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Analysis of Electricity and Water Consumption in Existing Mosque Buildings in the UAE

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Abstract: According to the World Economic Forum, the building sector is responsible for 40% of global energy consumption and 33% of greenhouse gas (GHG) emissions, and this is expected to increase due to population growth and the subsequent impact on the environment, economy and health. To tackle the problem, countries have set new construction codes, policies and regulations for the construction of new buildings in an effort to make them greener. However, there is a need to enhance the status of the existing buildings, especially mosques, as they are the main contributors to energy usage and water consumption in the United Arab Emirates (UAE). Therefore, this research seeks to fill this gap, aiming to evaluate the energy usage and water consumption practices employed in the existing mosque buildings within the UAE and to provide recommendations for improving the sustainability of mosques, with a focus on the environmental and economic pillars. The methodology relies mainly on data collected from 146 existing mosque buildings that have undergone energy saving audits across the UAE. Descriptive statistical analysis is performed to analyze the data from the period of 2018–2019 in order to determine the most significant factors related to energy inefficiency in existing mosque buildings in the UAE and to determine the most cost-effective and energy-saving corrective measures for energy and water conservation. The findings further enhance the standard of experience for mosque visitors (social aspect); reduce energy bill expenses, providing an acceptable return on investment from the proposed energy conservation measures for stakeholders (economic); and reduce the overall energy consumption, which can reduce the total CO_2 emissions from mosque buildings (environmental).

Keywords: energy; mosques; electricity; consumption; EPI; ECM

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1. Introduction

Over the last two decades, the consumption of energy around the world has increased by 49% and CO_2 emissions have increased by 43%, with an average yearly rise of 2% and 1.8%, respectively, due to the rapidly increasing global energy use that has sparked worries about supply issues, energy resource depletion and the severe environmental consequences. As a result, the worldwide contributions to energy consumption by buildings, both residential and commercial, has gradually grown and has surpassed the other main sectors: transportation and industry [1]. Moreover, population growth, a rising demand for building services and comfort levels and an increase in time spent within buildings, especially with the outbreak of COVID-19, all suggest that the increase in energy and water consumption will continue. As a result, energy efficiency in buildings is now a top priority for energy policy makers at the regional, national and international levels [2].

1.1. Improving the Energy Efficiency of Existing Buildings

Globally, 40% of energy is consumed by the building stock, and it releases one-third of the total GHG emissions [3]. Therefore, improving the energy efficiency of buildings is essential for tackling climate change and achieving net zero-energy. This has been the focus

of several recent studies focusing on existing buildings that have tackled customer needs but increased their energy insufficiencies. Accordingly, all stakeholders need to collaborate to improve building performance. The basic actions to be considered to decrease energy usage in buildings include mechanical solutions, such as changing the heating, ventilation and air conditioning system (HVAC) and using natural ventilation for cooling, in addition to installing automated lighting systems or upgrading the building envelope. It is worth mentioning that each suggested solution for improvement comes with its own benefits and drawbacks, which create the need to evaluate such measures in real setups and not just rely on the proposed theoretical solutions.

All buildings, from the tiniest school to the highest skyscraper, rely on energy provided mostly by the combustion of fossil fuels. The combustion of fossil fuels emits GHG into the atmosphere, contributing to the problem of climate change. Worldwide, the building sector consumes electricity more than any other sector [4]. With rising urbanization, particularly in developing nations, the number and size of buildings in urban areas will grow, resulting in a greater need for electricity and the other kinds of energy widely utilized in buildings.

Studying the nature and structure of energy usage in buildings is critical for developing the appropriate future energy and climate change strategies. The literature reports how to improve buildings' energy operations, while assessing the advantages and disadvantages of energy efficiency improvement initiatives, such as energy conservation measures (ECMs). Such examples illustrate the possibility of implementing a framework to improve buildings' energy operations and to provide policy and decision makers with better solutions to tackle insufficient energy usage in the building sector. Whether these frameworks are applicable at the level of the United Arab Emirates (UAE) remains to be further addressed and evaluated. Nonetheless, the study and evaluation of implementing ECMs in warmer climates, such as the UAE, remains a gap in literature [5], as most of the existing studies are focused on improvements in the building envelopes in colder or mild climate regions. Therefore, the proposed study focuses on the existing mosques within the UAE and provides input to address the effectiveness of implementing ECMs in reducing energy consumption and the carbon footprint.

1.2. Energy (Electricity), Water Consumption and Buildings

According to the 2022 Global Status Reporting for Buildings and Construction issued by the United Nations Environment Program [6], the global energy demand reached around 135 Exajoule (EJ) in 2021, showing an increase of 4% compared to 2020 due to businesses resuming normal operations and buildings being operated more intensively than during the COVID-19 pandemic. Overall, the building energy demand, which included residential, non-residential and building construction industry, reached 34% of the total global energy demand in 2021, as shown in Figure 1. On the other hand, operational energy-related CO_2 emissions from buildings reached around 37% of the global CO_2 emissions in 2021, and showed an increase of around 5% compared to 2020, which indicates that the overall energy efficiency of existing buildings has not seen significant structural changes.

Within the context of the UAE, the State of Energy Report issued by the Ministry of Energy and Infrastructure in 2019 [7] shows that the UAE is moving toward a reduction in energy consumption to protect the environment by reducing the consumption of electricity, as the country relies on consuming natural gas to generate more than 90% of its power to meet the demand. The UAE is currently shifting towards employing other resources for electricity generation, such as renewable energy, but the current situation shows a high electricity demand, mainly due to a high consumer per capita rate and a population increase, coupled with economic growth.

Moreover, the latest available statistical report, issued in 2019 by the UAE's Ministry of Energy and Infrastructure [8], shows that the energy sector has experienced an upward trend in terms of increasing the energy generation. As shown in Figure 2, Abu Dhabi has produced the highest amount of energy amongst all the UAE emirates, as per the data obtained from the Department of Energy (DOE), followed by Dubai, as per the Dubai

Electricity and Water Authority (DEWA). The next highest was Sharjah, according to the Sharjah Electricity, Water and Gas Authority (SEGWA), and lastly, the rest of the emirates, as per the Federal Electricity and Water Authority (FEWA). In terms of energy consumption (Figure 3), the report also shows the increase in the overall energy consumption in the UAE from 2016 until 2018, which is a reflection of the increase in energy generation.

