

## Article

# Assessing Mosque Energy Efficiency Using Smart Occupancy Sensors to Mitigate Climate Change in Hot Regions

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**Abstract:** Mosques are distinguished from other buildings functionally and operationally, so there has recently been great interest in the energy consumption inside them in Egypt. Consequently, the novel proposed methodology in this study is integrating smart occupancy sensor systems inside mosques and analyzing their current and further impact on energy consumption. Thus, the main aim is to reduce mosque energy consumption with the integration of smart sensors inside mosques besides the prediction of the efficiency of this approach based on climate change during the future periods of 2050 and 2080. Hence, the DesignBuilder software program was used to build the model and investigate the improvement of energy consumption after integrating smart occupancy sensors currently and in the future. The findings indicate that the reduction in total energy consumption ranges from 16.2% to 21.2%, while the energy index reaches 69 kWh/(m<sup>2</sup>·yr). The study proves the efficiency of smart occupancy sensors in reducing energy consumption in the short and long term, in addition to being an eco-friendly system and not requiring changes to the building structure.



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**Keywords:** smart sensors; energy index; energy efficient building; climate change

## 1. Introduction

Mosques are unique among religious buildings due to their high energy demands, driven by the varying usage patterns during the five daily prayers. The intermittent schedules and fluctuating user density make analyzing indoor thermal comfort and energy consumption distinct from other building types, such as residential or administrative facilities. In response, the Egyptian government has focused on optimizing energy use in mosques to reduce electricity costs for lighting, ventilation, and air conditioning, while maintaining comfortable indoor conditions and air quality for worshippers [1]. A number of studies have shown the critical role played by the architectural design of mosque elements in terms of minimizing energy consumption in mosques. Ref. [2] investigated the impact of architectural elements, such as roof type, floor plan, and size, on thermal comfort and energy consumption. They found that flat roofs and rectangular plans reduced annual energy consumption by 105 kWh/m<sup>2</sup> (about 23%) and 129 kWh/m<sup>2</sup>, respectively. Similarly, ref. [3] examined passive design strategies and architectural features to create sustainable mosque guidelines, highlighting four key design considerations: spatial layout and volume,

orientation, occupancy patterns, activity levels, and user clothing. Furthermore, ref. [4] stressed that modern mosques incorporate flexible architectural designs, allowing for smarter operations that adapt to future needs and evolving requirements.

Presently, smart mosque designs are being adopted globally, driven by the need for sustainability. Meanwhile, smart building technology affects all aspects of building control and management such as indoor temperature, humidity, airflow, energy, and light intensity. For this purpose, different strategies and sensors are used, such as the determination of indoor temperature, humidity, airflow, energy, and light intensity by different strategies and sensors such as air conditioning systems, window and door opening/closing systems, etc. [5]. In addition, thermal comfort, quietness, visual comfort, energy, and water rationalization during prayer times were all cited by [6] as the target elements of a smart mosque. A number of studies have compared the different smart mosque technologies, strategies, and systems. The DesignBuilder simulation tool and DIALux simulation software were used by [7] to evaluate a smart control system in terms of enhancing energy efficiency and indoor environment in hot-arid-climate mosques. The results revealed that using an LED lighting system led to a corresponding 9% decrease in energy consumption. Smart sensors showed their potential to save 21% of the total energy consumption. Ref. [8] developed an automated digital timer on/off control system that manages energy consumption in mosques. They achieved a 52–88 kW reduction in energy consumption in daily operations and on Fridays. In addition, ref. [9] studied a smart LED lighting system in a mosque. To collect data, they used communication protocols to control a wireless sensor and actuator network. It was found that the smart system could help save 60–70% of the energy needed for lighting, without impacting the recommended lighting level. In Turkey, ref. [10] evaluated six operation strategies, such as an underfloor heating system, in a mosque using dynamic computer simulations. They concluded that 9% of the energy consumption and 136 kg of CO<sub>2</sub> can be reduced by implementing the appropriate underfloor heating system. A number of retrofitting strategies were assessed by [11] with the aim of improving indoor thermal comfort in mosques and enhancing energy efficiency. Their results revealed that a 50% reduction in energy consumption can be achieved by applying a zoning strategy and an intermittent air conditioning operating system. Further, a number of energy-saving strategies used in mosques were evaluated by [1], such as LED lighting and installing solar PV panels.

To develop sustainable and efficient retrofitting strategies for smart mosques, it is crucial to assess their effectiveness and adaptability to future climate conditions, as discussed by [12,13]. For example, ref. [14] proposed a methodology that integrates machine learning, deep learning models, and energy prediction techniques to estimate energy usage in mosques. Their study demonstrated that the Convolutional Neural Network is a reliable tool for evaluating retrofitting options and predicting annual energy consumption. Furthermore, ref. [15] suggested innovative design concepts and passive strategies to improve the sustainability of mosque architecture. Last but not least, ref. [6] highlighted that future smart mosques will contribute significantly to advancing the technology sector in their respective regions.

To sum up, previous studies have shown differences in mosques' architectural characteristics and operation processes. Yet, there is a gap in research concerning the smart mosque concept. There is a need to assess the effect of retrofitting strategies in reducing energy consumption in mosques—both now and in the coming decades—to achieve sustainability in response to the expected climate changes. Therefore, this study aims to investigate the efficiency of smart occupancy sensors and LED lighting systems as retrofitting strategies to enhance energy efficiency and visual comfort, without any architectural changes, inside a mosque in Asyut, Egypt. In addition, the novelty of this study is that the prediction

of smart occupancy sensor performance will be investigated to prepare for the foreseen climate changes in 2050 and 2080. The findings of this study can be used for Egyptian mosques in general, and in hot arid climates, to rationalize energy consumption and achieve indoor comfort.

