation, and natural ventilation from passive design criteria [19]. Al Homoud et al. made thermal optimization along with physical and usage properties through simulation software for a medium-sized mosque in a hot humid and hot dry climate type. A design guide was presented as a result of the study. With the mosque's envelope optimization, 21 % and 18.8 % savings were achieved in annual energy consumption [20]. Budaiwi evaluated the potential energy savings on envelope design parameters in hot humid climate conditions through simulation software. It was emphasized that the thermal resistance of the roof and the air tightness rate of the mosques were the major factors affecting the energy performance of the mosques [21]. In large-scale mosques, zoning in the prayer area according to the density of users provides significant savings in energy consumption [22]. Ahriz et al. tried to improve the energy performance of mosques in hot dry climate type with architectural design criteria (size, form, openings, etc.). They stated that case studies with specific limitations should be developed and diversified [23]. Reda et al. compared dome and flat roof mosque designs in air-conditioned mosques with measurements and CFD calculations. According to the results, in the hot climate region, the flat roof offers lower indoor temperature than the dome roof [24]. Majid et al. evaluated the effect of thermal penetration on the indoor surfaces of a mosque envelope in Malaysia through simulation software in terms of orientation (wide and narrow sides of the rectangular form) and massing (volume alternatives). Form alternatives with narrow façades directed towards the qibla and large volumes are better in terms of thermal comfort [25]. Bughrara observed indoor climate conditions in a historical mosque in Izmir, Turkey, for one year. The actual data obtained were compared with the dynamic simulation model [26]. The energy performance of mosques can be improved by retrofit work by organizing the HVAC system operation schedule and lighting equipment and arranging the transparent area thermal properties [27]. Budaiwi and Abdou conducted energy simulations on the HVAC system's intermittent use strategies and operational zoning alternatives to increase the energy performance of mosques while providing thermal comfort in hot climates. In their study, they reduced the cooling load by 23 % with the appropriate HVAC usage strategy. In addition, 30 % of savings in the energy use were achieved with appropriate usage of zoning [28]. Diler et al. were investigated retrofit studies in a historical mosque through simulation software. It was stated that intermittent use of the HVAC system can save 46.9 % compared to continuous use [29]. Al Rasbi and Gadi made analyzes with the software in terms of thermal loads in two mosques of historical and contemporary architecture in Oman. According to the study, the cooling loads per unit area are less in the contemporary architecture mosque, but the historical mosque was found to be more successful in terms of passive cooling [30]. Yüksel et al. developed scenarios on the operating strategies of the floor heating system while providing thermal comfort in a mosque in Turkey. They also made measurements and simulations to reduce $CO_2$ emissions. They stated that with the appropriate selection of the operating strategy of the underfloor heating system, the annual $CO_2$ emission and fuel consumption can be reduced by 9 % [31]. In the literature, there is hardly a study on the design criteria in order to keep the thermal comfort level of mosques within acceptable ranges and to minimize the amount of energy consumption in temperate humid climate conditions. However, existing studies have analyzed either HVAC system alternatives or the design of mosques in terms of energy consumption and thermal comfort. They did not focus on this issue holistically. Therefore, there is a need for a holistic method and design strategies that designers and users can benefit from both at the design and at the use phase of mosques.

The aim of this study is to create a method and evaluate design strategies for designers and users in order to minimize energy consumption by determining the passive design criteria and choosing the type of air conditioning equipment while keeping the thermal comfort level in acceptable ranges in mosques. According to the method created for the aim, scenarios consisting of design parameters were analyzed through the simulation software, which was validated with actual data. The obtained simulation results were examined and the energy consumption levels of the design criteria were compared. In accordance with the results, this study presented the energy consumption differences between the design criteria and the appropriate design options for users and designers.

## 2. Methodology

Mosques are generally large-volume, wide single-space public buildings that allow many people to pray at the same time. Prayer is the most basic form of worship in mosques. The worship is done by directing the human body towards the Kaaba. Therefore, the direction of the mosques should be facing Arabia-Mecca. The buildings can be designed in various forms, plan schemes, and sizes according to the needs of the region. Although mosques are worshiped collectively at least five times a day, the users can pray individually at any time of the day. The worship times vary throughout the year depending on the movement of the sun. These situations make it difficult to use energy effectively while keeping the indoor thermal comfort within acceptable ranges. Hence, the energy efficient design of the buildings and the appropriate selection of heating and cooling equipment require both ensuring thermal comfort during use and minimizing energy consumption.

Fig. 1 shows the details of the evaluation stages of the energy efficient design criteria of the mosques created within the scope of the study. The method of the study consists of four main stages: data determination, validation of the software, comparison of the results,