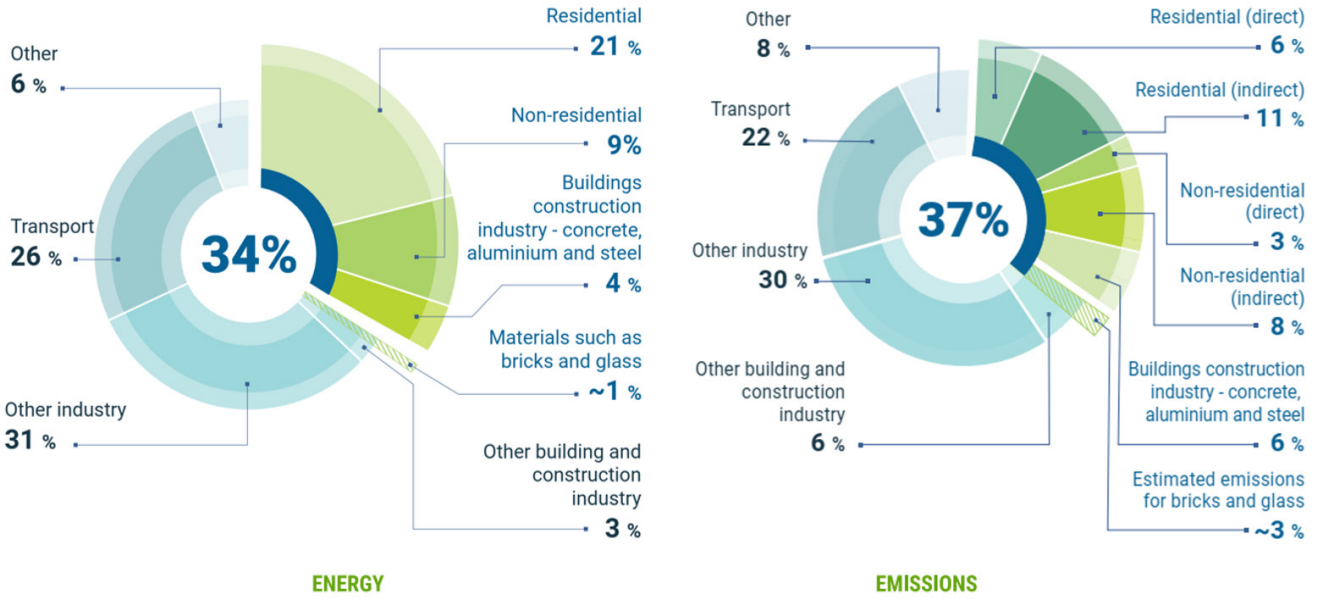


Figure 1. Buildings and construction's share of global final energy and energy-related CO_2 emissions, 2021. Adapted from [6]. Note: numbers in pie charts are rounded figures and should not be summed up to calculate total values.

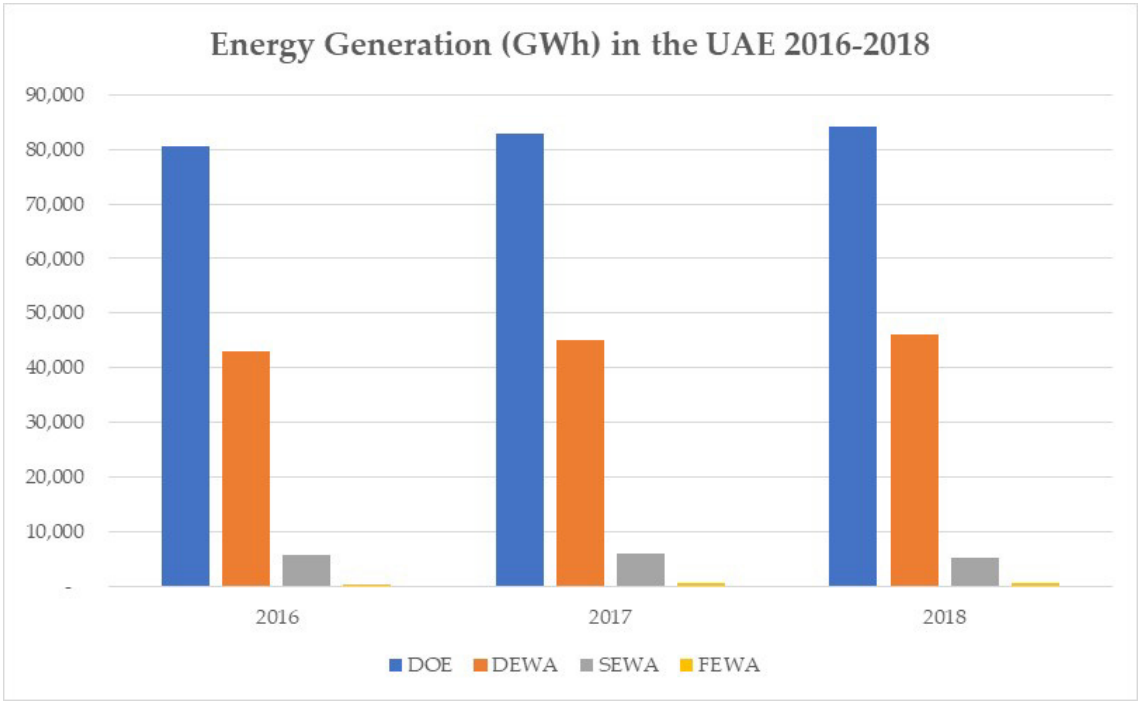


Figure 2. Energy generation in gigawatt hours (GWh) in the UAE between 2016 and 2018. Source: [8].

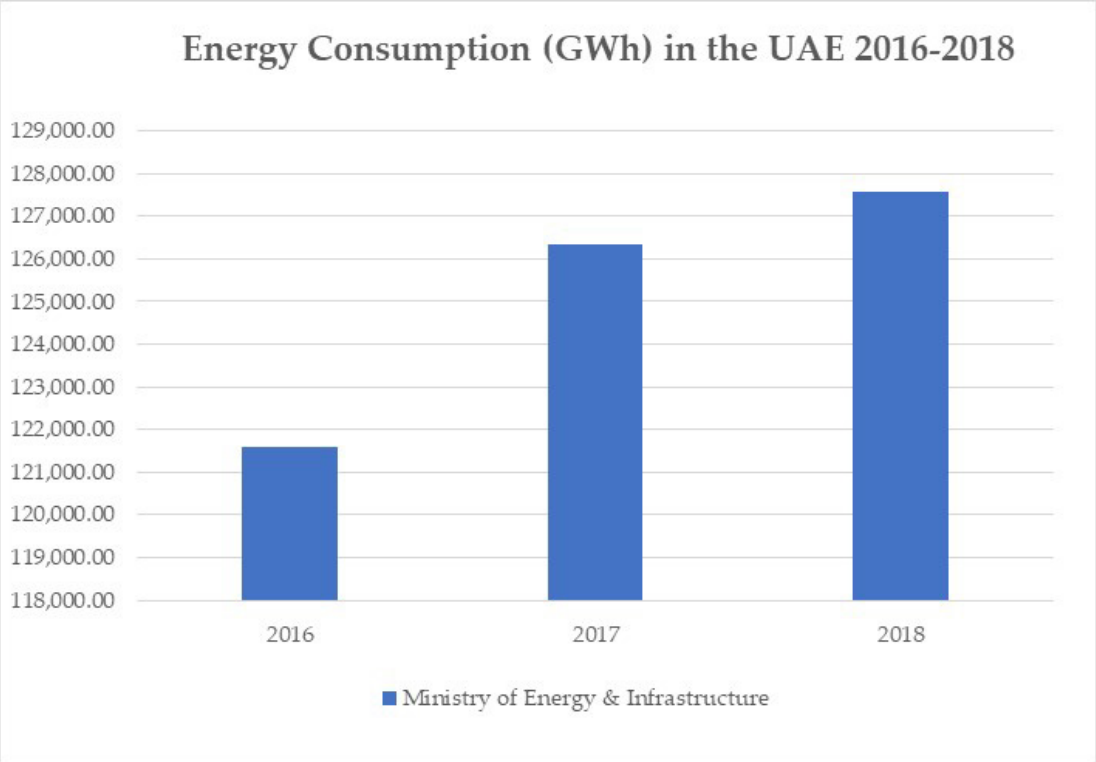


Figure 3. Energy consumption in gigawatt hours (GWh) in the UAE between 2016 and 2018. Source: [8].