## 2. Case Study Description

In this study, a mosque in a hot Egyptian city has been selected to conduct the assessment and simulation process. The Teaching Staff (AUTS) Western House Mosque is located in the Western residential complex. Hence, the mosque is located in the city of Asyut at a latitude of  $27^{\circ}30'$  N and a longitude of  $31^{\circ}15'$  E with a temperature range  $41\text{--}46$  °C during daylight hours and  $16\text{--}21$  °C during nighttime hours in summer. The intermittent operation of the mosque is during the five prayer times (around 30 min for each prayer) and 15 min before and after the five prayer times, except for Friday prayers and Ramadan month prayers when the mosque's occupancy hours may exceed 90 min. The AUTS mosque consists of a two-floor plan while the architectural characteristics and the internal equipment are shown in Table 1.

**Table 1.** The architectural characteristics and the internal equipment of AUTS mosque (summary of [7]).

		The Assiut University Teaching Staff (AUTS) Western House Mosque	
		Ground Floor	First Floor
Inner spaces		Prayer hall Ablution area Entrance	Prayer hall Entrance
Activities		Daily prayers	Friday prayer, Ramadan month prayer, weddings, and special occasions
Area		115 m <sup>2</sup>	79 m <sup>2</sup>
Height		3.5 m	6 m
External wall	Material	Brick (finishing) air cavity red brick inside wood coating clay tile (roofing) with slope insulation	
	Thickness	0.48 m	
	U-value	0.986 W/m <sup>2</sup> K	
Roof	Material	Concrete slab Cement plaster (coating)	
	Thickness	0.60 m	
	U-value	2.93 W/m <sup>2</sup> K	
Glass window	Material	Single glass	
	Thickness	0.006 m	
	U-value	5.7 W/m <sup>2</sup> K	

The architectural characteristics

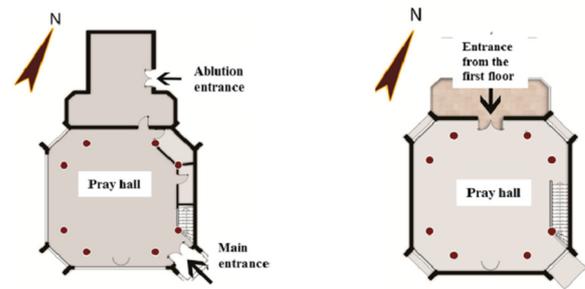
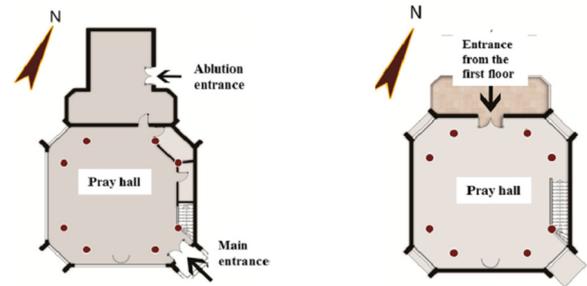


Table 1. Cont.

		The Assiut University Teaching Staff (AUTS) Western House Mosque	
		Ground Floor	First Floor
Indoor equipment	Lights	Number	36 florescent light (120 cm) 70 florescent light (60 cm)
		Energy	1440 Watt
	Fans	Number	12 small wall fan
		Energy	1440 Watt
	Air conditioners	Number	9 split units
		Energy	31095 Watt
	Air heaters	Number	2 units
		Energy	7000 Watt



### 3. Methodology

This study investigates the reduction in the annual energy consumption of lighting and cooling inside the case study (AUTS mosque) by using smart occupancy sensor technology in the present and predicts the energy savings for the two future periods, 2050 and 2080. Firstly, field measurements were conducted inside the mosque to observe and analyze the indoor thermal comfort (air temperature and relative humidity) and visual comfort (lighting distribution) and determine the energy consumption. Consequently, the indoor air temperatures and relative humidity were collected by using a set of tripods with temperature/humidity data loggers at a height of 0.6, which were installed in the prayer hall when worshippers were praying and practicing different activities. Thus, the tools used were Thermo recorder data loggers (model TR72Ui) with a measuring accuracy of  $\pm 1\%$  RH,  $\pm 0.1$  °C. On the other hand, a zoning strategy was applied inside the mosque to divide the total area into grid points and measure each point to indicate the illumination level by using Surfer 10 software. Secondly, the simulation model of the base case was constructed using DesignBuilder software (V.5.0.3.007) to provide the real energy model of the mosque. Thereby, the simulation model was validated based on energy consumption monitoring inside the mosque with strong agreement and a value of coefficient of determination ( $R^2$ ) equal to 0.987 [7,16]. Thirdly, smart occupancy sensors and an LED lighting system were proposed as retrofitting strategies to improve energy efficiency and reduce energy consumption without any architectural changes. A smart occupancy sensor is smart control technology that contains smart sensors to detect occupancy and switch lighting and air conditioning on/off accordingly. On the other hand, to achieve sustainability in the coming years inside the mosque, the effect of the proposed retrofitting strategies should be predicted and investigated in the future in response to the upcoming climate changes. The proposed methodology of this study is detailed in Figure 1 and consists of three main strategies:

- (1) Stage 1: Collecting field measurements for indoor air temperature, relative humidity, lighting distribution, and energy audit monitoring.
- (2) Stage 2: Conducting simulation modeling for the base case and proposed retrofitting strategies (smart occupancy sensors and an LED lighting system) by using DIALux

software 4.10 to improve lighting intensity inside the mosque and enhance the sense of a worship place with a presence of divinity. Then, DesignBuilder software is used to investigate the effect of the smart occupancy sensors and LED lighting system on reducing the total energy consumption (as shown in Figure 2).

- (3) Stage 3: Preparing the future weather files based on a prediction of two periods in 2050 and 2080 by using the CCWorldWeatherGen tool, and predicting the future effect of the retrofitting strategies in terms of reducing the energy consumption relative to the base case.