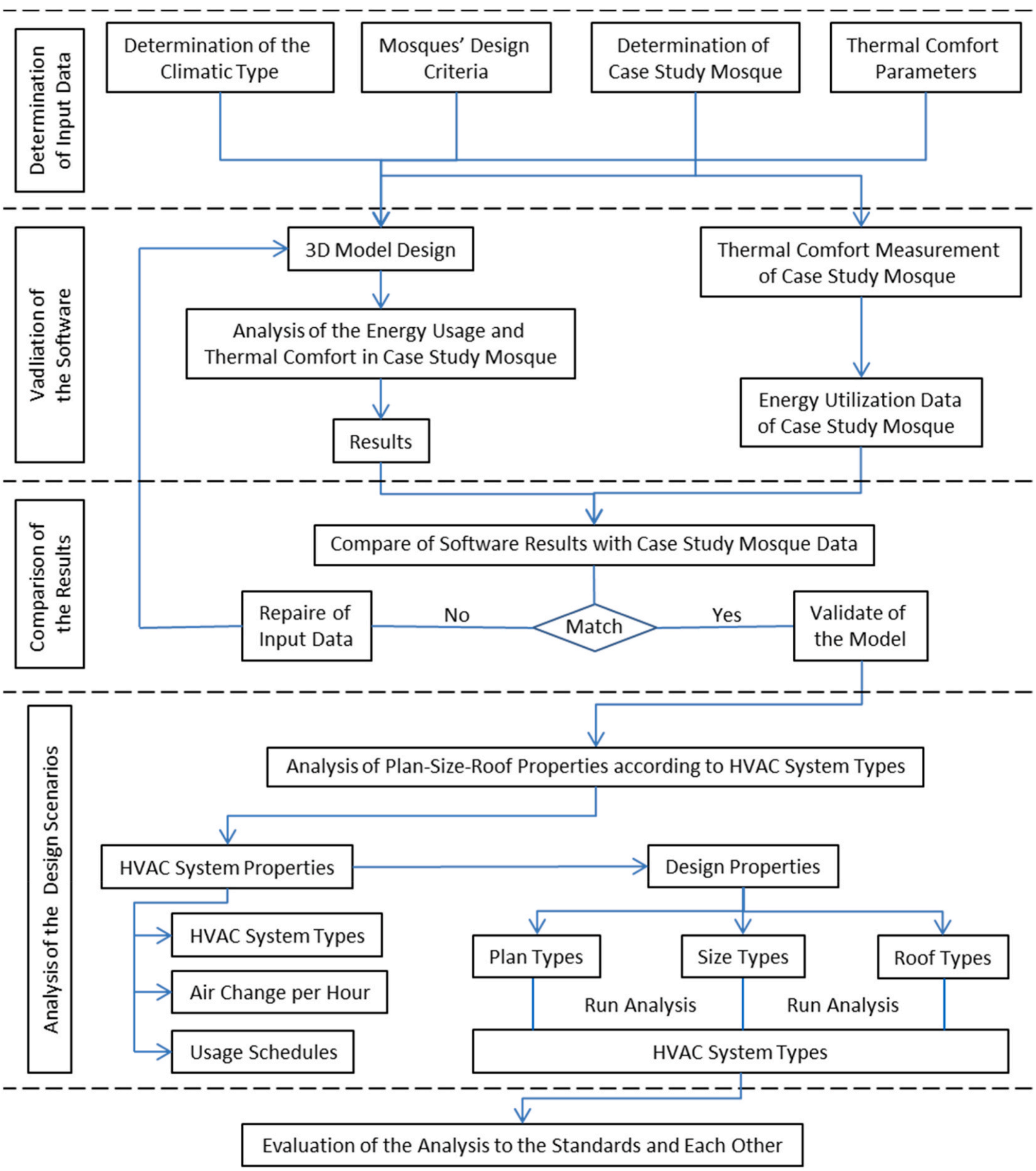


**Fig. 1.** The stages of design strategies of mosques.

and analysis and evaluation of design scenarios. First of all, data collection about the design scenarios, determination of the climate in which the analyzes will be made, the selection of the case study (existing) mosque for the verification of the software and the determination of the appropriate thermal comfort conditions for the comparisons were made. After the determination of the case study mosque, the thermal comfort level and energy consumption data of the selected mosque were obtained [32–34]. In addition, the architectural features of the case study mosque were modeled in the 3D software. In this study, the 3D drawing of case study mosque and other scenarios was made in the SketchUp – 2019 software [35]. The data of the case study mosque were entered into the dynamic building energy simulation software. The thermal comfort and energy consumption simulations were made in the Energyplus-based OpenStudio version 1.1–2021 software, which has a plugin to the 3D software [36,37]. The simulation results were analyzed in detail through the Dataviewer software [38]. In order to make energy consumption simulations, the usage data in actual conditions were obtained from the officials. The obtained simulation software results were compared with the measurement results in actual conditions. If the results match and the software verification were completed, the scenario analysis was started. If the simulation results did not match the actual data, the data entered into the software was repaired by returning to the 3D dimension stage. After the software verification, first of all, the HVAC system properties were analyzed. The heating, ventilation, and air conditioning (HVAC) system type (fan coil system (FCS), heating with hot water radiator and chiller type cooling system (RS), wall mounted split air conditioning system (ACS), underfloor heating and cooling system (FS), ground source heat pump systems (GSHP)), usage schedule of the HVAC system (intermittent and continuous usage), and air change per hour (ach) were analyzed. Ach rates were determined by using the existing values in the literature [21,28,39]. After the HVAC system properties were determined, the simulation scenarios were made according to the HVAC system types and architectural design features of the mosques. Architectural design parameters of mosques were classified as plan type, scale size and roof cover. By comparing the obtained data, design and usage recommendations were created.

### 2.1. *Determination of case study mosque and data collection*

There are 89,302 mosques in Turkey, according to 2022 data of the Republic of Turkey, Directorate of Religious Affairs [40]. Approximately 25 % of this number of mosques is in the Marmara region of Turkey, which also includes Istanbul. It is the city with the highest number of mosques in Turkey with 3554. Case study mosque (Hz. Ali Mosque) selected for the validation of the software is located in the province of Istanbul, which is located in the temperate humid climate zone of Turkey. The annual average temperature of Istanbul is 15.8 °C, the average sunshine duration (hours) is 1.5, the average monthly rain (mm) is 672.8, the average number of rainy days is 115.2 [41]. According to the Turkish Standard (TS) 825, Istanbul is in the 2nd Region on the climate map [42]. According to the Köppen climate classification, it is classified as a climate with mild winters and very hot and dry summers (Csa) ("Turkish State Meteorological Service, accessed 26.06.2023″). The direction of mosques in Istanbul should be directed towards Mecca, Arabia. This situation requires the mosques to be oriented with an angle of approximately 146.7°. Fig. 2 shows the category of Istanbul in the climate maps according to TS 825 (a) and Köppen Climate Classification (b) [43,44].

Fig. 3 shows the climate data of Istanbul between 1987 and 2017. In addition, the climate data of the simulation software are indicated in the figure. Actual data and simulation data were compared. The outdoor average temperature data are very close to each other. Average relative humidity values vary depending on the month.

Hz. Ali mosque was built in 2012 with traditional Ottoman architectural style. Ventilation, heating, and cooling systems in the mosque were designed with traditional methods. The heating and cooling system in Hz. Ali Mosque consists of electrically powered floor heating systems under the carpet and floor-type split air conditioners in front of the walls. The mosque has 11 radiator-type split air conditioners and an electrically operated underfloor heating system under a 220 $m^2$ carpet. The underfloor heating system of the mosque becomes active 30 min before the prayer time during the heating period. The split air conditioners are usually operated on Fridays and other days depending on indoor conditions. The window system allows the indoor environment to be ventilated naturally. Table 1 shows the physical and HVAC system properties of case study mosque. The walls of the building envelope consist of 40 mm stone coating, 50 mm air gap, 250 mm autoclaved aerated concrete (AAC), 50 mm air gap, 250 mm AAC, 30 mm interior plaster, and 10 mm gypsum plaster. There is uncoated double glazing with 16 mm air gap in the windows. The wall to window ratio (WWR) of the mosque is 8.5 %.

