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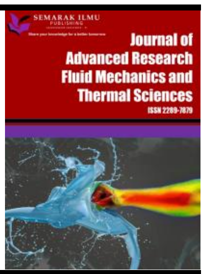

Cooling Period Strategies in an Intermittent Usage Building: A Case Study of a Mosque in the Tropical Climate of Malaysia

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ABSTRACT

Mosques are used five times a day according to the prayer schedule, which follows the sun's position. Indoor thermal conditions in air-conditioned mosques are maintained with a cooling time pattern that follows prayer times. Therefore, an effective air conditioning operating strategy is needed for energy efficiency. This study aims to investigate the effect of air conditioning intermittent operation time strategies on the energy usage of a mosque. It involves reducing the cooling period before prayer time and swapping active air conditioning periods from pre-prayer calls to post-prayer in the base case. Field measurements in Universiti Teknologi Malaysia – Kuala Lumpur (UTMKL) mosque and simulation using DesignBuilder software were conducted to predict annual specific energy consumption. The results indicate a reduction in specific energy consumption of 5% by operating the air conditioning 10 minutes before the call to prayer. Shifting the pre-prayer call-post prayer cooling period results in an insignificant reduction in energy consumption of 0.3-0.6%; however, it can accommodate extended periods of comfortable conditions for people who perform prayers outside of congregational prayers on time. Furthermore, the results indicate that the cooling period after the prayer time affects the cooling load of the following prayer. This study provides information for architects, engineers, and other stakeholders towards improving energy consumption in religious buildings with intermittent occupancy.

1. Introduction

Muslims use mosques as hubs of worship and social and educational activities. However, the main building is generally used for daily prayers, consisting of praying five times a day following a prayer schedule that depends on the sun's height. Mosques with large capacities accommodate congregational prayers once a week, namely Friday prayers, which are held after midday. The mosque's main hall is usually rectangular with a niche as the Imam's space along the length. The long side with the niche faces the Qibla in Mecca, Saudi Arabia.

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In tropical hot-humid climates like Malaysia, mosques face challenges from solar radiation, high temperatures, and humidity [1]. Air conditioners and ceiling fans are commonly used to maintain comfort, leading to substantial energy consumption. Ineffective use of air conditioning (AC) systems results in energy inefficiency, and thermal comfort is often not achieved [2].

Studies on mosque's energy consumption and its relationship to thermal comfort have been the subject of research for several years [3,4]. Several studies from various climates reported high annual energy consumption of mosque buildings: 288 kW/m^2/year in a hot-dry climate, 186 kW/m^2/year in a hot-humid climate, and 142 kW/m^2/year in a temperate climate [5-7]. These findings surpass the energy-efficient building standards outlined in Malaysian standards (MS1525:2019) and the National Energy Efficiency Action Plan (NEEAP), which prescribe annual consumption limits of 90 and 135 kW/m^2/year, respectively [8].

Studies on enhancing energy consumption in mosques encompass a variety of approaches. Given that air conditioning energy usage constitutes approximately 70% of the total energy consumption, direct retrofits to the heating, ventilation, and air Conditioning (HVAC) systems present a highly effective strategy [9]. Specific improvements to these systems can involve retrofitting existing equipment and implementing optimized operational strategies [4]. By addressing these aspects, significant reductions in energy use can be achieved, contributing to overall energy efficiency in mosques.

Retrofitting existing ACs with energy-saving units such as variable air volume can result in substantial energy savings of more than 25% [8,10,11]. Utilizing intelligent control on AC also has a significant impact on energy use. Aftab *et al.,* [12] utilizing an AC on-off algorithm during unoccupied periods and temperature prediction during pre-cooling saved energy up to 39%. Another study by Abdallah [13] saved energy up to 21% by using smart controls that read the density inside the mosque.

Studies related to AC operation scheduling on improving mosque energy consumption show positive results. Budaiwi *et al.,* [6] adjusted the AC operating system of a mosque in a hot climate by turning off the AC one hour after prayer time, which resulted in a 16% reduction in annual energy consumption. Another study by Budaiwi and Abdou [14] showed significant improvements by limiting AC operation time to only 1 hour per prayer compared to continuous operation. The intermittent operational strategy in Diler *et al.,* [15] showed a significant improvement in mosque energy consumption compared to continuous active HVAC throughout the day. Later, Yüksel *et al.,* [16] analyzed operating strategies by reducing AC operating time. Their study indicates that the shorter the operating time, the lower the energy consumption, but thermal conditions must be a concern due to limited AC capacity.