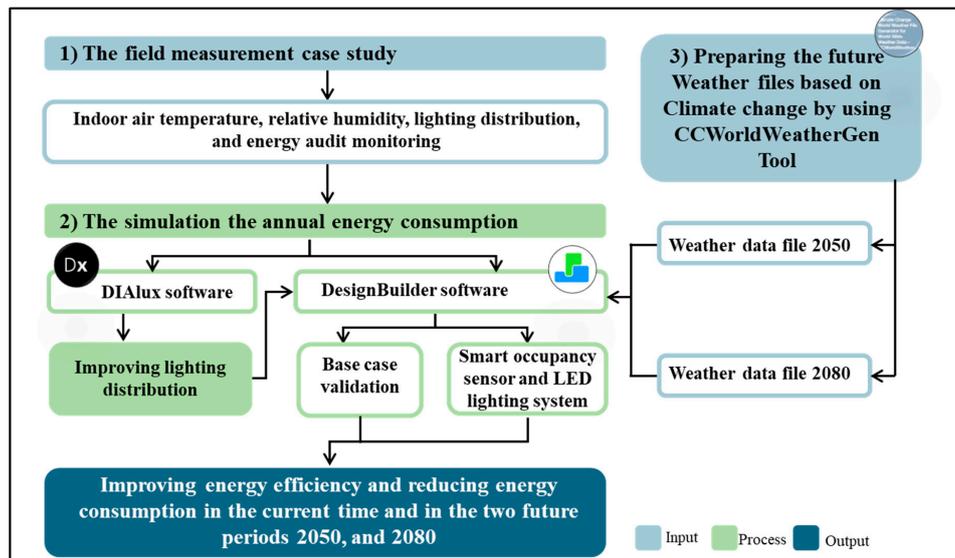


Figure 1. The proposal methodology.

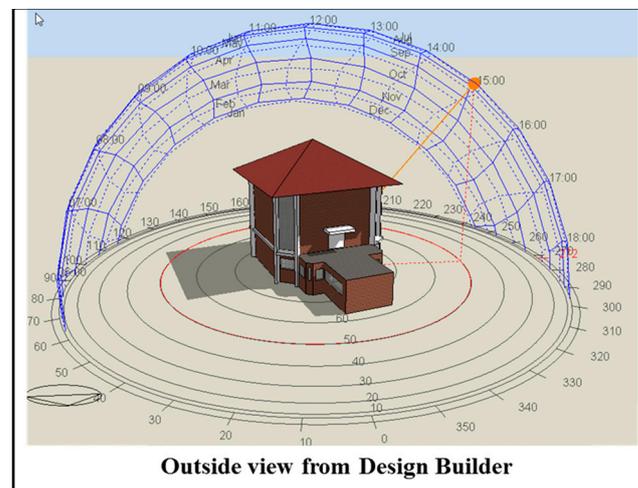


Figure 2. A simulation model of the base case in DesignBuilder software.

Hence, the outcome of this methodology is improving energy efficiency and reducing energy consumption in a real model and the two future periods, 2050 and 2080. Moreover, the methodology helps integrate different smart control technologies to provide spirituality, tranquility, thermal comfort, and low energy consumption in the mosque.

The future weather data tool CCWorldWeatherGen was used to predict the weather in the upcoming periods. This tool is easy, rapid, and accurate for obtaining the weather file of the city of Asyut in the future periods 2050 and 2080 in the “epw” format [17,18]. The abilities of this tool are analyzing the weather during a time of around 30 years and obtaining the weather data in the last year of the study period based on meteorological

observations. For example, the program studies the weather data for the period between 2020 and 2050, finally, it outputs the weather file for 2050, and so on for other years such as 2080. On the other hand, one of the limitations of the CCWorldWeatherGen tool is that it is accurate only for annual air temperature prediction, while ignoring other climate elements such as relative humidity and solar radiation. As shown in Figure 3, the average annual air temperature will be highly raised by 3.44 °C and 5.70 °C in the future periods 2050 and 2080, respectively, compared with the air temperature in the current period.

As a result, the weather data files for the two cases could be obtained to modify them in element software and EnergyPlus converter. Finally, energy modeling processes for the base case and retrofitting strategies could be conducted by using DesignBuilder software to estimate the annual energy consumption for the present, 2050, and 2080 as shown in the next section. Therefore, the energy consumption for the base case was estimated during the three study periods as clarified in Figure 4. It can be observed that the total energy consumption will increase by ratios of 30.24% and 34.9% during the two future periods, 2050 and 2080, respectively. The energy index of the base case was also calculated as 87.5 kWh/(m<sup>2</sup>·yr) for the present, while also rising to reach 113.9 and 134.4 kWh/(m<sup>2</sup>·yr) for the two future periods 2050 and 2080. So, sustainable retrofitting strategies should be applied to the base case to reduce energy consumption now and in the future.

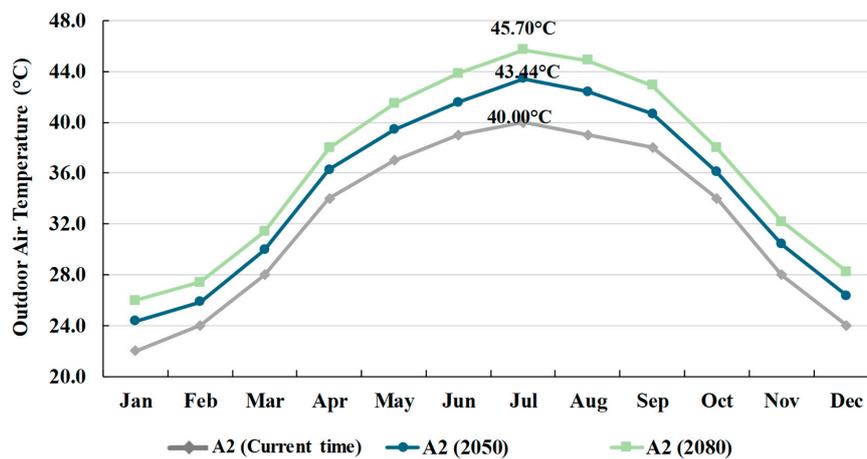


Figure 3. The predicted annual air temperature in the city of Asyut currently and in the two years 2050 and 2080.