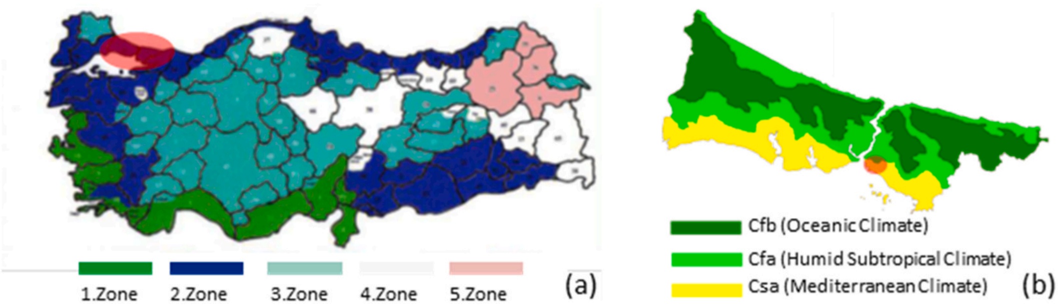


**Fig. 2.** Istanbul's category to TS 825 (a) and Köppen Climate Classification (b).

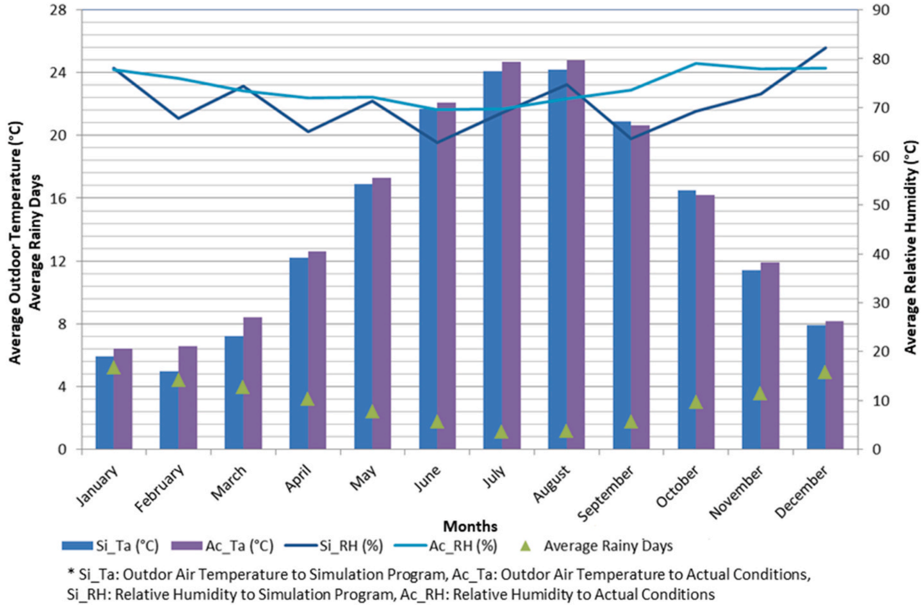


**Fig. 3.** Average climate data of Istanbul between 1987 and 2017.

**Table 1**
HVAC Systems and physical properties of Hz. Ali Mosque.

| Mosque name | Usage Type | Physical Data | | | | HVAC System Data | | |
|---|---|---|---|---|---|---|---|---|
| | | Area | Capacity | WWR | U Value | Type | Operation | Control |
| Hz. Ali Mosque | Daily -Friday | 401,25 -Front Zone 64,38 $m^2$ – Rear Zone | 605 Person | 8,5 % | 1,29-window 0,69-wall | Split Unit Floor Heating | 30 min before the start of prayer | – |

Fig. 4 shows the view (a) and floor plan (b) of case study mosque. Also, there is example measuring zone in Fig. 4 (c). In previous studies, the thermal comfort measurements were made at six different points in three different seasons, depending on the directions, in order to determine the thermal comfort level of case study mosque [33,34]. Testo 480 multifunctional thermal comfort measuring device was used in the measurements. This device has probes for indoor air temperature, relative humidity, mean radiant temperature and air velocity. In addition, when the clothing insulation value and activity level parameters are entered into the device, it shows the thermal comfort level of the indoor environment.

Table 2 shows the prayer times and the user density information entered in the software. Prayer hour data and the occupant density learned from the staff will also be used in the software for the scenarios of other stages of the study. The prayer times refer to the first

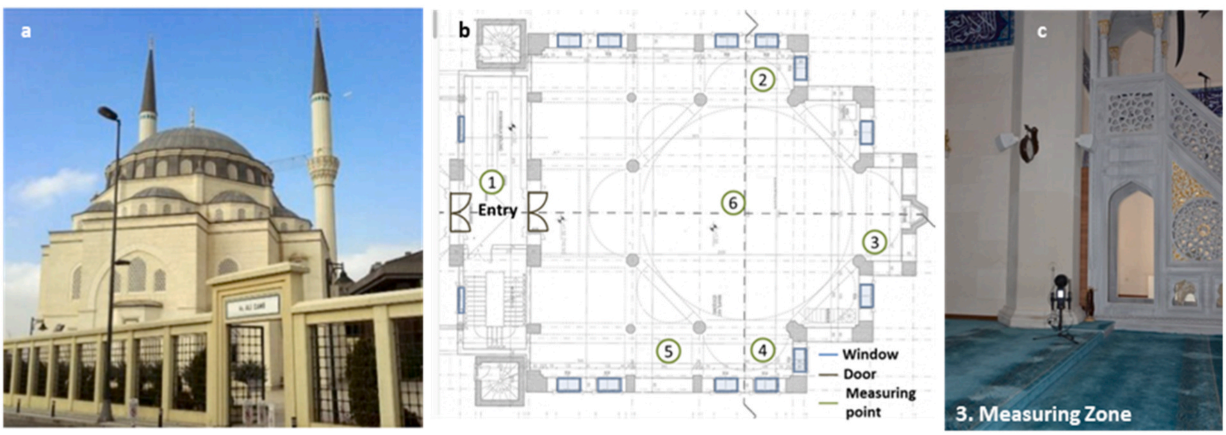


**Fig. 4.** Exterior view, floor plan and sample measuring zones of case study mosque.

**Table 2**
Case study mosque's occupant density and prayer times [29].

| Months/Prayer Time | Dawn-prayer (Fajr Time) | Sunrise (End of Fajr Time) | Mid-day prayer (Dhuhr) | Afternoon-prayer (Asr) | After-sunset prayer (Maghrib) | Night-prayer (Isha) |
|---|---|---|---|---|---|---|
| January | 06:51 | 08:29 | 13:08 | 15:29 | 17:47 | 19:20 |
| February | 06:40 | 08:14 | 13:18 | 16:00 | 18:22 | 19:51 |
| March | 06:07 | 07:38 | 13.17 | 16:25 | 18:56 | 20:22 |
| April | 05:12 | 06:47 | 13:08 | 16:43 | 19:30 | 20:59 |
| May | 04:15 | 06:02 | 13:02 | 16:53 | 20:01 | 21:41 |
| June | 03:31 | 05:34 | 13:02 | 17:02 | 20:31 | 22:25 |
| July | 03:30 | 05:35 | 13:08 | 17:09 | 20:41 | 22:38 |
| August | 04:10 | 05:59 | 13:11 | 17:06 | 20:21 | 22:04 |
| September | 04:55 | 06:30 | 13:05 | 16:45 | 19:37 | 21:08 |
| October | 05:31 | 07:00 | 12:54 | 16:12 | 18:47 | 20:12 |
| November | 06:03 | 07:34 | 12:48 | 15:36 | 18:00 | 19:28 |
| December | 06:33 | 08:09 | 12:54 | 15:18 | 17:37 | 19:09 |
| Occupant Density (%) | 10 | 10 | 10 | 15 | 15 | 15 |
| Duration (minutes) | 20 | – | 30 | 25 | 20 | 30 |

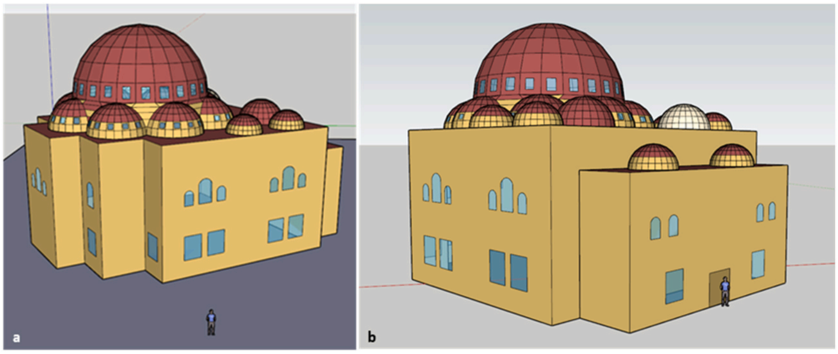


**Fig. 5.** The software visuals of case study mosque.

day times of the month in the table. The mosque reaches full occupancy during the noon prayer at all Fridays of the year. In addition, the density of the mosque increases during the Tarawih prayers in Ramadan and funeral prayers. These situations are also included in the software. The heating and cooling equipment in the mosque is operated intermittently. All other information regarding the use of the mosque and its heating and cooling were processed in the simulation software in detail. Fig. 5 (a - b) shows the 3D software visuals of case study mosque.