Indoor thermal conditions in air-conditioned mosques are regulated by a cooling schedule that aligns with prayer times. Consequently, an efficient strategy for operating air conditioning systems is imperative to ensure energy conservation. The previous studies regarding AC operation scheduling mentioned earlier investigated the overall time reduction to reduce energy consumption. To our knowledge, no one has considered the effect of reducing pre-prayer time and prolonging post-prayer cooling on subsequent prayers and overall energy. Therefore, this study aims to investigate the effect of AC scheduling on energy consumption by comparing each reduction or addition of pre- or post-prayer time. This study offers valuable insights for architects, engineers, and other relevant stakeholders aiming to enhance energy efficiency in religious buildings characterized by intermittent occupancy.

2. Methodology
2.1 Description of Building, Climate, and Field Measurements

The UTMKL mosque (Figure 1 and Figure 2) in Kuala Lumpur was singled out for examination due to its consistent hosting of daily and Friday prayers, typical representation of a large air-conditioned mosque in Malaysia, and its convenient proximity to a weather station for accessing annual climate data. This mosque stands as a quintessential example of a large mosque in the area. Additionally, similar architectural styles are prevalent in tropical regions, especially in Malaysia and Indonesia.

The mosque is in Kuala Lumpur, which has a hot-humid climate as stated in the Koppen World climate classification [17]. Field measurements were conducted from 26 January to 2 February 2023. Later, the results would be used to validate the simulation as a base case. The devices were positioned in the main hall and attached to a stand at a height of 1.1 m from the floor level, as in Zaki *et al.,* [18]. The parameters measured were indoor air temperature and relative humidity (RH) using Hobo-U12-013 with an accuracy of ±0.5 °C and ±5% RH (at 25°C, 50%), respectively. On the other hand, the outdoor conditions were downloaded from MJIIT-UTM weather station.

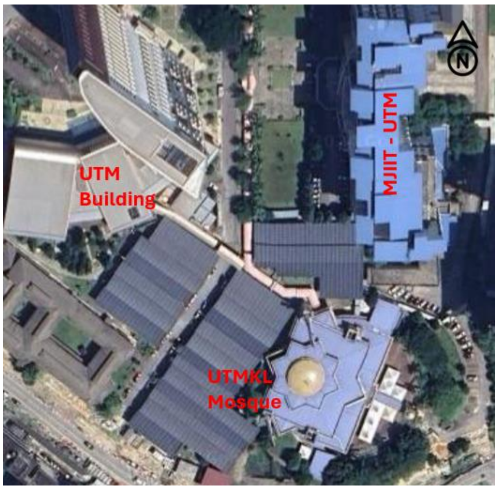

Fig. 1. Satellite view of UTMKL mosque

Fig. 2. Aerial view of UTMKL Mosque from MJIIT-UTM Building

2.3 Simulation

Base case development is based on the layout plan from the mosque management. The layout plan was transformed into a 3D model with DesignBuilder software (Figure 3), as in previous studies [15,16]. The thermophysical properties of the materials are unknown; therefore, some material properties used data from the software library, and others were obtained by fine-tuning the field measurements data as in previous study [19]. The materials are plastered brick wall (U-values: 2.5 W/m^2K), concrete floor with carpet (0.3 W/m^2K), metal deck roof and polystyrene dome with insulation (1 W/m^2K).

The cooling period was obtained from observation and field measurements as in Table 1. During the cooling period, windows and doors are kept closed, and the air conditioning temperature is typically set between 20 °C and 25 °C. The time interval between sunset and night prayer is close, so the cooling period is combined until the end of the night prayer. This period is not shown in the table and is excluded in this study since prolonging the cooling period after night prayer will not affect the initial temperature of the following prayer, i.e., dawn prayer. The system is assumed to run regularly for one year in the base case simulation.