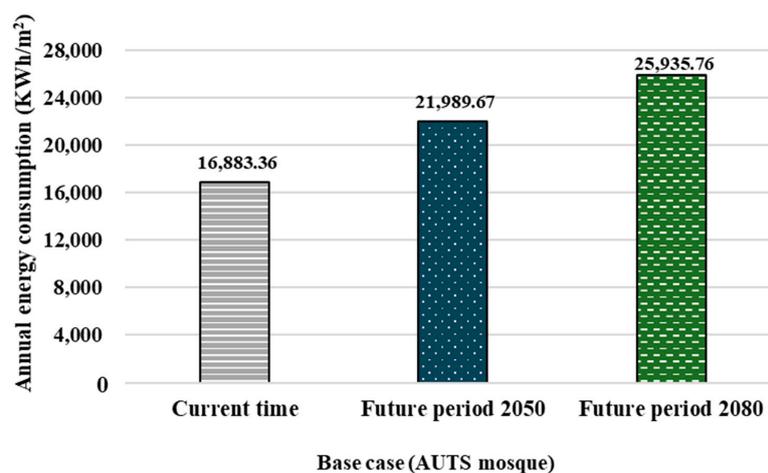


Figure 4. The predicted annual energy consumption currently and in the future periods, 2050 and 2080.

## 4. Results and Discussion

### 4.1. Base Case Measurement Results

In this step, the study monitored the illumination levels and energy audits inside the AUTS mosque for a short time and compared the measurements with the previous measurements by [7]. A great deal of convergence in the measurements was found, which makes it possible to rely on the reference measurements by [7] as a preliminary step and then focus on studying the impact of the smart sensor system in the future as the novelty of this study. The illumination levels were measured inside the AUTS mosque on the ground floor, as shown in Figure 5. While the illumination values were from 54 to 186 lux, there is a low illumination level generally, except on the west side, based on the illumination scale [19]. Accordingly, the west side of the prayer hall and next to the stairs had the highest and lowest illumination levels, respectively, during the times Dhur and Asr. Consequently, the illumination level and lighting intensity should be improved especially near Mehrab where the Imam's place is located and lectures and congregations occur. On the other hand, the energy audits were monitored and the energy consumption patterns were obtained on 22 April 2015, as shown in Figure 6. The results reveal that the highest energy consumption observed was about 5100 W between the times Maghrib and Isha and based on the number of prayers and equipment used (such as fans and air conditioners).

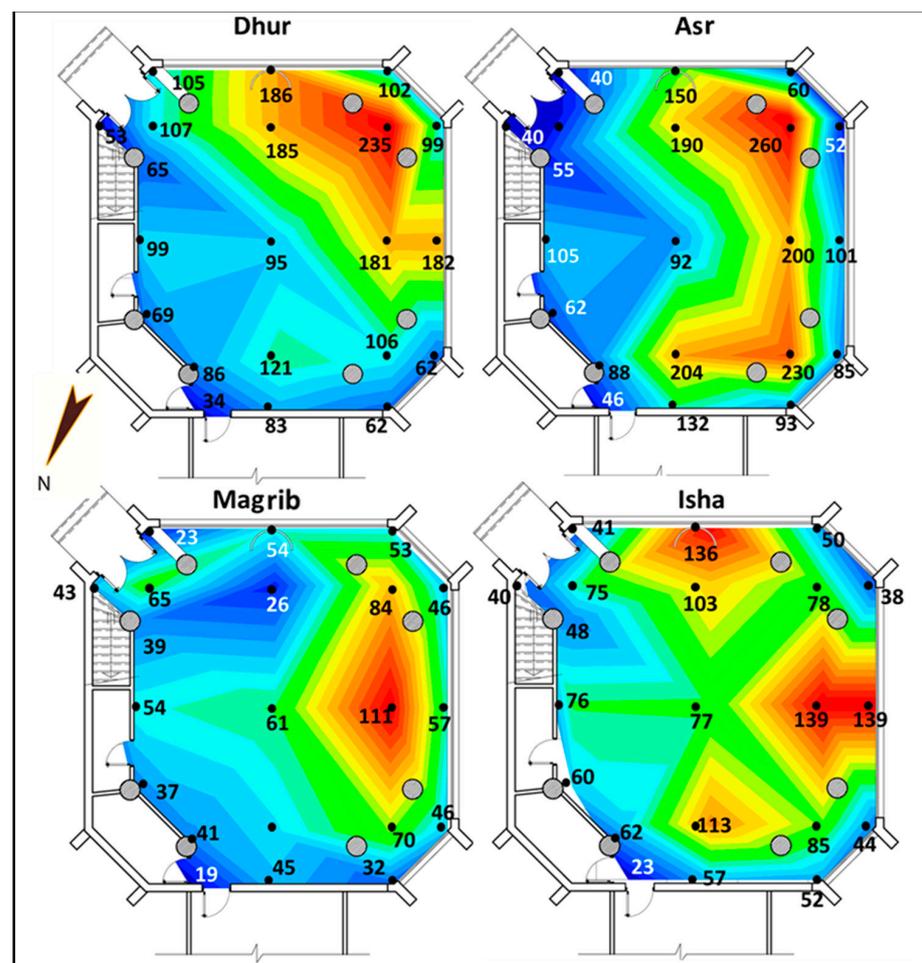


Figure 5. The illumination levels on the ground floor of the AUTS mosque (by [7]).

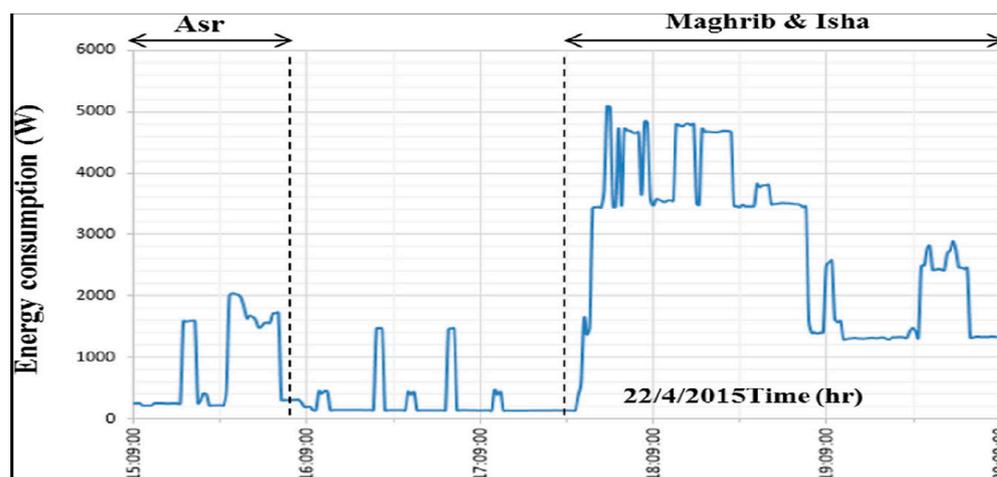


Figure 6. The energy consumption patterns of the AUTS mosque (by [7]).