## *2.2. Design scenario properties and input data*

The energy consumption performance and the thermal comfort level of five different system types were investigated in constant design properties according to the square-planned, large-scale, and single dome design. The usage density and prayer times of the mosque scenarios are shown in Table 2. The heating and cooling programs of the scenarios have been specially adapted to each scenario in order to provide the thermal comfort level at the indoor environment. Table 3 shows the building envelope properties, software input data and design scenarios.

In this part of the study, it is examined the effect of HVAC system properties on the mosque energy consumption. The effect of the usage schedule of the HVAC system and the air change per hour on energy consumption and thermal comfort were investigated. In these scenarios, the fan coil system was chosen as the constant property for the HVAC system of the mosques. In addition, other constant properties were square plan and large size from design criteria. The usage schedules consist of two scenarios as continuous use and intermittent use. In the intermittent use program, the HVAC system is turned off outside of the collective prayer hours. The air change per hour in the mosque is 0.2, 0.5, 1.0, 1.5, 2.0 ach. Fig. 6 shows sample HVAC system schedules during the heating (a-b) and cooling periods (c-d).

There are studies to determine the size and classification of mosque plan schemes. Mosques are classified according to size of interior space, occupant density, and usage area in the studies. In the study prepared by Onay A., the size of the mosques is specified to be min. 750 $m^2$ for great mosques, min. 500 $m^2$ for central mosques, and min. 150 $m^2$ for bazaar mosques [45]. In the study prepared by Oral M., the A type is 256 $m^2$ (medium-sized mosque), the B type is 400 $m^2$ (large mosque), and the C type is 729 $m^2$ (central mosque) [46]. In the scenarios in this study, the sizes of the mosques are classified as small 256 $m^2$, medium 576 $m^2$, and large 900 $m^2$.

Table 4 shows the characteristics of the parameters according to the plan, size, and roof type of the mosques in the scenarios. The

**Table 3**
Simulation parameters in the mosque scenarios.

| | | | | | |
|---|---|---|---|---|---|
| Building Envelope Properties | Transparency Ratio | 50 % (all façades) | Shading Element | Horizontal - Vertical | |
| | Wall U value | 0.34 W/m$^2$K | Foundation U value | 0.26 W/m$^2$K | |
| | Roof U value | 0.25 W/m$^2$K | Window U value | 0.92 W/m$^2$K | |
| Software Input Data | Air Velocity | 0.15 m/s | Activity Level | 1.3 met | |
| | Lighting load | 7.75 W/m$^2$ | Electric Equipment load | 3.98 W/m$^2$ | |
| | Clothing Insulation | Winter – 1.1 clo/Spring – 0.9 clo/Summer – 0.5 clo | | | |
| | People definition | 1.2 person/m$^2$ | | | |
| HVAC System Scenarios | HVAC System Types | FCS, RS, ACS, FS, GSHP | | | |
| | ACH Types | 0.2 – 0.5 – 1.0 – 1.5 – 2.0 ach | | | |
| | Usage Schedule Types | Intermittent – Continuous use | | | |
| Mosque Design Scenarios | Plan Types | Square | Rectangle | Circular | |
| | Size Types | Large Size | Medium Size | Small Size | |
| | Roof Types | Single Dome | Multi Dome | Pyramidal Roof | Flat Roof |

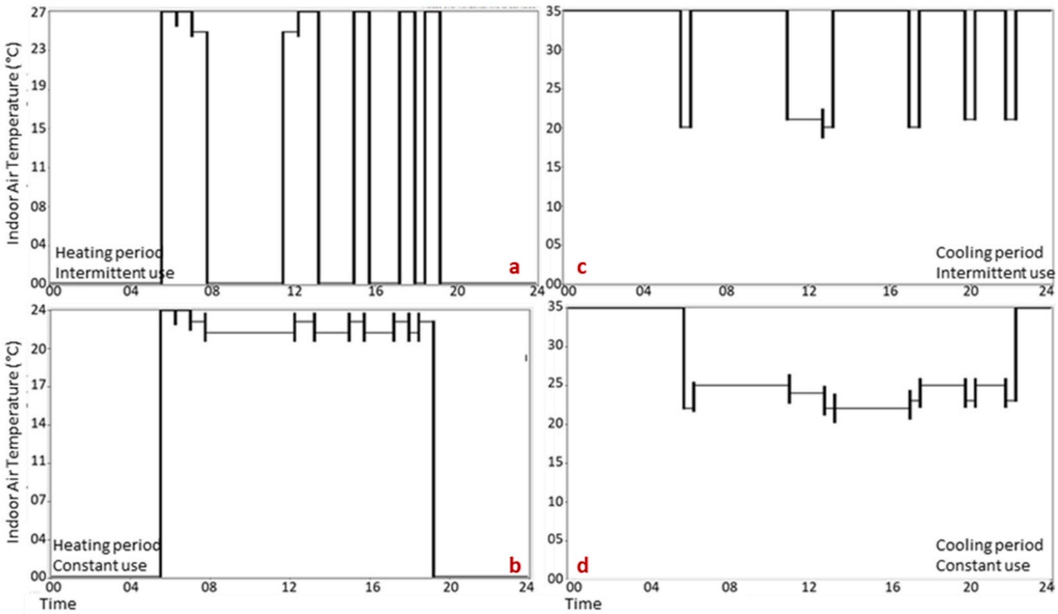


**Fig. 6.** The usage schedules the HVAC system according to Intermittent and Continuous Use.

mosques can be designed in different forms and plan schemes through evolving technology and construction systems. In the past, the basic units of Ottoman mosque architecture were "dome-square-cube". When the mosque plan schemes in the past and today are examined, it can be seen examples of designs such as square, rectangular, circular, triangle, polygon, hexagon, octagon, and amorphous [47]. The study examines the scenarios of Square-Rectangle-Circular plan schemes in terms of thermal comfort and energy consumption. Different roof shapes of mosques can be seen in different cultures and climates types. In this study, single dome top cover, multi dome top cover, pyramidal roof, and flat roof types were investigated in the simulation scenarios. The selected alternatives are the basic mosque architectural forms that are generally preferred in mosque design today [48–50]. Fig. 7 shows the views of the

**Table 4**
Characteristics of design parameters in the scenarios.

| Type | Parameter | Area (m$^2$) | Volume (m$^3$) | Dimension (m) |
|---|---|---|---|---|
| Plan Type | Square | 900 | 11094 | 30-30-10 |
| | Rectangle | 900 | 11094 | 25-36-10 |
| | Circular | 899.39 | 10145 | r = 16.92 |
| Size Type | Large Size | 900 | 11094 | 30-30-10 |
| | Medium Size | 576 | 5205.5 | 24-24-7.5 |
| | Small Size | 256 | 1541.7 | 16-16-5 |
| Roof Type | Single Dome | 900 | 11094 | 30-30-10 |
| | Multi Dome | 900 | 11084 | 30-30-10 |
| | Pyramidal Roof | 900 | 11083 | 30-30-10 |
| | Flat Roof | 900 | 11088 | 30-30-12.32 |