In terms of carbon emissions, the report also highlights the contribution of several sectors, such as electricity and water production, as shown in Figure 4, along with the manufacturing industries and construction. Overall, the carbon emissions seem to have declined in the manufacturing and construction sectors, whereas they have increased over the period of 2015–2018 in the electricity and water sector, further confirming that the increase in energy consumption has led to an increase in electricity generation.

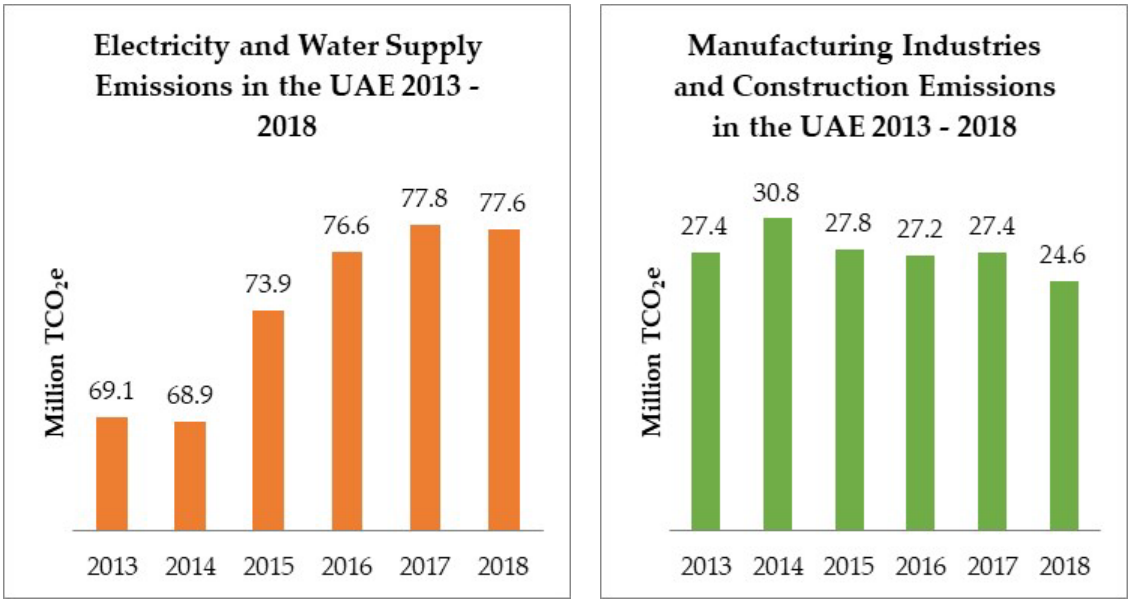


Figure 4. Carbon emissions in the UAE electricity and water supply sector vs. the construction sector between 2013 and 2018. Source: [8].

Regarding non-commercial buildings, such as mosques, it was reported through the Annual Statistics 2021 Report of DEWA [9] those non-commercial buildings consumed 7.44% of the total electricity consumed in 2020, equivalent to 3304 GWh, in addition to consuming 7.15% of the total water consumed in 2020, which is equivalent to 31.16 million cubic meters (m^3). As the vast majority of the UAE's population are Muslim, mosques, the holy place for worshipers in the Muslim community, are considered a major contributor to the UAE's water and electricity consumption. There are approximately 9083 mosques, as per the latest counts reported in 2020 [10]. Therefore, this study aims to identify the factors that correlate significantly with inefficient energy usage and water consumption in the existing mosque buildings in the UAE; to identify the most cost-effective and energy-saving conservation measures to resolve the inefficient energy usage and water consumption in the existing mosque buildings from the economic, environmental and social perspectives; and to identify how policymakers and stakeholders can improve the energy efficiency and reduce water consumption and CO_2 emissions by mosque buildings.

1.3. Contributing Factors to the Inefficient Use of Energy in Existing Buildings in the UAE

The UAE has seen an increase in the number of buildings constructed, as reported by the latest statistical federal report released in 2022 by the UAE's Ministry of Energy and Infrastructure [11]. The total number of federal buildings constructed in 1971 was 37, which increased to 805 in 2000 and then began to decline, reaching 96 in 2019. The previous numbers indicate that the initial increase in federal buildings was necessary to drive the progress of the country, but after a period of time, the number of new buildings decreased upon satisfying the intended purpose of their construction. Moreover, when considering the local governments of the emirates, Dubai has seen an increase in the total number of constructed buildings, (i.e., residential, commercial, industrial, investment or private villas) from 121,584 in 2015 [12] to 160,128 in 2019 [13], which further shows that the growth of the construction sector is associated with a higher rate of energy consumption. Accordingly, the need to retrofit such buildings may arise after observing the energy consumption rates and realizing the potential for savings in terms of the cost and environmental impact.

Energy can be wasted in buildings due either to the buildings' designs [14,15] or the occupants' behaviors [1,16] within the building. Table 1 summarizes the factors most commonly identified in the literature that are related to the building design, which is the subject of focus in this paper.

Previous studies have addressed the factors mentioned above. For instance, a simulation of the energy performance of a single-family two-story villa in Dubai [17] showed 23% energy savings upon applying insulation, while another study [18] revealed that AC cleanliness and chiller condition significantly impacted the energy use levels in mixed-used buildings in Abu Dhabi, UAE, further emphasizing the importance of tackling the parameters related to human behavior. Furthermore, a study on the electricity consumption per capita targeting 36 residential units and 15 villas in Abu Dhabi revealed the possibility of energy savings either by one or more of the following measures: adjusting the AC thermostat temperature to 24 °C; switching off the AC; switching off the domestic water heating system; retrofitting vials with roof insulation [19]. Overall, it seems that studies have focused on residential villas, but little is known regarding other types of buildings, such as commercial or industrial buildings, and particularly mosques, within the UAE. There must be a focus on improving the operation of existing buildings through much more detailed studies with bigger scopes and realistic improvement measures, rather than suggestions or measures fitted for the design-stage of buildings.

1.4. Energy Efficiency and Conservation Actions in the UAE

In light of the UAE's Agenda for 2050 and the target of reducing the contribution of hydrocarbons, both in the overall energy sector and in electricity generation in particular, several initiatives have been taken to further diversify the energy sector and to tackle the

reduction in energy consumption [20]. Table 2 summarizes some of the initiatives taken on the federal and local levels.

Table 1. Factors contributing to insufficient energy usage in buildings [14,15].

No.	Dimension	Description
	Buildings' Designs	
1	Insulation	Insulation that is ripped, compressed, holding moisture, or inefficient owing to outdated technology presents a major possibility for energy leakage from the structure.
2	HVAC	HVAC (Heating, Ventilation, and Air Conditioning) consumes a large quantity of energy. Poorly maintained or older technology consumes far more energy than modern ones, which have continually improved efficiency rates.
3	Lighting	Lights in old buildings are often inefficient and are either on or off dependent on old-fashioned light switch system. Using occupancy-sensor lighting systems with lighting management software programs will help in reducing lighting expenditures.
4	Windows	Windows that are badly planned leak air which will cause energy waste. This will also have a greenhouse effect, increasing the expense of air conditioning. Replacing outdated window designs with modern ones will increase the efficiency. Adding energy-efficient film to existing windows will significantly reduce the energy waste.
	Occupants' Behavior	
5	Leaving the Lights On	Leaving the lights on is one of the energy wasting behaviors, yet it's also one of the simplest to solve by just turning off the lights when leaving the occupied place or by utilizing a smart home system to manage the lighting.
6	Using Incandescent Bulbs	Incandescent lights use a large amount of energy. Switching to energy-efficient lights is an easy approach to cut energy use.
7	Leaving Electronics Plugged In	Even when switched off, appliances and devices use energy.
8	Freezers and Refrigerators	Owning multiple freezers to store food causes more harm than good. A working freezer takes up around 103 kWh. People spend around 10 h annually opening fridge or freezer, accounting for 7% of the appliance's overall energy usage.
9	Dishwashers	The average dishwasher uses approximately 1800 watts of power to operate; operating every day would cost $66 per year.
10	Washing Clothes in Hot Water	Nearly 90% of the energy used by a washing machine is utilized on heating water.
11	Setting the Thermostat Too High	Water heater settings are frequently set too high in many homes. Lowering the thermostat reduces your energy bill by 3–5%.
12	Not Programming the Thermostat	Heating and cooling account for roughly half of a home's energy use. When home is empty, a smart thermostat can save money on heating and cooling since they since they can be operated remotely
13	Air Filters	HVAC units contain air filters that must be cleaned and changed on a regular basis in order for the HVAC to work properly since air filters collect particles in the air. When the air filter becomes clogged, the HVAC system has to work harder to pull in air.

