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Energy Performance and Cost-Effectiveness Assessment towards the Nearly Zero-Energy School Buildings in Mild Climates

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Abstract: The study presented an approach to accomplish the nearly zero-energy school building through the assessment of energy and economic performance of the design solutions with renewable energy systems. For energy use in the school building, the energy was mainly consumed by artificial lighting through the analysis of two years' energy consumption. Available passive and active solutions were adopted to improve energy efficiency in the school building and the energy performance of each design solution was analyzed. To achieve the nearly zero-energy school building, the remaining energy was offset by solar PV panels. Comparing the payback time for design solutions with the PV systems, the most appropriate design solution was selected to achieve the nearly zero-energy school building design under mild climates. In sum, the present study has revealed the challenges of achieving nearly zero-energy school building design under the climate conditions in Saudi Arabia. Moreover, the outcome of the study can lead to the development of a nearly/net-zero-energy building design under hot climates.

Keywords: school building; nearly zero-energy design; energy performance; cost-effectiveness; mild climates

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1. Introduction

Energy is one of the most important requirements for all economic systems and human well-being. Consecutive energy consumption has caused environmental problems. Over the last three decades, the annual global energy consumption has increased significantly, and energy-related carbon emissions have also increased rapidly [1]. While other countries worldwide have employed energy policies to apply low-carbon energy-saving measures to buildings, the building sector is still one of the large contributors accounting for about 30% of the total energy consumption worldwide [2].

In a developing country such as Saudi Arabia, building industries have undergone enormous development with an increasing population [3]. Moreover, economic growth caused a high demand for various types of buildings [4]. According to the annual report of the Saudi Energy Efficiency Center, the building sector has accounted for more than half of the total energy consumption [5]. While about 20% of the total building energy was consumed by governmental buildings, most studies have investigated the energy efficiency improvement of commercial or residential buildings in Saudi Arabia [6–10]. In addition, there have been few studies about energy performance in governmental buildings, especially school buildings [11]. As with the rapid growth of the population in Saudi Arabia, the number of school buildings also rapidly increased. Therefore, it is required to consider the energy consumption of school buildings [12,13].

Increasing the energy efficiency of buildings can offer an opportunity to lengthen a building's life span and reduce operating costs but is a challenge to Saudi Arabia [14]. According to the study of Park et al., an effective strategy is to use proper insulation for building envelopes [15]. In Saudi Arabia, even though the average air temperature reaches around 45 °C, reinforced concrete has been used as the main material for building envelopes in that the thermal comfort indoors has been heavily dependent on air conditioning [7,16]. To reduce the primary energy consumption of buildings, energy-saving techniques and an energy management plan are adopted in all buildings in Saudi Arabia by Saudi Arabia's Vision 2030 [17].

The study explores energy-efficient design strategies for school buildings in Saudi Arabia which is the second largest part of government buildings [17]. There are three stages of methodology: (1) the analysis of the characteristics of school buildings in Saudi Arabia, (2) the energy performance analysis of passive and active solutions, and renewable energy systems, (3) the cost-effectiveness analysis of selected design strategies. In the first stage, the building design and materials used for school buildings in Saudi Arabia are identified. In addition, the energy consumed by school buildings is analyzed to find out the design parameters influencing energy consumption. Moreover, the reference school building is chosen for energy modeling and is located in a mild climate in Saudi Arabia. In the second stage, possible design strategies are applied to the reference school buildings, and their energy performance is assessed by using energy simulation. The remained energy use is offset by renewable energy systems. In the third stage, the cost-effectiveness of the chosen design strategies is analyzed. In sum, the proper design strategies are determined to reach the goal of the nearly zero-energy school building design in Saudi Arabia. The outcome can be used to develop a nearly/net-zero-energy building design under hot climates.