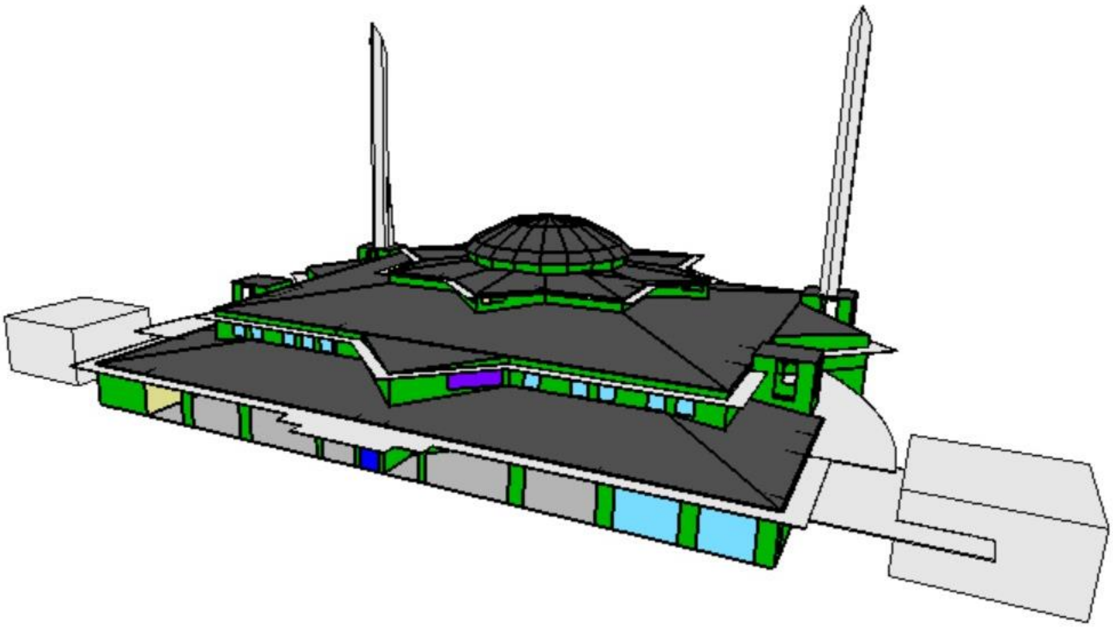

Fig. 3. A 3D model of UTMKL mosque using DesignBuilder

Table 1
Base case cooling period before and after prayer timetable

Prayer	Pre-cooling	The call to prayer begins	Pre-prayer	Prayer + post prayer cooling
Dawn (D)				
Midday (M)				
Afternoon (A)				
Sunset-night (S)				

Each segment represents 10 min. interval. The grey colour is the cooling period. The call to prayer is based on Kuala Lumpur's prayer time

As was applied in previous studies, mosque's indoor air temperature from field measurements is compared to the simulation to ensure the accuracy and validity (Figure 4) [14,15,20]. Therefore, a base case calibration was carried out using a statistical approach by comparing simulated indoor air temperature (*T_simulation*) with field measurements (*T_field measurements*) in Figure 4 using the following Eq. (1) to Eq. (3) [15,19]

$$MBE\ (\%) = \frac{\sum_{i=1}^{Ni}(Mi-Si)}{\sum_{i=1}^{Ni} Mi} \times 100 \tag{1}$$

$$CvRMSE\ (\%) = \frac{RMSE}{\frac{1}{Ni}\sum_{i=1}^{Ni} Mi} \times 100 \tag{2}$$

$$RMSE = \sqrt{\sum_{i=1}^{Ni} \frac{(Mi-Si)^2}{Ni}} \tag{3}$$

where MBE is Mean Bias Error, CvRMSE is Coefficient of variation of the Root Mean Square Error, RMSE is Root Mean Square Error, M_i is instantaneous measured data at n, S_i is instantaneous simulated data at n, and N_i is total data used in the calibration. The standard of this is the MBE of ±10% and CvRMSE of less than 30% [21]. Based on Figure 4, the model is considered valid since the MBE is 10% and CvRMSE is 3%. Discrepancies in low temperatures due to the setpoint temperature in the simulation were based on interview results. On the other hand, the actual temperatures were lower, possibly due to ACs being set lower or the actual temperatures being lower than the set point.