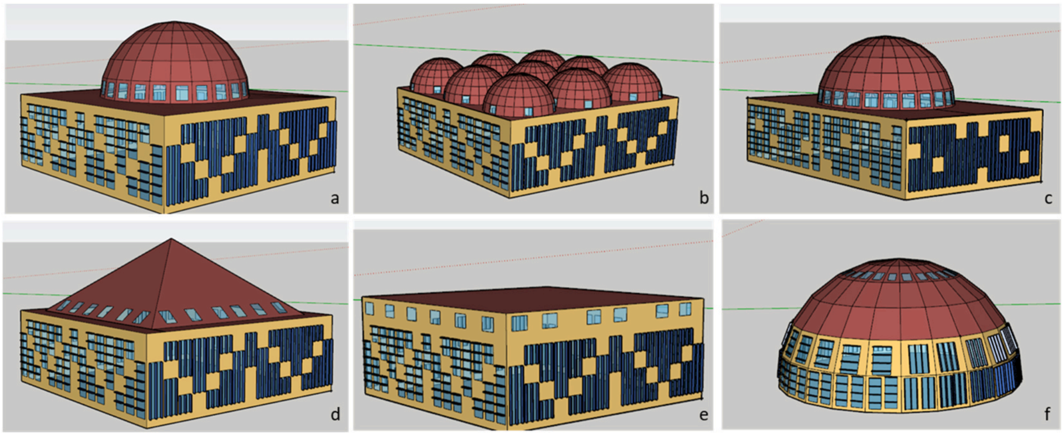


**Fig. 7.** The scenarios' views created for energy consumption analysis.

mosque scenarios created for energy consumption analysis. In the figure, there are the scenarios' views that single dome - square plan (a), multi dome-square plan (b), single dome-rectangle plan (c), pyramidal roof-square plan (d), flat roof-square plan (e), circular plan (f).

### *2.3. Thermal comfort levels according to the standards*

It is examined the evaluation of the plan type (square, rectangle, circular), size type (large, medium, small), and roof type (single dome, multi dome, pyramidal roof, and flat roof) of the mosques according to the HVAC system types. In order to examine the energy consumption by HVAC system type of a single design scenario, other parameters are left constant. During the comparison of the scenarios with respect to the energy consumption values, the indoor thermal comfort level is kept within acceptable ranges. The acceptable thermal comfort comparisons are made according to the values in specified standards. (the International Organization for Standardization 7730–2005 (ISO 7730) and the American Society of Heating, Refrigerating and Air-Conditioning Engineers 55–2017 (ASHRAE 55), $-0.5 <$ predicted mean vote (PMV) $< +0.5$ and predicted percentage of dissatisfied (PPD) $< 10$) [6,51].

## 3. Results

### *3.1. Validation of the software with the actual data of case study mosque*

The structural properties and the usage schedules of case study mosque were processed in the simulation software in detail, taking into account the actual conditions. First of all, a 3D model was created in the program according to the structure, shape, and size characteristics. Starting from the climate and location data in the energy analysis software, the actual data were entered into the dynamic building energy simulation software. There were the usage data such as the usage schedule, heating and cooling schedule, lighting, and electronic equipment assembly information in the computer software. The clothing insulation value was calculated as 1.1 clo for the winter season, 0.9 clo for the spring season, and 0.5 clo for the summer season. The activity level was entered into the software as 1.3 met. Table 5 shows the measured thermal comfort values of case study mosque and the simulation mean results. The measurements were made at the time of the noon prayer on weekdays. The simulation results indicated in Table 5 are shown according to the time interval at the measurement times. The mosque remained outside of the acceptable comfort ranges in both measurement results and simulation results. When the simulation results with actual data are examined, it is seen that the results are close to each other, although there are differences in some values. The difference according to the measurement and simulation average values is

**Table 5**
The measured and simulation results of case study mosque.

| Parameter/Season | Measured Mean Values | | | Simulation Mean Values | | |
|---|---|---|---|---|---|---|
| | Winter 19–23 Dec. | Spring 10–14 Apr. | Summer 28–30 Jun. | Winter 19–23 Dec. | Spring 10–14 Apr. | Summer 28–30 Jun. |
| Indoor Air Temperature (°C) | 13,2 | 16,8 | 27,7 | 10,74 | 17,42 | 25,73 |
| Mean Radiant Temperature (°C) | 13,4 | 17,1 | 27,9 | 8,62 | 16,6 | 25,93 |
| Relative Humidity (%) | 55,9 | 55,6 | 54,1 | 70,6 | 55,1 | 50,3 |
| Air Velocity (m/s) | 0,15 | 0,13 | 0,25 | 0,13 | 0,13 | 0,13 |
| Operative Temperature (°C) | 13,3 | 17 | 27,8 | 9,68 | 17,01 | 25,83 |
| PMV (±0,5) | −1,7 | −0,8 | 0,6 | −2,12 | −0,69 | 0,65 |
| PPD (<10 %) | 59,8 | 20,3 | 22,48 | 79,0 | 14,67 | 13,85 |

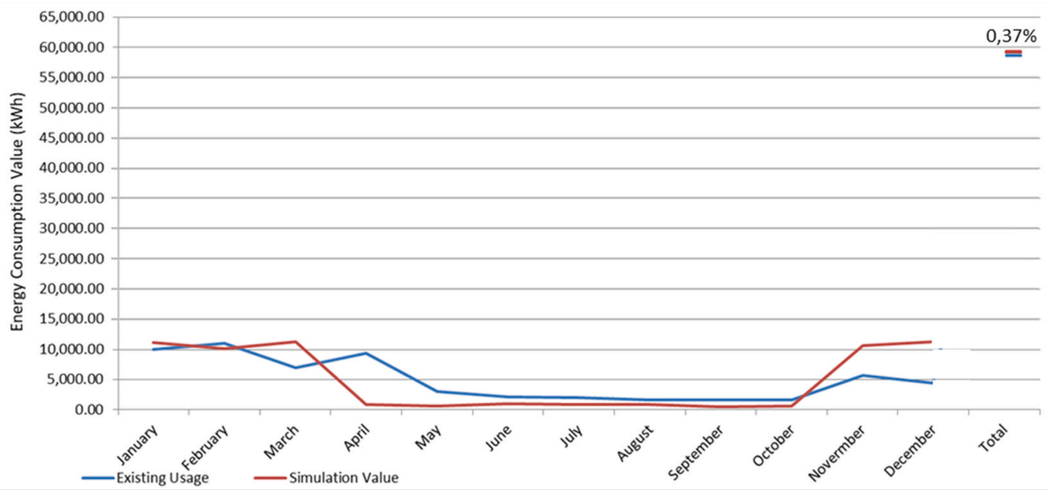


**Fig. 8.** Actual and software energy consumption values of case study mosque.

seen in the mean radiant temperature, relative humidity and PMV values in winter measurements. However, the differences between these values may be due to the climatic dynamic conditions in the simulation software and actual conditions. This difference is between the limit values specified in the standard [52].

Fig. 8 shows the energy consumption data obtained from the electricity bills of case study mosque and the results of the simulation software. According to the energy consumption data, the total consumptions are very close to each other. However, when analyzed monthly, it can be seen that there are differences between the values. This may be due to the fact that Energyplus-based climate data is different from the climate data in the measurement year (2017). Since the simulations of the scenarios created according to the method in the study will be made on the same climate data, the margin of mistake will be very low in comparing the values with each other.