1.5. Sustainability and Energy-Efficiency Strategies

When it comes to policy and decisions makers [21], some general recommendations for setting up strategies could be formulated, as follows:

- Consider solar shading devices for windows and doors;
- Replace existing windows with high-performance windows appropriate for the climate and exposure;
- Reduce heating and cooling loads through alternatives such as natural ventilation and fresh air intake;
- Evaluate the optimum performance of energy and water systems by recommissioning to minimize consumption;
- Achieve the optimization of resources by reusing or recycling construction waste and demolition debris;

- Apply HVAC, daylight and lighting sensors in the appropriate places within projects upon an evaluation of the occupancy pattern;
- Install smart or submeters for electric, gas, water and other utilities for real-time consumption monitoring, demand control and increase accountability (cost control).

Table 2. Energy efficiency and conservation actions taken on the federal and local levels in the UAE [20].

Level	Entity	Action	Purpose
Federal	Ministry of Energy and Infrastructure	Establishment of new department for energy conservation and efficiency	Establish a database of energy consumption by different sectors across the UAE
	Emirates Authority for Standardization and Metrology (ESMA)	Launch of an efficiency-labelling scheme for window and split-unit air-conditioning systems	Eliminate highly inefficient units from the market
		Ban of imported inefficient incandescent light bulbs since July 2014	Cut energy use by 500 MW per year
	UAE Cabinet	Approval of Green Building and Sustainable Building standards	Save 10 billion United Arab Emirates Dirhams (AED) by 2030 and reduce around 30% of carbon emissions
Local	Regulation and Supervision Bureau (Abu Dhabi)	Campaigns with residents	Reduce electricity and water consumption and demand
	H.H. Sheikh Mohammed bin Rashid Al Maktoum (Dubai)	Resolution to implement green building specifications and standards (PDF) in new buildings	Implemented building code for all new buildings, mandatory in the emirate since 2014
	Sharjah Electricity, Water and Gas Authority (SEWGA)	Creation of conservation department	Conserve electricity, water and gas
	Ajman Municipality and Planning Department	Formation of green building committee	Support energy conservation efforts
	Ras Al Khaimah Municipality	Minimum sustainability standards for the Green Building Regulation (Barjeel)	Reduce energy and water consumption by 30%
			Made mandatory for all new buildings starting January 2020

Overall, whether the previous strategies would be effectively implemented within the context of the UAE remains a subject for further evaluation, taking into consideration the climate, nature of buildings, residents' behaviors and other factors. Such an evaluation could be addressed through studies conducted on a large scale by including a significant number of buildings from different sectors (residential, industrial and commercial) and focusing, in particular, on existing buildings or recently established buildings that will have a long life cycle and be more eligible for maintenance or improvements compared to older buildings, which would reduce efforts and cost and improve the ultimate results.

1.6. Mosques in the UAE and Energy Consumption

The building sector in the UAE consists mainly of residential, commercial and industrial buildings. Among them, around 9123 mosque buildings currently exist in the different emirates [22], with 2305 mosques located in Abu Dhabi, 2154 mosques in Dubai, 2813 mosques in Sharjah and the remaining 1851 mosques distributed throughout the emirates. Such a huge number of mosque buildings must have a high consumption of energy, therefore resulting in high CO_2 emissions and a need for the implementation of proper energy conservation measures to improve their energy efficiency and lessen their negative impact on the environment.

Mosques are considered to be part of the non-commercial building sector. Moreover, mosques are known for their high consumption of energy, particularly due to two main

factors: HVAC systems as the top factor, followed by lighting [23]. In addition, energy use in buildings is generally attributed to the characteristics determined through the construction and operation processes; therefore, it is crucial to evaluate the energy usage of any building throughout the different stages of its life, such as the design, construction and operation. For Mosques in particular, other social factors can contribute to the inefficient use of energy, such as the behavior of mosque visitors (similar to the behavior of school students, as mosques and schools are both considered educational places). Visitors might not be aware of how their actions affect the energy efficiency of the mosque, such as using the lights all the time when natural sunlight could be a substitute or turning on the AC during colder weather when natural ventilation could be an alternative.

1.7. Energy Performance Index (EPI), Energy Conservation Measures (ECMs) and Water Unit Intensity (WUI)

Energy conservation measures (ECMs) are known mainly as technological resources that can be implemented to improve the energy performance of a building [24], with the aim of reducing the consumption of energy caused by a process, a certain technology used or an installation. There are several types of ECMs, such as passive (reducing energy needed to heat or cool a building), active (replacement of HVAC energy supply components with better-performing options), renewable (employing renewable energy resources to reduce carbon foot print) and control (reprogramming start and end times for energy systems).

ECMs can also be categorized into the following groups [25]: building envelope, energy recovery ventilation, ground source heat pump systems, lighting, advanced controls, efficient refrigerant systems, radiant systems, fault detection and diagnostics and plug loads, with the most commonly used ECMs being high-performance building envelope (better insulation), HVAC control and lighting controls. These types of ECMs can be observed in buildings in general, such as residential or commercial buildings, and some are applicable in the case of mosques. As AC systems remain turned on most of the time while using mosques, switching to more efficient systems could reduce the energy demand of mosques while maintaining the occupants' comfort [26].

To further assess energy usage, certain indicators can be applied, such as the energy performance index (EPI) [27]. The EPI can be calculated by dividing the energy consumption of any building by a factor or a standardized reference of comparison, as this representation of energy usage determines the accuracy of the index. In addition, it is not sufficient to rely on the value of energy usage throughout the year as an indicator for energy performance. Therefore, the use of a single factor for normalization (for example, area of a building) can address the variations in type or location. Such an index can be measured to indicate the "specific consumption" by dividing the energy consumption over the area (kilowatt-hours per square meters or m^2) and may not yield values with normal distribution all the time. Nevertheless, it is still considered to be a good indicator for energy-efficient buildings.

Water usage can also be assessed in several ways, one of which is the water unit intensity (WUI) [28], which can be defined as the rate of water use in a specified area. The WUI reflects the amount of water that a building needs during its operation, eventually enabling the sustainable allocation of water resources and proper management over time, and it can be calculated by dividing the consumed water (in m^3) over the total area (in m^2) per year.