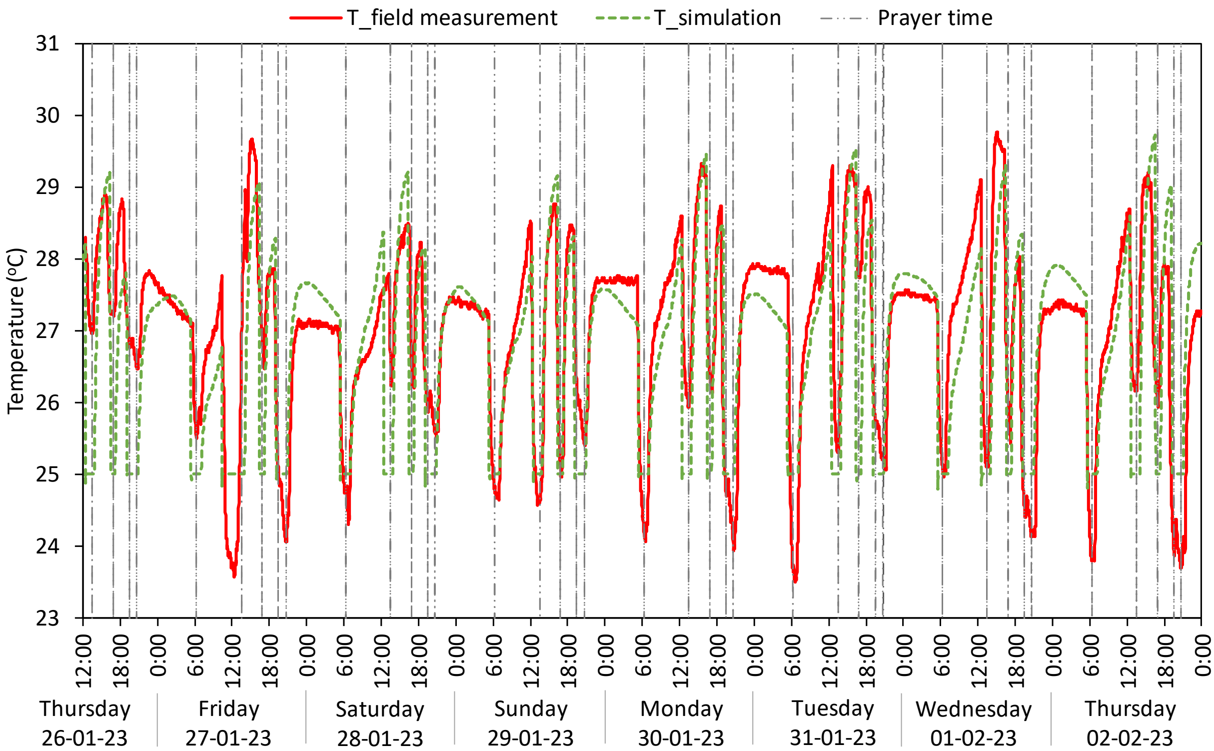

Fig. 4. Indoor air temperature of field measurements and simulations

The strategy to improve building performance was carried out by simulating several scenarios as follows: Scenario I is a straightforward approach that involves gradually reducing the pre-cooling time by 10 minutes from the base case (50, 40, 30, 20, 10 min.). Scenario II extends the cooling period by 10 or 20 minutes at the end (post-prayer cooling) and exchanges cooling times by reducing pre-cooling time and adding 10 to 50 minutes after prayer. These scenarios are shown in tables in the following sections.

3. Results and Discussion

3.1 Effects of A/Cs Operating Time Reduction

Table 2 and Figure 5 show the reduction of individual scenarios to the base case. Reducing time to 10 minutes before prayer time can reduce energy consumption in the range of 0.6 to 1.9%, depending on the prayer time. Energy consumption includes electricity used for lighting, cooling, and miscellaneous. At dawn, the optimum time is 20 minutes because it is influenced by the outdoor temperature factor, which starts to rise slightly before the sun rises. The insignificant reduction can be seen in the time reduction for the base case by 10 minutes, especially when the relative outdoor temperature does not change drastically, viz. 0.15% at dawn and sunset prayers. Meanwhile, midday prayer and afternoon prayer times produce a decrease in energy that is two times greater than the two prayer times mentioned previously.

Table 2
Cooling period and total site energy per scenario

Prayer	Scenario	Pre-cooling (min)	Call to prayer [a]	Pre-prayer (min)	Prayer [b] (min)	Total site energy (kWh/year)
Dawn (D)	Basecase	60	The call to prayer begins	20	20	236,945
	D1	50	(e.g. 06.12 on January [a])	20	20	236,576
	D2	40		20	20	235,875
	D3	30		20	20	235,224
	D4	20		20	20	234,359
	D5	10		20	20	234,445
Midday (M)	Basecase	60	The call to prayer begins	10	20	
	M1	50	(e.g. 13.25 on January [a])	10	20	236,049
	M2	40		10	20	235,486
	M3	30		10	20	234,990
	M4	20		10	20	233,476
	M5	10		10	20	232,485
Afternoon (A)	Basecase	30	The call to prayer begins	10	10	
	A1	20	(e.g. 16.47 on January [a])	10	10	236,068
	A2	10		10	10	234,786
Sunset-night (S)	Basecase	30	The call to prayer begins	After the sunset prayer,		
	S1	20	(e.g. 19.22 on January [a])	ACs remain turned on		236,607
	S2	10		until the night prayer is finished		235,457