### *3.2. The effect of usage schedule and air change per hour on energy consumption of mosques*

The scenarios of intermittent use schedules have been focused on providing an acceptable level of thermal comfort, especially during collective prayer times. The operation of the HVAC system has been stopped outside the hours of collective prayer times. In the continuous use schedules, the system performance has been regulated in order to provide the thermal comfort level during prayer hours. In continuous use schedules, the indoor environment has been adjusted so that it remains within the thermal comfort limits in the times between the hours of collective prayer times. Fig. 9 shows the indoor thermal comfort level of the mosques according to the intermittent usage schedules (a-b-c-d) and the constant usage schedules (e-f-g-h) for the sample days. Also, the indoor thermal comfort levels are similar to the ones in the figure on the other days of the year, as well as the sample days. The acceptable thermal comfort level was achieved during all usage hours (collective and individual use) of the mosque in the continuous use schedule. According to the intermittent use schedule, the indoor environment remained outside of the acceptable comfort levels, as the HVAC system was turned off except for collective prayer hours during the cooling period. By increasing the system performance, it was tried to bring the indoor environment to an acceptable thermal comfort level during the times between the hours of collective prayer. However, acceptable thermal comfort could not be achieved within the specified time period. With the shutdown of the system, the indoor environment suddenly reached the level of discomfort.

Table 6 shows the energy consumption of the mosque scenarios with fan coil system according to the intermittent and continuous use schedules. According to the energy consumption results, there is more energy consumption in the intermittent use schedule during the heating period. On the contrary, the continuous use program during the cooling period consumed more energy than the intermittent use. However, the thermal comfort level during the cooling period of the intermittent use schedule is outside of the acceptable thermal comfort ranges. During the heating period, the HVAC system was operated at maximum performance in order to provide an acceptable level of thermal comfort in the intermittent use program. This situation caused too much energy consumption to provide thermal comfort in a short time. Moreover, during the cooling period, the indoor environment remained outside the acceptable thermal comfort ranges, outside of collective prayer hours in the intermittent use program. This resulted with less energy consumption in the intermittent use program compared to continuous use. In terms of total consumption, 8 % more energy is consumed in the intermittent use schedule. In this study, the intermittent use schedule is insufficient to provide the acceptable thermal comfort level.

Air infiltration consists of undesirable airflow that occurs directly from the outdoor environment to the indoor environment. It is usually caused by the opening and closing of the doors and windows facing the outside or small gaps in the building elements. It changes indoor air. This can cause an increase in energy consumption or a change in thermal comfort. In this section, the air change per hour in the mosques is examined for the effect of thermal comfort and energy consumption. In the scenarios, the indoor air changes are arranged to be 0.2, 0.5, 1.0, 1.5, 2.0 ach. In all scenarios, the indoor thermal comfort is within acceptable ranges on the sample days

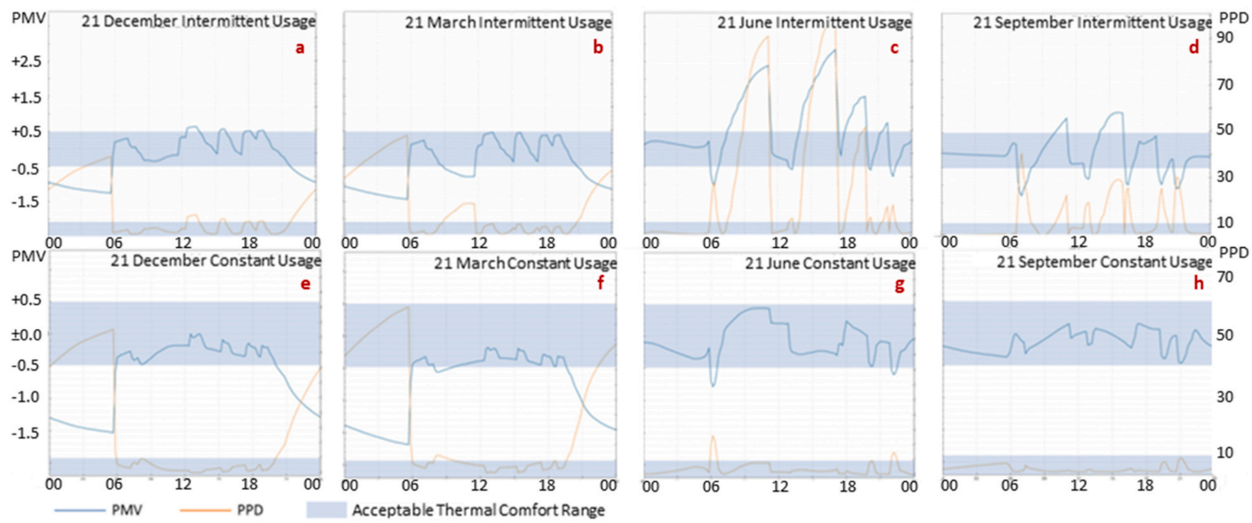


**Fig. 9.** The thermal comfort level of scenarios to the usage schedules.

**Table 6**
The energy consumption amounts of the scenarios to the usage schedules.

| Schedule Type | Heating (kWh) | Cooling (kWh) | Total Consumption (kWh) | Unit Area (kWh/m$^2$) | Unit Volume (kWh/m$^3$) |
|---|---|---|---|---|---|
| Intermittent Usage | 89169.45 | 28800.00 | 143613.9 | 159.57 | 12.95 |
| Continuous Usage | 61677.78 | 47869.44 | 131991.7 | 146.66 | 11.90 |

**Table 7**
The energy consumption levels of scenarios to air changes per hour.

| Air Change per Hour | | | | | |
|---|---|---|---|---|---|
| | Heating (kWh) | Cooling (kWh) | Total Consumption (kWh) | kWh/m$^2$ | kWh/m$^3$ |
| 0.2 ach | 60647.22 | 46666.67 | 129708.3 | 144.12 | 11.69 |
| 0.5 ach | 61122.22 | 47869.44 | 131991.7 | 146.66 | 11.90 |
| 1 ach | 62213.89 | 50302.78 | 135061.1 | 150.07 | 12.17 |
| 1.5 ach | 61458.33 | 53013.89 | 137097.2 | 152.33 | 12.36 |
| 2 ach | 61316.67 | 55666.67 | 139816.7 | 155.35 | 12.60 |

and other days of the year.

Table 7 shows the energy consumption amounts and comparisons according to air changes per hour of the scenarios. According to the air changes per hour, 1.0 ach is the maximum energy consumption in the heating period, and 2 ach is the maximum energy consumption in the cooling period. In total, the highest energy consumption is realized in 2 ach conditions with a difference of 5.93 % compared to 0.5 ach conditions. It is experienced in the cooling period the biggest difference in energy consumption according to scenarios between air changes per hour. Creating the 0.2 ach scenario in actual conditions is a difficult situation in buildings such as mosques where many different types of users and large numbers of people are used. Therefore, it is recommended to create a 0.5 ach scenario in terms of indoor air change per hour in the study. Heat energy is transferred from the warmer environment to the colder environment. For this reason, high air change per hour in the heating period increases the amount and speed of heat transfer to the outdoor environment. During the cooling period, unwanted warm air moves to the indoor environment. These factors increase energy consumption both in the heating period and in the cooling period.