1.8. Mosques' Energy Consumption and Carbon Foot Print

Regarding the building sector and its contribution to carbon emissions, particularly CO_2, the Abu Dhabi State of Environment Report shows that the CO_2 emissions produced by electricity consumption were 0.42 kg of CO_2/kWh [29]. As the levels of CO_2 are increasing faster than the population, the values of CO_2 emissions remain the main indicator of the GHG emissions, fueling the need to properly assess its significance in the building

sector. The main activity contributing to the increase in CO_2 emission is the production of public electricity, which is a major factor in operating buildings, including mosques.

Overall, the reviewed literature addressed the main aspects of energy consumption in the building sector and highlighted the importance of addressing energy efficiency in the building sector, with a particular focus on mosques, due to the lack of literature related to the matter. The literature review discussed the most important measures for assessing the energy performance in buildings, including the EPI, and its relation with the ECMs that can be implemented to improve the energy usage in buildings, as well as the resulting reduction in CO_2 emissions, which contributes to environmental sustainability. The literature review also discussed the importance of measuring the WUI to assess the water consumption status in mosques.

2. Materials and Methods

2.1. Data Collection

A total of 146 existing mosque buildings within the UAE that have undergone an energy audit process were assessed by collecting the data regarding their electricity consumption from a private company within the UAE that specializes in performing energy audits. In addition, 136 of the mosques were assessed by collecting the data regarding water consumption. The data were obtained by accessing the energy audit records of existing buildings and receiving clearance to access the archive records from the company, followed by accessing individual reports for each building, with a focus on the records spanning the period between 2018 and 2019, to identify the parameters listed in File S1.

2.2. Data Analysis

The following parameters were calculated from the collected data using Microsoft Excel:

- Pre-audit energy performance index (PEPI) by dividing the pre-audit energy consumption (kWh) over the total mosque area (m^2);
- Total ECM savings in kWh by summing up the individual savings of each ECM;
- Total ECM implementation cost by summing up the individual implementation costs of each ECM;
- Payback period (PBP) by dividing the implementation cost of the ECMs by the cost savings of each ECM;
- Post-audit electricity consumption in kWh by subtracting the total energy savings from the pre-audit electricity consumption;
- Post-audit energy performance index (PAEPI) by dividing the post-audit energy consumption (kWh) over the total mosque area (m^2);
- Post-audit CO_2 emissions by multiplying the post-audit electricity consumption in MWh by 1000 to obtain the values in kWh and then multiplied by 0.4 (factor of kg of CO_2 per kilowatt);
- Percentage of the total electricity savings by dividing the total energy savings over the pre-audit electricity consumption.

In addition, the following parameters for water consumption were calculated from the collected data using Microsoft Excel:

- Pre-audit water unit intensity (EWUI) by dividing the water consumption in m^3 over the area in m^2;
- Total implementation cost by summing up the investment costs of all the WCMs;
- Total WCM savings in m^3 by dividing the percentage of ECM savings over the pre-audit water consumption;
- Total ECMs savings in Dirhams by multiplying the total ECM savings in IG by a factor of 0.4 (Tarif rate);
- PBP in years by dividing the benefits (savings) over the total investment cost;

- Post-audit water consumption by subtracting the pre-audit water consumption minus the total ECM savings in m^3;
- Post-audit water unit intensity (PWUI) by dividing the water consumption in m^3 over the area in m^2;
- Water saving % by dividing the total savings in m^3 over the pre-audit water consumption in m^3.

In addition, statistical analysis was performed using SAS studio to achieve the following:

- Determine the most energy efficient ECMs and water conservation measures (WCMs) that impact the energy inefficiency in existing mosque buildings;
- Determine the most cost-effective ECMs and WCMs that yield the fastest PBP;
- Forecast the total CO_2 emissions reduction that could be achieved in the UAE if energy-efficiency audits and implementations were conducted across all mosques;
- Forecast the total energy savings in kW and economic savings in Dirhams across all mosques in the UAE, in addition to the savings in m^3 of water and the associated cost in Dirhams (AED).

3. Results and Discussion

3.1. Electricity Consumption

3.1.1. Year of Construction vs. Existing and Post-Audit Energy Performance Index

The first variable to be evaluated was the year of construction (Y) for each mosque in order to determine whether this variable had an effect on the value of the EPI, and consequently, the effect of the year built on both the value of the PEPI and the value of the post-audit energy performance index (PAEPI), after implementing the ECM was analyzed using Box Plot Analysis on the SAS program.

Upon performing the descriptive analysis and exploring the association between the continuous variables (EEPI and PAEPI) and the categorical predictor of the year of construction (Y) (Table 3), it was clear that the mosques in the first category (1991–2000) had a higher mean value of EPI than those in the second category (2001–2010) and third category (2011–2017). This was observed in the pre-audit phase, before implementing the ECMs, and in the post-audit phase, after implementing the ECMs, which indicates that the older mosques had higher electricity consumption compared to the newer mosques. This is expected as technology usually plays a big role in electrical consumption, and the applied energy systems in older mosques do not usually have the technological enhancements and advancements that newer ones have. These new technologies could help make energy use more efficient and lower the value of the EPI. It can also be seen that the mean value of the EPI among the three year categories decreased after implementing the ECMs, as follows:

- 1991–2000: from 142 to 92 (kWh/m^2), disregarding the size variation of the mosques;
- 2001–2010: from 114 to 78 (kWh/m^2);
- 2011–2017: from 102 to 75 (kWh/m^2).

Table 3. Comparison of different categories of mosques based on year built, showing the existing and post-audit energy performance index mean values.

Parameter	PEPI (kWh/m^2)			PAEPI (kWh/m^2)		
Year	1991–2000	2001–2010	2011–2017	1991–2000	2001–2010	2011–2017
Mean	142	114	102	92	78	75

The above analysis shows the success of implementing the ECMs in enhancing the efficient use of energy and decreasing electricity consumption, which will in turn decrease the CO_2 emissions (CO_2) that result from the electricity generation processes by DEWA within the buildings, where:

$$CO_2 = EC \times 0.44 \quad (1)$$

where CO_2 denotes the total carbon dioxide emissions, EC denotes the electrical consumption in kWh and 0.44 denotes the rate of CO_2 emissions in kg per one kilowatt of consumed electricity.

3.1.2. Year of Construction vs. Percentage of Energy Savings

The second factor that was analyzed was whether the year of construction (Y) of the mosque affected the total percentage of total energy saving (%TES) achieved after implementing the ECMs. This analysis was conducted using the SAS program.

Upon performing the descriptive analysis and exploring the association between the continuous variable (%TES) and the categorical predictor of year of construction (Y), it was clear that the mosques in the first category (1991–2000) had a higher median value of %TES than those in the second category (2001–2010) (Table 4) and third category (2011–2017). This indicates that the %TES is reduced over the years after implementing ECMs as there is a lower margin of enhancements to be made due to the technological advancements in the systems used in newer mosques. This finding is also evident from the year of construction (Y) vs. existing EPI and PAEPI analysis, where the EPI values are as follows:

- 1991–2000: decreased from 142 to 92 (kWh/m^2) with estimated savings for each mosque in this category of 50 kWh/m^2;
- 2001–2010: decreased from 114 to 78 (kWh/m^2) with estimated savings for each mosque in this category of 36 kWh/m^2;
- 2011–2017: from 102 to 75 (kWh/m^2) with estimated savings for each mosque in this category of 27 kWh/m^2.

Table 4. Comparison of different categories of mosques based on year built, showing the mean and median values of total percentage of energy savings.