2. Nearly Zero-Energy School Buildings Considering Current Building Context in Saudi Arabia

2.1. Current Building Context in Saudi Arabia

With regard to the growth of the population, the demand for the commercial sector is also experiencing significant growth in Saudi Arabia [4]. Accounting for more than half of the building sector, the design of modern buildings in Saudi Arabia is no longer based on the principles of vernacular architecture even though there might be a chance to reduce building energy consumption by using local building resources, as well as implementing less energy-intensive design strategies for both air conditioning and lighting [18]. Thus, current buildings in Saudi Arabia are largely dependent on mechanical systems that consume excessive electricity to maintain thermal comfort in buildings [19]. In addition, renewable energy design strategies such as photovoltaics are rarely used in Saudi Arabia. Even though there are building codes that include the principles of sustainable architecture, their influence has not had a lot of influence over building construction [20,21]. Since the building industry has negative impacts on the consequences of climate change and other related issues such as global warming, it is required to move towards a sustainable building sector to appropriately find solutions to energy and environmental issues in Saudi Arabia [22–24].

2.2. Applicable Energy-Efficient Measures for Nearly Zero-Energy School Building Design in Saudi Arabia

Contrary to residential or commercial buildings, school buildings have different energy consumption patterns and design parameters [25]. According to the study of Sekki et al., most school buildings built from 1970 to 2004 in Finland have used mechanical supply and exhaust systems with heat recovery and U-values of 0.24–0.4 and 0.15–0.35 for walls and roofs, respectively [26]. The number of occupants, occupants' density, and building age are important key parameters of the energy consumption of school buildings [27]. The average densities of the school buildings in Finland were about 15 m^2/student and averaging daily operating hours were 5.5 h [28]. Moreover, passive design parameters such as building shape, height, and orientation also significantly influenced energy consumption. Most school buildings in Cyprus consist of two floors with a height of 3.5 m and an average density of 2 to 3 m^2/student [29]. In the case of school buildings in Italy, the number of building floors varied from two to six floors with an average floor height of 3.5 m [30].

While school building design in other countries has various shapes and roofs, most school buildings in Saudi Arabia have courtyards, which are surrounded by buildings with flat roofs [17]. In addition, school buildings in Saudi Arabia have generally consisted of three floors. The values of thermal transmittance of walls and roofs are about 0.6 and 0.72, respectively. Most school buildings have consumed about 110,000 kWh/year. Thus, it can be seen that design parameters for school buildings in Saudi Arabia have been significantly influenced by their weather conditions. Moreover, it is necessary to apply proper energy conservation measures for nearly or net-zero school building design.

To apply proper strategies for achieving a goal of nearly zero-energy school building design, several studies have investigated the impact of building envelope systems, mechanical systems, or applications of renewable energy systems. Lapisa et al. have applied passive design solutions to the building envelopes to target nearly zero-energy buildings under climatic conditions [31]. González-Mahecha et al. have conducted an energy performance analysis of renewable technologies for nearly zero-energy commercial buildings [32]. In addition, Stritih et al. have used phase change materials (PCMs) in building envelopes [33]. In their study, the application of PCMs to walls reduced building energy consumption in that the goal of nearly zero-energy building design was reached passively. Moreover, Vanaga et al. have applied solar façade modules and PCMs for building envelope systems to achieve nearly zero-energy goals [34]. In the case of the study of Ajla et al., passive design solutions were applied for the retrofitting building to reduce energy consumption and the rest of the energy consumption was offset by the use of renewable energy technologies [35]. For residential buildings, renewable energy technologies were dominated. Vieira et al. used a solar PV system with an energy storage system for making net-zero-energy residential buildings [36]. In their study, about 90% of the total building energy consumption was reduced. For the nearly zero-energy school buildings, it is required to implement both combined passive and active design strategies and renewable energy systems.

3. Method

The primary research goal is to achieve a nearly zero-energy school building design considering situations such as weather conditions and available design strategies in Saudi Arabia. For this study, a public school building in Abha City was chosen as a reference case. Even though the climate condition in Abha City is mild compared to other regions in Saudi Arabia, similar construction materials are used for buildings in Saudi Arabia. As mentioned in the introduction, the characteristics of energy consumption for the reference building were specifically analyzed. By applying two years of electricity consumption, the energy simulation was verified. In addition, the energy performance of available passive and active design solutions and renewable energy systems were analyzed aiming at the nearly zero-energy school building design. Moreover, the proper design solutions were chosen through the cost-effectiveness analysis.