### *3.3. Comparison of energy consumption of HVAC system types according to size, plan, and roof properties of mosques*

In the study, the energy consumption amounts of square, rectangular, and circular plan schemes, which are the most preferred simple plan types in mosque design, were analyzed with respect to HVAC system types. In addition, the analysis was made according to the single dome, multi dome, pyramidal roof, and flat roof types to examine the effect of top cover type on energy consumption. In the plan and roof scenarios, the area and volume sizes were arranged to be equal to each other. The evaluations were made over the unit area. At the same time, the energy consumption level comparisons were made according to five different systems in order to determine the suitable HVAC system for the plan, size, and roof types. According to the data obtained as the HVAC system schedule, the

**Table 8**
Energy consumption values to design criteria and HVAC system types.

| Design Criteria | | Constant Criteria | FCS (kWh/m$^2$) | RS (kWh/m$^2$) | GSHP (kWh/m$^2$) | ACS (kWh/m$^2$) | FS (kWh/m$^2$) |
|---|---|---|---|---|---|---|---|
| Plan Type | Square | Large size | 146.66 | 129.19 | 82.90 | 148.02 | 103.01 |
| | Rectangle | Single dome | 161.55 | 136.89 | 88.71 | 153.66 | 105.50 |
| | Circular | | 124.73 | 112.53 | 83.39 | 122.21 | 82.47 |
| Size Type | Small Size | Square plan | 153.48 | 126.54 | 93.39 | 142.38 | 100.15 |
| | Medium Size | Single dome | 153.57 | 124.59 | 90.74 | 140.61 | 99.87 |
| | Large Size | | 146.66 | 129.19 | 82.89 | 148.01 | 103.00 |
| Roof Type | Single Dome | Square plan | 146.66 | 129.19 | 82.89 | 148.01 | 103.00 |
| | Multi Dome | Large size | 182.12 | 138.01 | 84.77 | 158.91 | 112.46 |
| | Pyramidal Roof | | 157.37 | 131.15 | 85.43 | 147.87 | 100.04 |
| | Flat Roof | | 163.02 | 128.45 | 82.31 | 146.70 | 103.20 |

* FCS: Fan coil system, RS: Heating with hot water radiator and chiller type cooling system, GSHP: Ground source heat pump systems, ACS: Wall mounted split air conditioning system, FS: Underfloor heating and cooling system

continuous usage program was selected in these scenarios. Table 8 shows the energy consumption per unit area with respect to the design criteria and HVAC system types.

Fig. 10 shows the energy consumption per unit area of the HVAC system types (d) according to the plan type (a), size type (b), and roof type(c). In these scenarios, the large scale and the single dome from the design parameters are kept constant for the square and rectangular plan schemes. The circular plan scheme is in the form of a hemisphere. It is also on a large scale. According to the HVAC system types, the energy consumption per unit area of the scenarios is generally seen at the lowest level in the circular plan scheme. The highest energy consumption is in the rectangular plan scheme. The wide façade of the rectangular plan scheme is perpendicular to the southeast-northwest direction. It has caused both an increase in the cooling load and an increase in the heating load of the mosque. In these scenarios, the square plan scheme and single dome top cover are determined as constant design criteria. The energy consumption per unit area is seen at least in the GSHP and FS systems. The highest energy consumption is seen in FCS and ACS systems. The max and min energy consumption per unit area varies according to the plan dimensions. The square plan scheme and large-scale design parameters are adjusted as the constant properties. The relationship between four roof types and five different HVAC systems is investigated in terms of energy consumption. According to the roof types, the most energy consumption per unit area is generally in the multi dome design. Among other roof types of roof, there are variations according to the type of HVAC system.