Parameter	**%TES**		
Year of mosque construction	1991–2000	2001–2010	2011–2017
Mean	40%	36%	34%

Overall, it can be concluded that the year of construction is a significant factor of the %TES achieved and a significant contributor to the value of the EPI. Therefore, more focus must be directed toward older mosques because these old structures, which still have tens of years in their life spans, are energy-inefficient and thus waste a lot of energy. By simply implementing ECMs, the energy usage efficiency could be greatly improved, which would automatically reduce the CO_2 emissions resulting from the power generating processes and reduce the negative environmental impact.

3.1.3. *T*-Tests and Confidence Intervals for Pre-Audit Energy Performance Index (PEPI), Post-Audit Energy Performance Index (PAEPI), Existing CO_2 Emissions (ECO_2) and Post-Audit CO_2 Emissions ($PACO_2$)

The *T*-tests and confidence intervals were determined using SAS software to assess the effectiveness of implementing the ECMs in terms of their effect on energy consumption, as evidenced by the EPI and CO_2 emissions. It can be seen that after implementing the ECMs, there was a successful reduction in the EPI value (Table 5), where the mean PEPI value was 123.4 kWh/m^2 with a confidence interval between 105.7 and 141.2 kWh/m^2, and the mean PAEPI value achieved was 84 kWh/m^2, with a lower confidence interval between 70 and 97 kWh/m^2, which means better energy efficiency that will yield lower CO_2 emissions. This will help reduce the negative impact of energy on the environment, as the mean CO_2 emissions pre-audit (ECO_2) was 54,892.5 kg of CO_2, with a confidence interval between 46,150.1 and 63,635.0 kg of CO_2, and the mean value of post-audit CO_2 ($PACO_2$) emissions achieved was 37,036.1 kg of CO_2, with a lower confidence interval between (30,270.2 and 43,801.9) kg of CO_2.

Table 5. *T*-test results with a confidence interval of 95% for the energy performance index (EPI) and CO_2 emissions for both pre-audit and post-audit phases.

Variable	Mean	Std Err	Min	Max	95% CL Mean		Std Dev	95% CL Std Dev	
PEPI [(1)]	123.4	8.9710	0.7428	520.0	105.7	141.2	108.8	97.5947	122.9
PAEPI [(2)]	83.5003	6.8640	0.6407	397.4	69.9347	97.0659	83.2213	74.6723	93.9985
PCO_2 [(3)]	54,892.5	4423.5	800.0	320,400	46,150.1	63,635.0	53,632.6	48,123.1	60,578.1
$PACO_2$ [(4)]	37,036.1	3423.4	213.8	273,423	30,270.2	43,801.9	41,506.7	37,242.9	46,881.9

[(1)]: Pre-audit energy performance index; [(2)]: Post-audit energy performance index; [(3)]: Pre-audit CO_2 emissions; [(4)]: Post-audit CO_2 emissions.

When analyzing the results of both of the *T*-tests that were performed to compare the means of the EPI in the pre-audit phase (EEPI) and post-audit phase (PAEPI), it is clear that the mean value of the EPI decreased (from 123.4 to 84 kWh/m^2) and that the Confidence Interval (CI) of the EPI decreased to a lower range, from 105.7 and 141.2 kWh/m^2 to 70 and 97 kWh/m^2, which indicates the success of implementing the ECMs. Consequently, this caused a reduction in the CO_2 emissions, as these emissions are the direct effect of the electricity generation processes. This reduction is evident in the *T*-tests that were performed to compare the means of CO_2 in the pre-audit phase (ECO_2) and post-audit phase ($PACO_2$), where the mean value of CO_2 decreased (from 54,892.5 to 37,036.1 kg of CO_2) and the CI of CO_2 emissions decreased to a lower range from 46,150.1 and 63,635.0 kg of CO_2 to 30,270.2 and 43,801.9 kg of CO_2.

3.1.4. Analysis of Energy Conservation Measures (ECMs) for Electricity Consumption

The following ECMs were found to be commonly used and adopted in the mosques (while other ECMs were implemented in only 1–2 mosques, so they were eliminated for purpose of comprehensive analysis), (A detailed description of each ECM can be found in File S2)

- LR: Replacement of existing inefficient lights/retrofitting;
- LT: Lighting automation;
- MSQTHR: Mosque thermostat;
- EEACU: Energy efficient air conditioning units;
- HVAC: Heating, ventilation and air conditioning;
- HVACA: HVAC options A (installation of energy saver for split units);
- IBSC: IOT-based smart control.

Furthermore, the distribution of the ECMs amongst the 146 mosques included in the study was analyzed, and it can be seen that the most adopted ECM was lighting automation (LT). It was implemented in almost 30.04% of all the mosques that were studied, as it is the easiest, cheapest and most applicable ECM to implement, followed by the replacement of existing inefficient lights/retrofitting (LR), which was implemented in 22.34% of the studied mosques, and mosque thermostat adjustment (MSQTHR), which was implemented in 6.96% of all the studied mosques.

3.1.5. Analysis of Energy Conservation Measures (ECMs) Adopted and the % Energy Saving Obtained from Each ECM (ECMS%)

Upon performing the analysis and exploring the association between the continuous variable (ECMS%) and the categorical variable (ECM), it can be seen that EEACU and HVAC were the most energy-efficient ECMs. They achieved the highest mean percentages of energy saved, contributing the most to the overall electricity savings of all the mosques that were analyzed. EEACU and HVAC contributed 22.09% and 39.49%, respectively (Table 6).

Table 6. ECMS savings % of the total energy consumption savings, ECMS% Mean.

ECM	ECM Energy Savings Mean (ECMS%)	ECM Payback Period (PBP) Mean
EEACU	35%	5.33
EIFWF *	40%	N/A **
HVAC	30%	1.12
HVACA	21%	0.69
IBSC	1%	N/A **
ISWIC	33%	N/A **
LR	7%	5.85
LT	19%	5.84
MSQTHR	10%	1.45

*: Efficiency Improvement for water fixtures, ECM implemented in one mosque only. **: Data not available.

3.1.6. Analysis of Energy Conservation Measures (ECMs) Adopted and the Payback Period (PBP) for Each ECM

Upon performing the analysis and exploring the association between the continuous variable (PBP) and the categorical variable (ECM), it can be seen that HVAC, LR and LT were the most cost-effective ECMs, as they achieved relatively low mean values of PBP for each ECM, with high mean values of ECMS% (Table 6). This makes them the most attractive measures to adopt, and they were the most commonly adopted measures among all the mosques that were studied. However, those three ECMs do not have the lowest mean values, which can be attributed to the size and design of the mosque buildings.

It has been reported in previous studies, and is shown in the present research, that a customized HVAC system could significantly lower the energy consumption of mosque buildings. It is a beneficial additional element to the building envelope components, such as walls, windows, floors and openings, which all work together to improve the energy efficiency. Regarding lighting, previous research [30] has shown that using LED and smart lights could be an effective solution for reducing energy demand, especially with the evolution of mosque designs over the years, from the traditional Islamic architecture, which relies mainly on natural lighting, to the incorporation of smart systems that tackle heat and lighting demands since the beginning of the 1990s.