#### 4.2. Simulation Results

The DesignBuilder 6 software program was chosen to build the model and simulate the cases. Thus, the validation process was conducted by comparing the field measurements of the energy audit with the simulation results. Accordingly, the coefficient of determination ( $R^2$ ) between the measured and simulated energy consumption was 0.98, which indicated a good correlation and confirmed the performance and accuracy of the simulated model. Then, DIALux software was used to apply an LED lighting system inside the base case. Hence, a type of LED fluorescent lamp, named the Philips SM461V, with an energy consumption of 21W, was used during the simulation process to enhance the illumination level and to enhance energy efficiency. Therefore, the mosque's ground floor was divided into three sections and the LED fluorescent lamps were distributed while the illumination of each section ranged from 100 to 150 lux, as shown in Figure 7. The DIALux results showed that visual comfort was improved by using an LED lighting system, which led to enhanced spirituality and tranquility. Also, these results were inserted as inputs into the DesignBuilder software, so the total annual energy consumption was reduced by a ratio of 9% by applying an LED lighting system. As mentioned before, the measurements in a previous study by [7] were compatible with our measurements and were more accurate because they were conducted over a long time, so they were relied on in Figures 5–7 with the citation of the reference in the captions.

Secondly, the efficiency of smart occupancy sensors as a retrofitting strategy was investigated by using DesignBuilder software. So, the model of the AUTS mosque was generated in DesignBuilder with the floor plan divided into three stages, so that each stage had a set of LED fluorescent lamps, one fan, and one air conditioner. Then, all of the stages were operated and controlled separately by the smart occupancy sensors based on the number of prayers (Figure 8). The capacity and equipment of each stage are clarified in Figure 8. The proposed smart sensor occupancy system is classified as a real-time occupancy detection system based on a passive infrared sensor that detects the presence or absence of people within a defined space by receiving infrared radiation. Hence, the system of smart occupancy sensors automatically controls the switching on and off of the internal equipment in the first, second, and third stages, when the number of prayers ranges from 2 to 47 persons, from 48 to 94 persons, and from 95 to 140 persons, respectively.

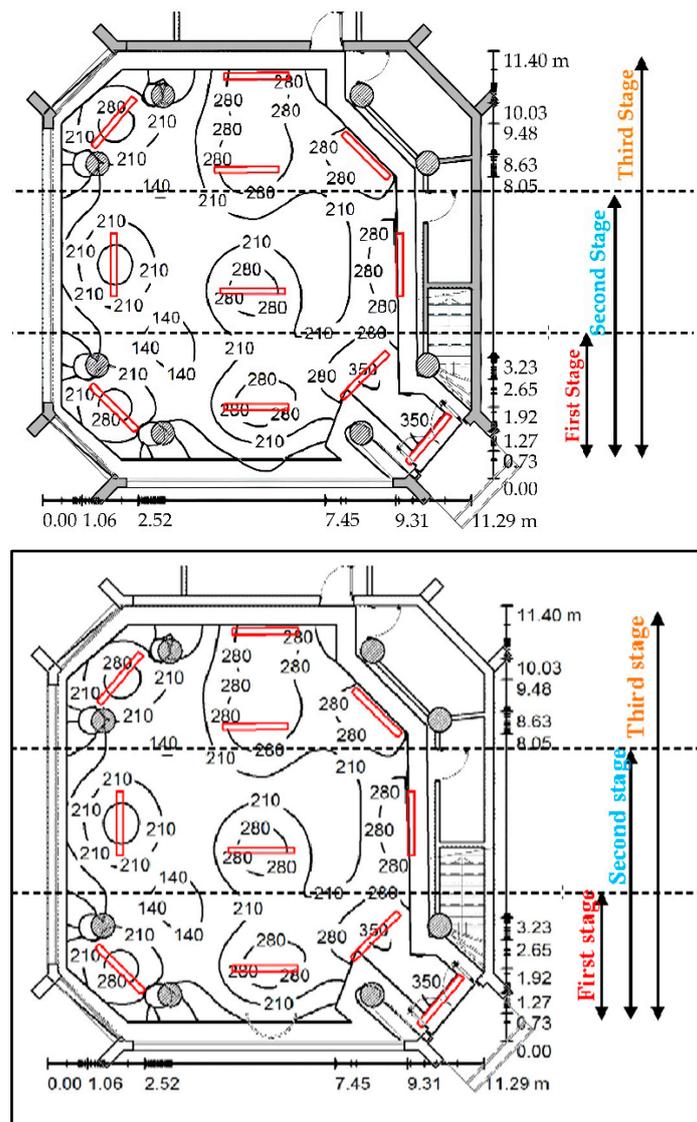
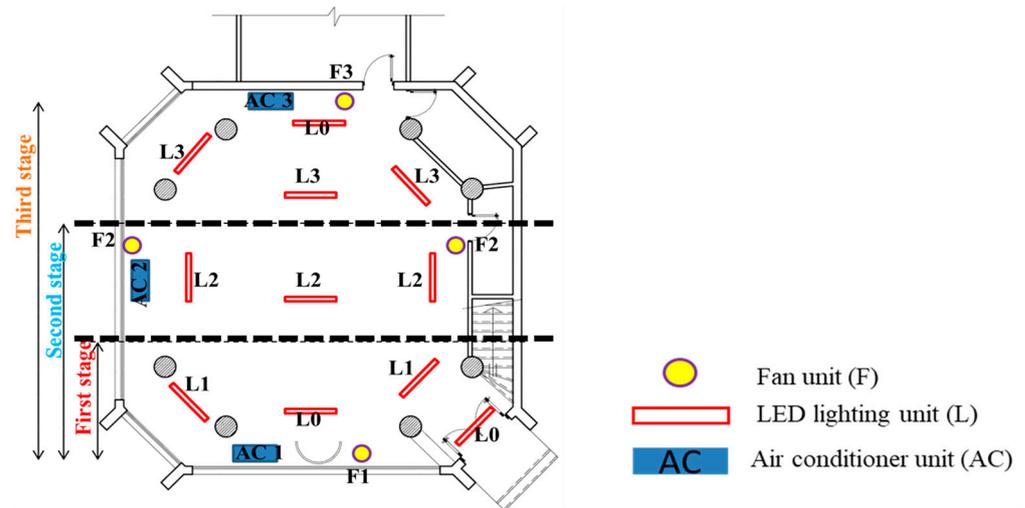