3.1. Reference Building Description

The reference school building is located in Abha, Saudi Arabia (Figure 1). The reference school building has three floors consisting of classrooms, laboratories, and office spaces. The gross floor area is 3509 m^2 and the building is square-shaped with a dimension of 1490 m^2. The area of the atrium is 240 m^2. The main façade of the buildings faces east–south. The construction of the school building was the reinforced concrete structure. The specific building information, thermal transmittances of building envelopes, and mechanical systems are presented in Table 1.

Figure 1. The reference school building.

Table 1. The reference building description.

Building		Location	Abha, Saudi Arabia
		Floors	3 floors
		Usage	19 classrooms
			6 offices
			7 laboratories
		Year constructed	2010
		Gross floor area	3509 m^2
Envelope systems	Thermal transmittance	External walls	0.72 W/(m^2K)
		Roof	0.69 W/(m^2K) (Atrium)
		Window	5.7 W/(m^2K)
		Window's SHGC	0.86
		Window-to-wall ratio	South (20%), north (17%), east (14%), and west (17%)
Mechanical system		Classroom and office	72 heat pump split units (2 ton)
		Laboratory	14 heat pump split units (2.5 ton)
		Others	Water pump system (2 unit: 4.5 hp and 1 unit: 15 hp)

3.2. Building Operation

The school building is mainly operated from 6 a.m. to 3 p.m. during weekdays. During the weekend, the occupancy ranged from 10% to 30% of the peak occupancy rate, and this dropped to 5% for vacation periods. Schedules for electric lighting and other equipment are set to occupancy schedules. For heating and cooling in the building, mini-split air conditioning heat pump systems were installed in each classroom, office, and corridor. The setpoint temperature for HVAC systems was 24 °C and 21 °C for cooling and heating, respectively. In addition, the atrium space is ventilated naturally. The specification of HVAC systems is presented in Table 1. For other conditions, the number of peak occupancies for the school is set at around 800 people.

3.3. Total Energy Consumption of the Reference Building

Due to its location in the mountainous region, Abha City has a mild climate condition. As presented in Figure 2, the mean temperature is about 18.5 °C and it can be increased to 25 °C in June. Conversely, the coldest temperature is about 13 °C in January. The total energy consumptions in 2017 and 2018 were 109,750 kWh and 116,754 kWh, respectively. Comparing the total energy consumption in these two years, about 6% of electricity was increased in 2017. Due to the mild climate conditions, it was observed that the electricity consumption during the winter was higher than that during the summer because of the high demand for domestic hot water.