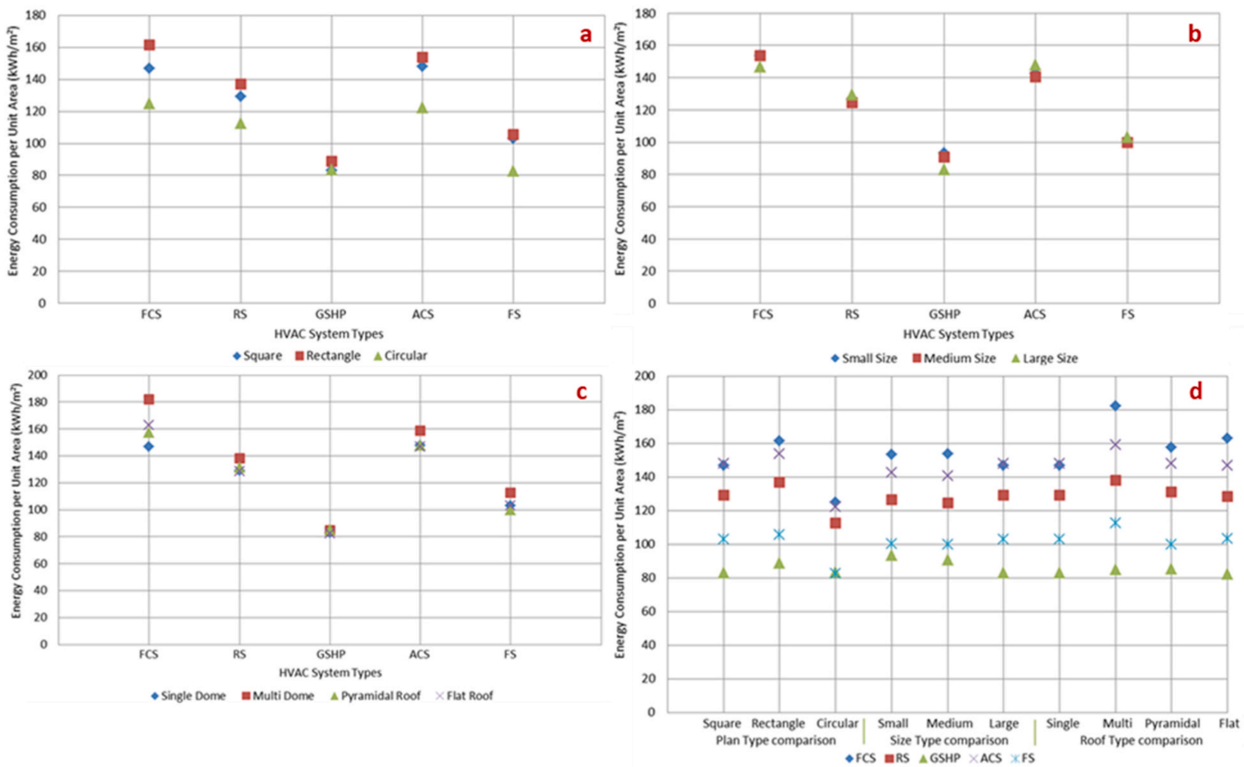


**Fig. 10.** The energy consumption values of the scenarios to the design criteria.

## 4. Discussion

In the mosque scenarios, the energy consumption amounts vary according to design criteria and HVAC system types. However, RS, FS, and GSHP systems are generally the HVAC systems with the lowest energy consumption per unit area. FCS and ACS systems are the systems with the highest energy consumption per unit area. According to the average energy consumption of the design criteria, FCS (153.5 kWh/m$^2$) caused an average of 79 % more energy consumption than GSHP (85.7 kWh/m$^2$) and 51 % more energy than FS (101.2 kWh/m$^2$) compared to the situation in which it was used. Similarly, ACS (145.6 kWh/m$^2$) average energy consumption resulted in 70 % more energy consumption than GSHP and 44 % more energy consumption than FS. In the study, the air conditioning of the mosques' indoors by radiant way consumes less energy than the fan systems. According to the plan schemes, the least energy consumption per unit area is in the circular plan scheme and hemispherical design. According to the average energy consumption values of the HVAC systems, there was 23 % less energy consumption in the circular plan (105.06 kWh/m$^2$) type than in the rectangular plan type (129.2 kWh/m$^2$). The average HVAC system energy consumption values of the mosques' sizes are close to each other. When the average energy consumption values of the HVAC systems are examined according to the roof type, 10 % less energy consumption is realized in the single-dome design (121.9 kWh/m$^2$) than in the multi-dome design (135.2 kWh/m$^2$). Similarly, multi-dome design scenario consumes 8 % more energy consumption than the pyramid (108.7 kWh/m$^2$) and flat roof type (108.4 kWh/m$^2$). Although the size and volumes are similar, the compact form of the circular plan scheme is effective in this situation. In another study, a similar situation exists in the hot dry climate zone. The octagonal plan design caused less energy consumption than the square and rectangular plan type. In addition, it has been stated that the passive system designs alone will not be sufficient to achieve thermal comfort, but authors can reduce the annual total energy consumption up to 10 % [19]. In this study, it can be seen that up to 10 % of annual energy consumption can be saved by changing only the roof type, which is one of the passive design criteria. The wide façade of the rectangular mosques' plan schemes is perpendicular to the southeast-northwest direction. This increases exposure to more solar radiation for the cooling period and to cooler airflow for the heating period. The multi-dome design causes more energy consumption per unit area than other roof types. The multi dome design makes it harder to cycle indoor air circulation compared to a single dome, pyramid and flat roof. The least energy consumption per unit area varies in other roof types.

Nowadays, the HVAC system's usage schedules of mosques vary due to climatic variations, HVAC system type, staff availability, and economic concerns. This situation can cause increased uncontrollable energy consumption. It may induce outside the acceptable ranges of the thermal comfort of the indoor environment. In the intermittent use schedules, HVAC systems are operated at high performance in order to provide acceptable thermal comfort ranges at a short time in the indoor environment. When the values in the study are examined, the continuous use schedule causes both the thermal comfort to be at an acceptable level and the energy consumption to remain at a lower level. FCS is a forced convection blower system. In the study, FCS was accepted as the HVAC system of usage schedules scenarios. Providing the large volume buildings such as mosques to the appropriate thermal comfort level with a blown system in a short time causes high energy consumption. In another study, the underfloor heating system (82.2 kWh and 88.3 kWh) consumes less energy than electric radiators (203.1 kWh) and split air conditioners (215.1 kWh) [29].

The energy consumption of the intermittent and continuous use schedules may vary according to climatic conditions and other parameters (HVAC system type, operation control, thermal comfort level). In hot dry climates, the intermittent use during the cooling period resulted in less energy consumption than continuous use [53]. In the literature, there are studies in which the intermittent use schedule (127 kWh/m$^2$) causes less energy consumption than the continuous use schedule (181 kWh/m$^2$) [53]. The thermal comfort level of mosques should be examined in detail. The climatic conditions and other design parameters may affect the energy consumption of usage programs [33]. In this study, 8 % more energy is consumed in the intermittent use schedule (159.57 kWh/m$^2$) than continuous schedule (146.66 kWh/m$^2$) in terms of total consumption. In addition, in another study on continuous use and intermittent use of the underfloor heating system, 9 % of fuel consumption can be saved with the appropriate operating strategy selection, while thermal comfort can be kept within acceptable ranges [31] The important issue is the selection of the type of HVAC system and suitable operating strategy for the climate type, mosque size, and usage strategies.

The air infiltration may be less in new public buildings constructed. This situation can be provided by the improvement of input and output control systems, the windbreak parameter, the development of openings filter systems, etc. Five different scenarios for air change per hour are examined in the analysis of the study. The least energy consumption is realized in the scenario with the least air infiltration (0.2 ach). The highest energy consumption is in the 2.0 ach scenario. This shows that the less infiltration of the indoor environment, the less energy consumption will be. Depending on the volume of the mosques, when the air infiltration of the mosque is reduced by 0.5 ach, a reduction of up to 10 % in the annual cooling load can be achieved [21]. The air infiltration is more difficult in public buildings than in residential buildings due to the variability and number of users. Therefore, it is recommended that 0.5 and 0.1 ach can be used as a reference in future studies [21]. In addition, future studies should examine the effect of airflow in the entrance, the creation of the narthex for the entrance hall.

## 5. Conclusion

In this study, a method consisting of energy efficient design strategies has been proposed in order to provide thermal comfort in mosques with minimum energy consumption. The scenarios examined the effect of the plan, size, and roof parameters of the mosques on the energy consumption while keeping the thermal comfort level within acceptable ranges according to the HVAC system type. In addition, it was investigated the usage schedule of the HVAC system type and the effect of the air infiltration of the indoor environment. The scenarios were analyzed with the energy simulation software validated in the case of the temperate humid climate.

- In the scenarios of mosque design, the amount of energy consumption varies according to the HVAC system types. However, RS, FS, and GSHP systems are generally the HVAC systems with the lowest energy consumption per unit area. FCS and ACS systems are the systems with the highest energy consumption per unit area.
- According to the average energy consumption values of the design strategies, the FCS average energy consumption resulted with an average of 79 % more energy consumption in the GSHP and 51 % more energy consumption in the FS.
- The air conditioning of the indoor environment by radiant way causes less energy consumption compared to the equipment with fan system.
- Compared to the single dome, multi dome, pyramidal roof, and circular roof types, the most energy consumption per unit area is generally in the multi dome design.
- When the average energy consumption values of HVAC systems are examined according to the roof type, 10 % less energy consumption is realized in the single-domed design (121.9 kWh/$m^2$) than in the multi-domed design (135.2 kWh/$m^2$).
- There is variation in the max–min energy consumption of HVAC systems according to the sizes of mosques. The average energy consumption values of the HVAC system of the mosques are close to each other (1.27 %).
- The energy consumption is 8 % less in the continuous use schedule (146.66 kWh/$m^2$) compared to intermittent use (159.57 kWh/$m^2$).
- In the air changes per hour scenarios of the mosques, the highest energy consumption is realized in 2 ach conditions with a difference of 5.93 % compared to 0.5 ach conditions.

## 6. Limitations and future studies

In this study, there are suggestions for the use of HVAC system and the design of mosques in the temperate humid climate zone in Turkey. In addition, with the developed method, the design parameters and their relationship are shown in order to reduce the energy consumption of mosques. This method can also be used for other climatic conditions for the analysis of mosques. However, there are several limitations in the scope of the study.

- The study was conducted for only one climatic region as an example. However, the results and the method should be supported and developed by providing analyzes in different climatic zones.
- The effect of the energy consumption of an HVAC system type on the usage schedule and air tightness was analyzed. In future studies, the effect of the usage schedule on energy consumption according to different HVAC system types should be investigated.
- In this study, the main prayer area was designed as a single place and the analyses were made according to this form. In future studies, the design criteria, including the multistory design of the mosques, the variable size design and flexibility of the main prayer area, should be compared according to the energy consumption levels for the selection of the appropriate HVAC system type.
- In order to examine the environment effect of mosques on thermal comfort and energy consumption, environmental data (effect of green texture on indoor thermal comfort, courtyard design effect, and presence in rural and urban areas) should be analyzed in detail in the future.

## Data availability statement

The data that support the findings of this study are available from the corresponding author, [A.B.A.], upon reasonable request.
Ahmet Bircan Atmaca: https://orcid.org/0000-0001-5907-3878.

## CRediT authorship contribution statement

**A.B. Atmaca:** Visualization, Validation, Software, Methodology, Data curation, Conceptualization, Writing - original draft, Writing - review & editing. **G. Zorer Gedik:** Validation, Supervision, Methodology, Writing - review & editing.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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