Figure 7. The distribution of the LED lighting system in the base case using DIALux software (by [7]).

Figure 9 illustrates the enhancement of energy consumption using an energy index for the base case and the three stages of installing the smart occupancy sensor. The energy index values for the first, second, and third stages are 68.9, 71.2, and 80.8 kWh/(m<sup>2</sup>·yr) compared with 87.5 kWh/(m<sup>2</sup>·yr) for the base case. Hence, the percentage of the reduction in the annual energy index is the highest in the first stage, by a ratio of 21.3%, and the reduction is by 18.6% and 7.7% in the second stage and third stages, respectively. Hence, by applying the smart occupancy sensor in the first stage and for the lowest occupancy level, the greatest improvement in energy efficiency occurred. So, the first stage of the smart system is suitable for the daily prayer times of the mosque, while during the Friday prayers and the Isha of Ramadan, the third stage will be applied. These results are compatible with the results of [7]. Consequently, enhancing energy efficiency in a mosque is related to the existing and changing occupancy patterns inside the mosque.



Stage	Prayer number	Lighting units (L)	Fan unit(F) If air temperature 25°C < T ≤ 28°C	Air condition(Ac) If air temperature >28°C
Initial stage	1	L0		
First stage	2:47	L0, L1	F1	AC1
Second stage	48:94	L0, L1, L2	F1, F2	AC1, AC2
Third stage	95:140	L0, L1, L2, L3	F1, F2, F3	AC1, AC2, AC3

Figure 8. The description of the 3 stages of the smart occupancy sensor system.

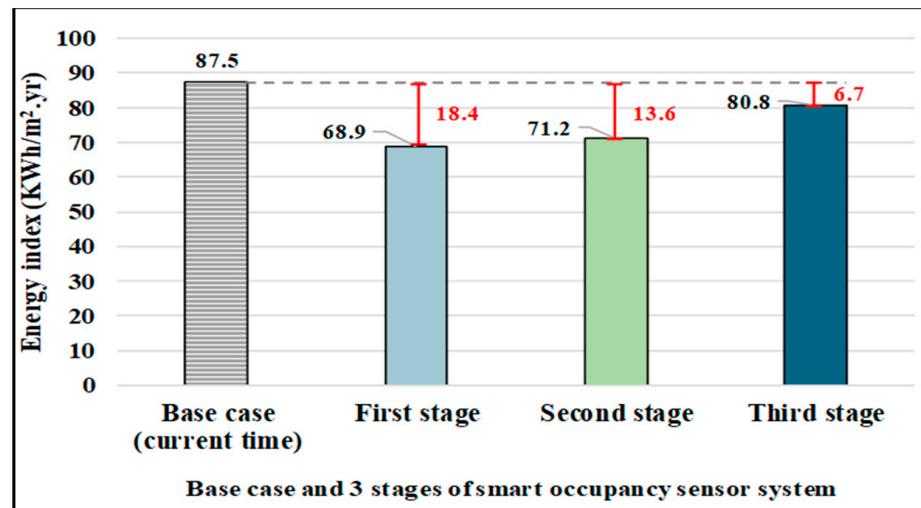


Figure 9. The simulation results of the energy index in the base case and the 3 stages of the smart occupancy sensor system for the present.

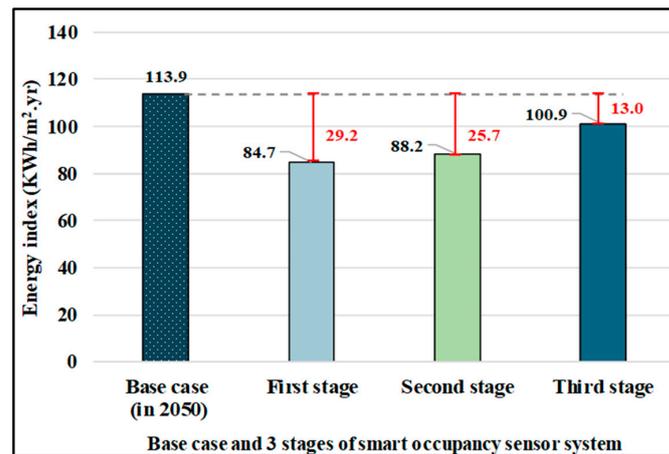
#### 4.3. Simulation Results in Two Different Periods of 2050 and 2080

To prove the efficiency of the two future retrofitting strategies, their impact should be predicted and investigated in the future to face the upcoming climate changes. So, the two weather files of the two future periods of 2050 and 2080 were obtained using the CCWorld-WeatherGen tool and inserted into the DesignBuilder software. Accordingly, during the future period 2050, the energy index of AUTS mosque is predicted to be 113.94 kWh/(m<sup>2</sup>·yr) without applying any retrofitting energy, but after operating the smart occupancy sensors the energy index will be reduced by 29.2, 25.7 and 13 kWh/(m<sup>2</sup>·yr) by applying the first, second, and third stages of the smart occupancy system, respectively, as shown in Figure 10a. Thus, the percentage of reduction by applying the smart occupancy sensor during the future period 2050 will be 25.6%, 22.3%, and 11.4% in the three stages in order. On