[a] The call to prayer is based on Kuala Lumpur's prayer time, [b] Prayer + post prayer cooling period
The base case refers to Table 1

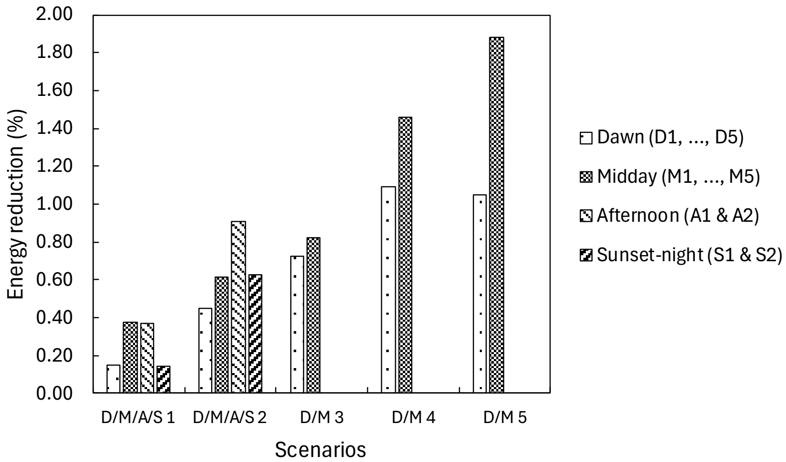

Fig. 5. Energy reduction using scenario I

3.2 Effects of Adding and Shifting A/Cs Operating Time

Table 3 shows the total site energy for the extended cooling period and the time exchange between precooling and post-prayer cooling periods. As explained in subsection 2.2, the sunset-night prayer period is disregarded because the extended cooling after the night prayer does not affect the dawn prayer's initial temperature due to the long interval between the two prayers.

Figure 6 shows the percentage of changes in energy consumption. Positive values indicate increased energy consumption, and negative results indicate the opposite: energy savings. From the figure, the additional 10-minute cooling period after dawn (D6), midday (M6), and afternoon (A6) prayers increased energy consumption by 0.1, 0.3, and 0.6%, respectively. Meanwhile, adding up to 20 minutes increases energy consumption by 0.2, 0.5, and 0.8% for dawn (D7), midday (M7), and afternoon (A7) prayers, respectively. The high cooling load due to the high outdoor temperature and thermal mass accounts for why the increases are high at midday and afternoon prayer. The results show that this scenario will only raise energy consumption.

Table 3
Cooling period and total site energy of prolonging and shifting cooling periods

Prayer	Scenario	Pre-cooling (min)	Call to prayer [a]	Pre-prayer (min)	Prayer [b] (min)	Total site energy (kWh/year)
Dawn (D)	Basecase	60	The call to prayer begins (e.g. 06.12 on January [a])	20	20	236,945
	D6	60		20	30	237,181
	D7	60		20	40	237,507
	D8	50		20	30	236,857
	D9	40		20	40	236,489
	D10	30		20	50	236,146
	D11	20		20	60	235,913
	D12	10		20	70	236,291
Midday (M)	Basecase	60	The call to prayer begins (e.g. 13.25 on January [a])	10	20	
	M6	60		10	30	237,629
	M7	60		10	40	238,128
	M8	50		10	30	237,334
	M9	40		10	40	237,732
	M10	30		10	50	238,020
	M11	20		10	60	237,702
	M12	10		10	70	237,538
Afternoon (A)	Basecase	30	The call to prayer begins (e.g. 16.47 on January [a])	10	10	
	A6	30		10	20	238,319
	A7	30		10	30	238,902
	A11	20		10	20	236,985
	A12	10		10	30	236,549

[a] The call to prayer is based on Kuala Lumpur's prayer time, [b] Prayer + post prayer cooling period.
The base case refers to Table 1

Table 4 and Figure 6 show that the shifting scenario resulted in energy consumption changes with the same total cooling period. Shifting scenarios at dawn and afternoon prayer contribute to decreasing energy consumption. The D11 and A12 show the highest energy savings, 0.4 and 0.2%, respectively.