3.2. Water Consumption

3.2.1. Year of Construction vs. Pre- and Post-Audit Water Use Intensity

Buildings in the UAE consume electricity either by direct consumption to operate AC units, with the costs added to the monthly electricity bill, or by being connected to a district cooling, in which case the AC bill comes separately from the district cooling company. These companies supply very cold chilled water to the occupants. The electricity bill of a home includes the electrical consumption of the unit, but the electricity consumption required to cool the water comes in the bill from the district cooling company that supplies the occupants with the chilled water. However, mosques have their own AC units within the building structure (not linked to district cooling), so the water consumption reported in the bill is the actual domestic water consumption. In contrast, in the buildings linked to district cooling, the chilled water consumption represents the chilled water consumed when the AC is turned on and not the water consumed when the tap is running water. Thus, the more the AC is kept on within the house, the more water from the chilled water network is consumed, which in turn increases the bill. Therefore, analyzing the rate of water consumption in mosques is beneficial for understanding their energy consumption patterns and to propose conservation measures.

Water use intensity (WUI) refers to the rate at which water is used in a given area. It is an indicator of how much water a building requires during its occupation. To determine the WUI, the year of construction (Y) of each mosque was analyzed against both the value of the pre-audit water use intensity (PWUI) and the value of the post-audit water use intensity (PAWUI) after implementing the water conservation measure in order to determine if the variable (Y) had an effect on the value of the WUI.

Among the 146 mosques studied, 136 mosques were analyzed for water consumption. Analyzing the association between the continuous variables (PWUI and PAWUI) and the categorical predictor of the year of construction (Y), it was clear that the older mosques had higher mean values of WUI than the newer mosques (Table 7), which is observed in the difference between the PWUI before implementing the WCMs and in the PAWUI after implementing the WCMs, which indicates that older mosques had higher water consumption compared to newer mosques. This is expected due to the improvements and advancements in the strategies, technologies and systems employed in managing the water consumed in a given facility, from water system designs to leak detection and repair, which help make the consumption of water more efficient and lower the value of the WUI. It can also be seen that the mean values of the WUI among the three year categories decreased after implementing the WCMs, as follows:

- 1991–2000: from 2.21 to 1.26 (m^3/m^2);
- 2001–2010: from 1.79 to 1.24 (m^3/m^2);
- 2011–2017: from 1.42 to 0.95 (m^3/m^2).

Table 7. Comparison of different categories of mosques based on year built showing the pre- and post-audit water use intensity mean values.

Parameter	PPWUI (m^3/m^2)			PAWUI (m^3/m^2)		
Year	1991–2000	2001–2010	2011–2017	1991–2000	2001–2010	2011–2017
Mean	2.41	1.79	1.42	1.26	1.24	0.95

The above analysis shows the success of implementing the WCMs in reducing the consumption of water.

3.2.2. Year of Construction vs. Water Savings

Upon analyzing the association between the continuous variable of the value of the total water consumption saving (TWCMS) in m^3/m^2 achieved after implementing the WCMs and the categorical predictor of the year of construction of the mosque (Y), it was clear that the mosques in the first category (1991–2000) had a higher mean value of TWSCMS than those in the second category (2001–2010) (Table 8) and those in the third category (2011–2017). This indicates that the TWSCMS is reduced over the years after implementing the WCMs, as there is a lower margin of enhancements to make due to the advancements in the systems used in newer mosques. This is also evident from the year of construction vs. existing and post-audit water use intensity analysis, which found the following:

- 1991–2000: from 2.21 to 1.26 (m^3/m^2) with estimated savings for each mosque in this category of 0.95 m^3/m^2, disregarding the size variation of the mosques;
- 2001–2010: from 1.79 to 1.24 (m^3/m^2) with estimated savings for each mosque in this category of 0.55 m^3/m^2;
- 2011–2017: from 1.42 to 0.95 (m^3/m^2) with estimated savings for each mosque in this category of 0.47 m^3/m^2.

Table 8. Comparison of different categories of mosques based on year built, showing the mean and median values of total water consumption saving.

Parameter	TWSCMS (m^3/m^2)		
Year	1991–2000	2001–2010	2011–2017
Mean	342.54	307.10	262.50

Overall, it can be concluded that the year of construction is a significant factor of the TWSCMS achieved and a significant contributor to the value of the WUI. Therefore, more focus should be directed toward older mosques because these existing old structures,

which still have tens of years in their life spans, are inefficient when it comes to water consumption. By simply implementing WCMs, the water usage efficiency could be greatly improved.

3.2.3. *T*-Tests and Confidence Intervals for Existing Water Use Intensity (EWUI), Post-Audit Water Use Intensity (PAWUI)

T-tests and confidence intervals were determined to assess the effectiveness of implementing the WCMs in terms of their effect on water consumption, as evidenced by the water use intensity (Table 9). It can be seen that after implementing the WCMs, there was a successful reduction in the value of the WUI, where the mean value of the pre-audit WUI was 504 m^3/m^2, with a confidence interval between (1.61 and 1.07) m^3/m^2, and the mean value of the post-audit WUI achieved was 312 m^3/m^2, with a lower confidence interval between (1.04 and 1.33) m^3/m^2, which means better water usage efficiency.

Table 9. Mean values and confidence intervals for water unit intensity (WUI) pre-audit and post-audit.

Variable	Mean	Std Err	Min	Max	95% CL Mean		Std Dev	95% CL Std Dev	
PWUI [(1)]	1.91	0.15	0.01	8.44	1.61	2.21	1.77	1.58	2.01
PAWUI [(2)]	1.18	0.07	0.003	4.27	1.04	1.33	0.86	0.76	0.97

[(1)]: Pre-audit water unit intensity; [(2)]: Post-audit water unit intensity.

It can be concluded that the mean value of the WUI decreased from 1.91 to 1.18 m^3/m^2 and that the confidence interval of the WUI decreased from 1.61 and 2.21 m^3/m^2 to 1.04 and 1.33 m^3/m^2, which indicates the successful implementation of the WCMs.

3.2.4. Analysis of Water Conservation Measures (WCMs)

The following WCMs were found to be commonly used and adopted in the 137 audited mosques (A detailed description of each WCM can be found in File S2):

- A: Aerators (implemented in 52.38% of the mosques);
- SCFWA: Self-closing faucets with aerators (implemented in 33.33% of the mosques);
- WR: Water recycling (implemented in 14.29% of the mosques).

3.2.5. Analysis of Water Conservation Measures (WCMs) Adopted and the Savings Obtained for Each WCM

Upon performing the analysis and exploring the association between the continuous variable water conservation measure saving (WCMS) and the categorical variable WCM (Table 10), it can be seen that the WR was the most efficient measure for water consumption savings, as it achieved the highest mean value of water saved (35%) from each WCM, followed by SCFWA (42%) and A (13%).

Table 10. Water conservation measures (WCMs) percentage of savings and payback period (PBP).

Water Conservation Measure (WCM)	WCM% Mean	Payback Period (PBP) Mean
A *	13%	0.42
SCFWA **	42%	3.69
WR ***	35%	7.28

*: Aerators; **: Self-closing faucets with aerators; ***: Water recycling.

3.2.6. Analysis of Water Conservation Measures (WCMs) Adopted and the Payback Period (PBP) for Each WCM

Upon performing the analysis and exploring the association between the continuous variable (PBP) and the categorical variable (WCM), it can be seen that A was the most cost-effective WCM, as it achieved the lowest mean value (0.4 year) of PBP, which means that in less than half a year, the cost of investment in this WCM would be covered and everything would be pure profit. This makes A the most attractive WCM to adopt, although it achieved

less water consumption savings than the other the two WCMs (Table 10), contributing to 30% of the water savings for all the mosques that were studied. It can also be seen that although WR achieved a higher mean value of WCMS% than A, contributing to 33% of the water savings of the total savings for all the mosques analyzed (Table 10), it has the highest mean value (7.2 years) of PBP, which makes it the least attractive WCM to adopt, as evidenced by its implementation in only 14% of all the mosques that were studied.