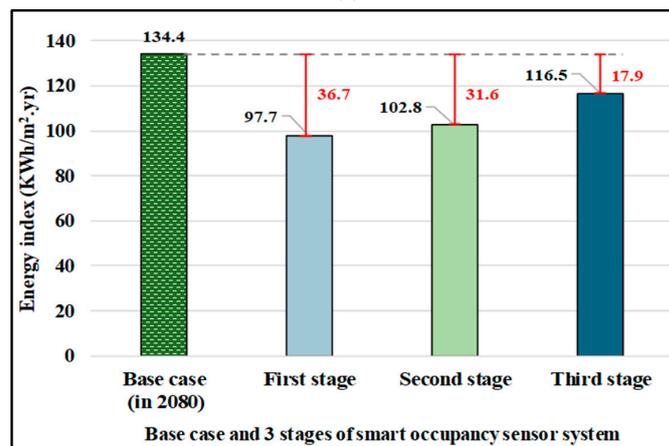
the other hand, in the future period 2080, the energy index will decline to 97.7, 102.8, and 116.5 kWh/(m<sup>2</sup>·yr) in the three stages of the use of smart occupancy sensors, respectively, compared with 134.4 kWh/(m<sup>2</sup>·yr) in the base case. Hence, installing smart occupancy sensors will save 27.3% of the energy index in its first stage, 23.5% in the second stage, and 13.3% in the third stage (Figure 10b). Consequently, the highest reduction in the energy index was obtained by applying the smart occupancy sensors in the long term for the future period 2080 (reached 27.3%), and this proves the efficiency and sustainability of the system over time.

Furthermore, Figure 11 clarifies the reduction in annual energy consumption in the three stages of smart occupancy sensors compared to the base case in the current time and the two different periods 2050 and 2080. It was found that by operating the first stage of the proposed smart system, the highest reduction was obtained, whether in the present or the future. While the annual energy consumption is reduced by 25.3% in the present, it is predicted to decrease by 25.6% and 31.1% in the future periods 2050 and 2080. Also, by operating the second stage of the smart occupancy sensors, the annual energy consumption reduced from 16,883.36 kWh/m<sup>2</sup> to 13,021.24 kWh/m<sup>2</sup> in the present (about 22.9%). In addition, energy consumption saw reductions of 22.6% and 27.5% in the future periods 2050 and 2080, respectively. Despite the third stage of smart occupancy sensors being operational, and there being a large number of lighting and ventilation devices operating, the decrease in annual energy consumption reached 14,786.77 kWh/m<sup>2</sup> by a reduction percentage of 12.4% for the present. Additionally, the predicted reduction percentage is 11.4% for the future period 2050. It is also expected that the percentage will reach its highest level, which is 17.8%, for the future period of 2080. Finally, the sustainability and durability of the proposed smart occupancy sensors in terms of reducing the annual energy consumption currently and in the future has been proven.

Finally, Figure 12 illustrates the average energy consumption of each category separately, such as the mosque's electricity, lighting, cooling, and equipment in the base case and the three stages of the smart occupancy sensor system. In the present, the base case consumes almost all of the energy for cooling, reaching 838.1 kWh/m<sup>2</sup>. But, by applying the smart occupancy sensor system, the energy consumption for cooling drops to 323.6, 367.3, and 304.4 kWh/m<sup>2</sup> in the first, second, and third stages, respectively. Also, the energy consumption for lighting is reduced by 82.6 kWh/m<sup>2</sup> in each stage separately. In the future period of 2050, the energy consumption for cooling demand will be up to 893.1 kWh/m<sup>2</sup>, so the smart occupancy sensor system will achieve reduction values of 429.8, 375.1, 322.2 kWh/m<sup>2</sup> in the first, second, and third stages, respectively, in addition to a reduction of 69.1 kWh/m<sup>2</sup> in lighting energy consumption. By the 2080 period, the average energy consumption for cooling in the base case will reach its highest value of 928.1 kWh/m<sup>2</sup> due to the increasing air temperature. Accordingly, the efficiency of the smart occupancy sensor system will assist in decreasing this value by 336.5 kWh/m<sup>2</sup> in the first stage, 288.7 kWh/m<sup>2</sup> in the second stage, and 278.8 kWh/m<sup>2</sup> in the third stage. While the reduction in lighting energy consumption will be 52.3 kWh/m<sup>2</sup> in each stage separately. Hence, the highest reduction in energy consumption for each category was obtained in the present and will be continued into the future periods, 2050 and 2080, with slightly smaller reductions.