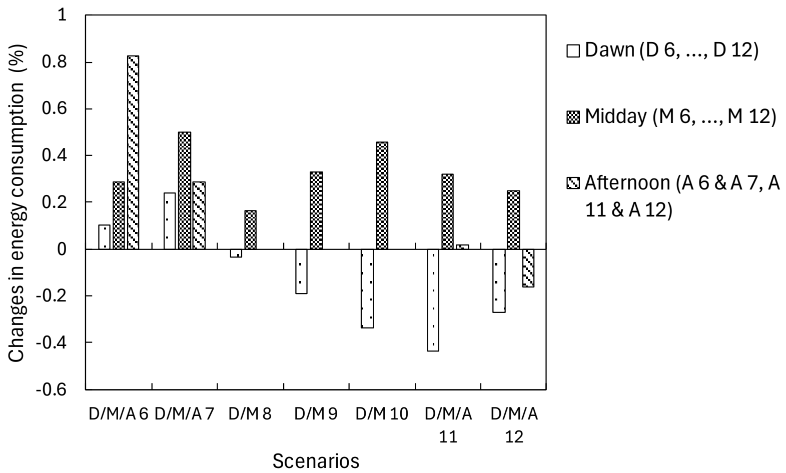

Fig. 6. Changes in energy consumption of scenario II compared with the base case

3.3 Effects of Combination Measures

Results indicate the potential to improve energy efficiency by combining the best results from each scenario (Tabel 4). First, combining scenario II of dawn and afternoon prayer (D11 and A12), scenario I of midday prayer (M12), and sunset-night prayer base case (SB) resulted in energy savings of 0.3%. Second, the same combination of those mentioned earlier except for midday prayer. Since M12 increases energy consumption, the second combination uses a midday base case (MB). This combination resulted in energy savings of 0.6%. Third, combining D11, M5, A12, and S2 resulted in energy savings of 3.3%. Fourth, the combination of the highest reduction of scenario I resulted in energy savings of 5%.

Table 4
Combination of individual scenarios

	Energy per total building area (kWh/m^2)	Energy savings %
Base case	183.6	
D11, M12, A12, *SB*	182.5	0.3
D11, *MB*, A12, *SB*	183.1	0.6
D11, M5, A12, S2	177.5	3.3
D4, M5, A2, S2	174.5	5.0

MB: Midday base case; *SB*: Sunset-night base case; D: Dawn; A: Afternoon; S: Sunset-night

These results are lower than those reported in other studies referenced earlier, specifically Budaiwi and Abdou [14], Diler *et al.,* [15], and Yüksel *et al.,* [16]. Nonetheless, this potential remains significant and should not be disregarded, as even a marginal increase warrants consideration. This is particularly pertinent when considering the minimal investment required to achieve such an increase. As a previous study has shown, a simple scenario, i.e. using components in good condition, can reduce energy by 6% [22]. Simple adjustments, such as modifying the air conditioning operating schedule, can yield benefits with little effort or cost. Therefore, even these modest gains should be factored into overall efficiency strategies, ensuring that all possible improvements are recognized and utilized to their full potential.

3.4 Limitation of This Study

Overall, the mosque is used five times a day throughout the year. However, mosques are also used for other religious events, such as during the month of Ramadan, where mosque use is very intense, as well as on other major Muslim holidays. This study only considered use during congregational prayers five times a day. Moments, as mentioned previously, are not included in this study. Therefore, further observations during these periods are necessary. However, what will be a challenge is that these events follow the lunar calendar system. Hence, the time continues to change according to the Gregorian calendar, making it complex to simulate.

4. Conclusions

Reducing the cooling period before prayer times effectively lowers annual energy consumption, with savings of 0.6 to 1.9% when the cooling time is cut to 10 minutes before prayer. Energy savings vary by prayer time, with midday and afternoon prayers achieving the most significant reductions.

Extending the cooling period 10 to 20 minutes after prayers increases energy consumption, especially during midday and afternoon due to higher outdoor temperatures. Shifting cooling periods can save 0.4% at dawn and 0.2% in the afternoon but increases energy use at midday due to high solar heat. This scenario shows insignificant changes in both energy increase and energy savings. Therefore, it can be considered to give time to worshippers who arrive late or those who pray late.

Combining the best cooling scenarios can enhance energy efficiency, with savings ranging from 3.3% to 5%. The optimal combination strategies include different scenarios for dawn, midday, afternoon, and sunset-night prayers, demonstrating the significant impact of tailored adjustments on overall energy consumption.

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