Regarding water consumption in mosques, the previous reviewed research [31] showed that the ablution process consumes a huge amount of water and requires access to more sinks compared to other buildings, such as residential or commercial buildings. Therefore, as shown in the current research, implementing self-closing faucets and using aerators can significantly reduce the water consumption and improve the sustainability of a mosque, as well as the potential for water recycling, especially in regions of water scarcity, such as the UAE.

Through the overall analysis, the older mosques showed higher energy and water consumption vs. the more recently built mosques. Accordingly, the potential energy savings of older mosques is higher than that of newly built mosques. In terms of the electricity consumption, it can be concluded with a 95% confidence interval that efficiently running mosques have a mean electrical consumption of 84 kW/m^2 per year. This can be used as an EPI to evaluate how efficiently a specific mosque is performing in comparison to the others. An average of 32% energy saving can be expected based on the average savings achieved within the collected data. Moreover, for water consumption, it can be concluded with a 95% confidence interval that efficiently running mosques have a water consumption mean of 1.18 m^3/m^2 per year. This can be used as a WUI index to evaluate how efficiently a specific mosque is performing in comparison to other mosques. An average of 38% water consumption savings can be expected based on the average savings achieved within the collected data. The detailed savings of the energy and water consumption measures (ECMs and ECMs) are presented in Table 11.

Table 11. Summary of the most energy-efficient and cost-effective energy conservation measures (ECMs) and water conservation measures (WCMs).

Type of Energy	Aspect	Conservation Measure	Abbreviation	% Savings	Payback Period
Electricity	ECMs	Replacement with energy efficient air conditioning units	EEACU	35%	5.33
		Heating, ventilation and air conditioning	HVAC	30%	1.12
		HVAC energy savers units	HVACA	21%	0.69
		Mosque thermostat (Azan programmed)	MSQTHR	19%	5.84
		Lighting (automation)	LT	19%	5.84
Water	WCMs	Self-closing faucets with aerators	SCFWA	42%	3.69
		Water recycling	WR	35%	7.28
		Aerators	A	13%	0.42

Overall, for electricity consumption, an average saving of 17,860 kg of CO_2 per mosque per year can be achieved, and as the UAE has more than 9123 mosques, the potential environmental CO_2 savings could be 162,937 tons of CO_2 per year, which is more than the CO_2 emissions of Samoa, Comoros or the British islands [32]. In addition, considering the average area of the studied mosques, the total financial savings per mosque would be 40 $kW/m^2 \times 2377\ m^2 \times 0.45$ = 42,786 AED/year, and when applied to all of the mosques within the UAE, as per the data from the year 2020, the total financial savings across the UAE is estimated to be 42,786 × 9123 = 390,336,678 AED.

For water consumption, an average saving of 726.80 m^3 per mosque per year can be achieved, and as the UAE has more than 9123 mosques, the potential water savings could be 6.62 million m^3 per year. The total water consumption of the Maldives and Monaco is less than 4.54 million m^3 per year [33]. Considering the average area of the studied mosques, the total AED savings per mosque is expected to be 0.7267990625 $m^3/m^2 \times 2479\ m^2 \times 13.208602618$ AED/m^3 = 23,798.4 AED per

year, and when applied to all of the mosques within the UAE, as per the data from 2020, the total savings in Dirhams across the UAE is expected to be 23,798.4 × 9123 = 217,112,803 AED per year.

The behavioral aspects of mosque occupants should also be considered and assessed if the target is to induce a behavioral change within the society that is home to mosque occupants or visitors. Increased activity in a mosque is correlated with the lunar calendar and Islamic events, as well as the five-times daily prayers of 0–60 min each (with Fridays having a special two-hour, more crowded occupancy for AlDuhr Prayers), which could be properly managed by implementing measures such as water recycling or HVAC system customization [34]. It is also recommended to further investigate the source of energy consumption or water usage, such as electrical utilities (sound systems, fans and water heating machines), or the exact locations within the mosque that are more demanding of energy and water, such as the Imam headquarters, ablution or toilet spaces, gardens or Mouazzin Minbar, which could provide a better understanding of the actual consumption patterns and how to improve the related processes.

Overall, the design of mosques should be properly assessed and studied at an early stage to address the various forms and elements of mosques, such as mihrab, patios, minbar and corridors, as well as ablution areas, toilets and the external surroundings, such as the garden, all of which dictate the electricity and water demands. Historically, mosques have had varying designs [35], such as Moorish, Andalusian, Egyptian, Seljuk, Indian, Safavid and Ottoman, and different shapes, such as Arab, Persian and Ottoman. In the Gulf Region, it is also critical to consider the geographical climate or the cultural conditions that affect the design of mosques, all while keeping in mind the energy and water demands that result from their design. Similar studies addressing commercial and residential buildings that have undergone energy audits should be conducted to provide a comprehensive overview of energy and water consumption and the effect of implementing ECMS and WCMs within the context of the UAE.

4. Conclusions

As the building sector is a major contributor to global energy consumption and GHG emissions, there is a need to address the energy usage efficiency within this sector, particularly focusing on existing mosque buildings and not just those in the design stage. Ultimately, this could lead to better economic outcomes and favorable environmentally friendly practices that will have a positive impact in light of the increased urbanization and population growth.

The proposed research addressed the factors affecting the energy usage efficiency and water consumption within mosques in the UAE, reviewing the available literature to assess the status of energy usage and water consumption. This work also reviewed the frameworks proposed for approaching this issue through extracting the contributing factors and assessing the improvement actions and initiatives adopted by the UAE government to facilitate energy demand reduction.

The data regarding the electricity consumption were collected from 146 mosques in the UAE. All of the mosques within the data sets had undergone an energy audit review, which provided the data on power and water consumption before and after the audit was implemented. The results for the post-audit consumption were therefore considered to be efficient and reliable to use for benchmarking purposes. The results also yielded information on the ways to achieve such efficiency, as well as the cost and PBP related to each implementation option. The average CO_2 emission savings across all of the mosques, disregarding the size variation of the mosques, was also determined.

To conclude, given the importance of mosques as holy places for prayer and religious gatherings, and given that mosques are highly visited buildings with a huge consumption rate for both electricity and water, policy makers should consider the potential savings that can be achieved in terms of both the environmental and economic aspects of sustainability, while remaining aware of the challenge facing the region and the country regarding water scarcity and the high consumption of electricity required to operate such buildings.

Several energy conservation frameworks exist on the international level, many of which have been addressed through studies that focus on buildings in general, particularly residential and commercial ones. The significance of this study can be attributed mainly to the fact that it addressed energy consumption in more than 100 mosques–which were built over a time span of more than 30 years, are of varying areas and have implemented different types of ECMs and WCMs–and evaluated them in terms of the efficiency in savings and PBP. These findings, which reflect the current situation at the local level, provide a better understanding of the current electricity and water consumption situation in mosques, as well as a better evaluation of the effectiveness of ECMs and WCMs. This contributes to achieving the sustainability goals intended to protect the environment, to reducing costs and to maximizing the economic benefits, all while providing holy places for worshipers in this society to exercise their Islamic practices.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/buildings13041007/s1, File S1: A list of abbreviations mentioned in the paper; File S2: The energy conservations measures (ECMs) and water conservation measures (WCMs) mentioned in the paper.

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