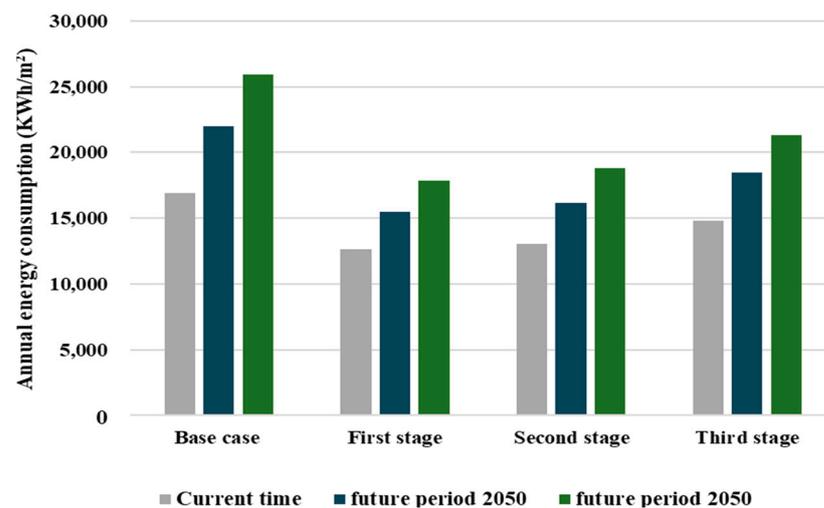


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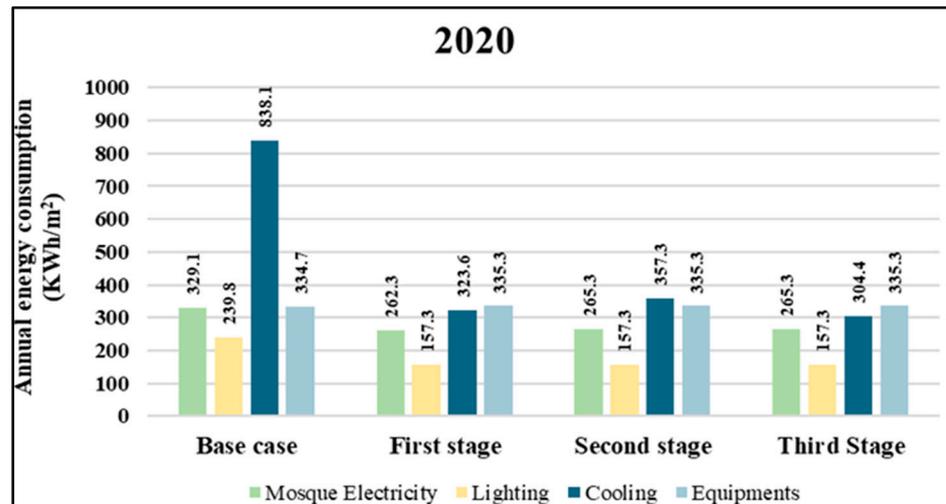


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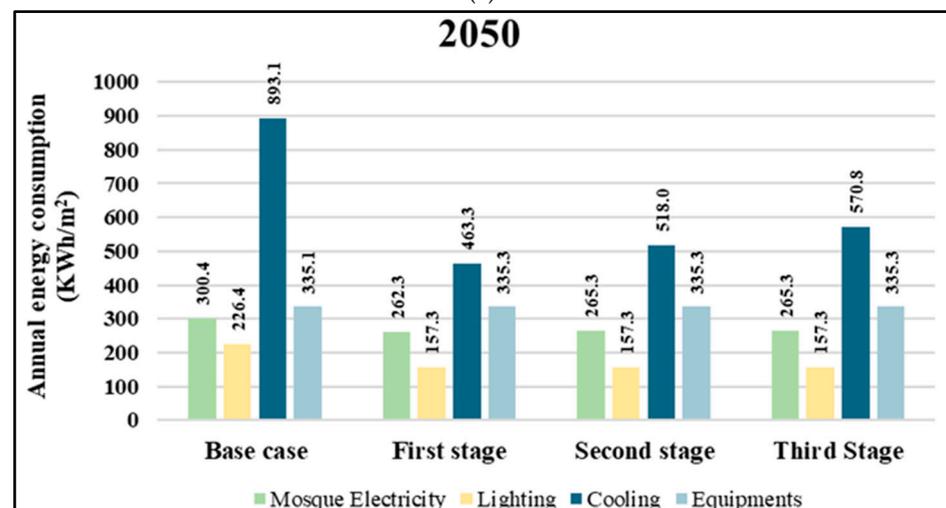
**Figure 10.** The simulation results of the energy index in the base case and the 3 stages of the smart occupancy sensor system; (a) for the future period 2050 and (b) for the future period 2080.



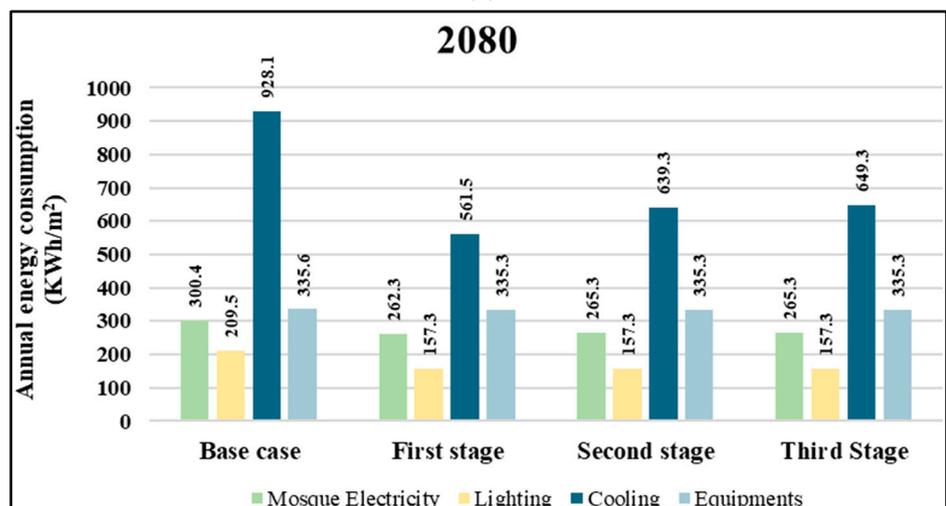
**Figure 11.** The annual energy consumption in the base case and the 3 stages of the smart occupancy sensor system.



(a)



(b)



(c)

**Figure 12.** The detailed energy consumption in the base case and the 3 stages of the smart occupancy sensor system; (a) in the current time of 2020, (b) in the future period 2050, and (c) in the future period 2080.

## 5. Conclusions

This study investigates and highlights the use of a smart control system as a concept of energy reduction that can be implemented inside mosques without requiring a significant change in the mosque's architecture, using DIALux lighting design software and DesignBuilder. The main results can be summarized as follows:

1. The monitoring of the mosque's indoor illumination level indicated the lowest intensity level on the ground floor during sunset, which ranges from 54 to 186 lux.
2. Based on the simulation, replacing traditional lighting units inside the mosque with efficient LED units achieved a 9% total energy reduction. All the fluorescent lamps were surface mounted in the ceiling to minimize the brightness for people and provide better visual comfort/working environment inside the mosque when reading the Quran, with an  $E_0 = 0.69$  (Eaverage/Emax).
3. A significant reduction in the annual energy consumption was based on using a smart occupancy plan (during prayers), with a percentage ranging from 16.2% to 21.2%.
4. The energy index inside the mosque reduced to 69 kWh/(m<sup>2</sup>·yr) compared to the base case.

Therefore, the occupancy and different use patterns inside the mosque strongly affect energy reductions by using a smart control system. This is applicable to most of the prayer times, except during many existing prayers at certain times such as Friday prayers and the month of Ramadan.

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