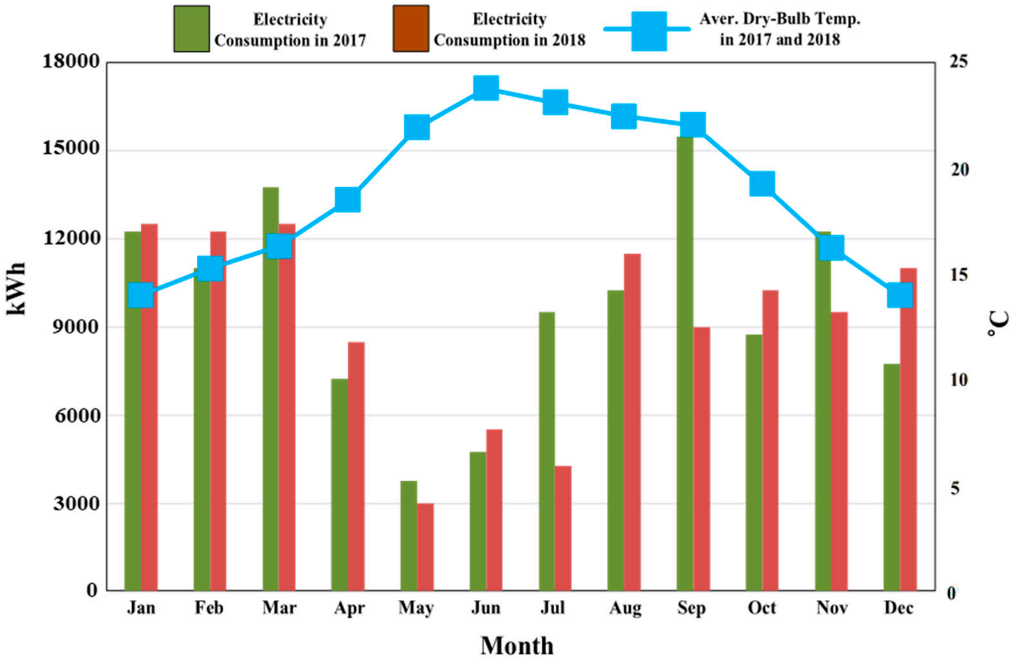


Figure 2. Monthly electricity consumption of the reference building in 2017 and 2018 and the averaging dry-bulb temperatures in 2017 and 2018 in Abha, Saudi Arabia.

3.4. The Energy Simulation

The reference school building is modeled by using energy simulation software and validated with energy consumption of the building. In addition, Green Building Studio was used, which uses EnergyPlus as a simulation engine to calculate heating and cooling loads [37]. Figure 3 shows a school building modeled by Green Building Studio.

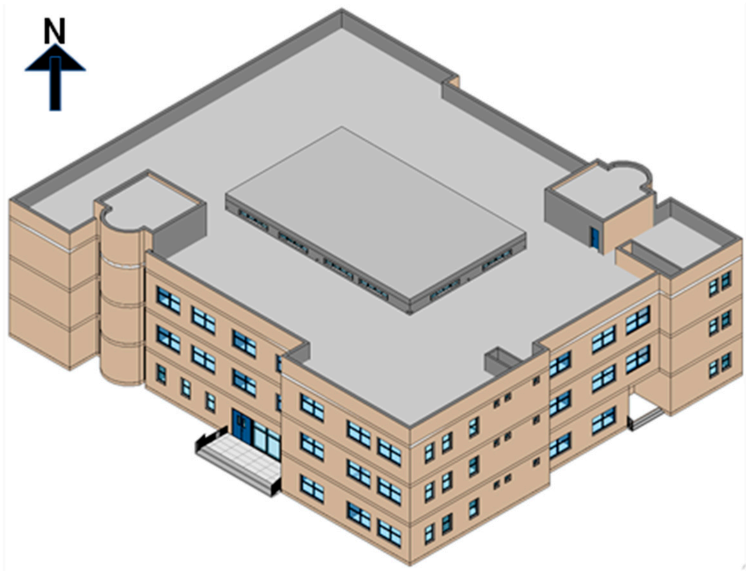


Figure 3. The school building model for energy simulation.

For the validation, statistical indices such as the coefficient of variation of the root mean squared error (CV(RMSE)) were used [38]. Using the equations below, the monthly energy consumption of the reference school building is compared with energy simulation.

The model is declared to be calibrated if they produce CV(RMSE)s within ±15% with monthly energy data.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(M_i - S_i\right)^2}{n}} \quad (1)$$

$$C_V(RMSE) = \frac{RMSE}{M_{avg}} \times 100 \quad (2)$$

where M_i is the energy consumption of the reference school building, while S_i is the monthly energy consumption from the simulation. n is the period and M_{avg} is the average for the energy consumption of the reference school building.

After the validation, the key design variables are chosen and the energy performance of the combinations of these key design variables is investigated. The rest of the energy usage is offset by PV panels. In addition, the cost-effectiveness of the combinations of key design variables with PV panels is assessed through the cost-effectiveness assessment towards nearly zero-energy school building design.

4. Results

4.1. The Energy Consumption Comparison

The monthly energy consumption between the reference school and the energy simulation was compared (Table 2). The total energy consumption predicted by the simulation was about 160,724 kWh, which was decreased by about 3% compared to the average energy usage in 2017 and 2018 by the reference building. In addition, the biggest energy consumption difference between the electricity consumption and the energy simulation result was observed in August, which was about 6% (Figure 4). Table 2 shows CV(RMSEs). They ranged from 0.35 to 4.65. Because the results were in the acceptable range, the simulation results met the requirement by ASHRAE Guideline 14 [38].

Table 2. The monthly energy consumption comparison.

School Building	Energy Consumption (kWh)			C_V (RMSE) (%)
	Average Energy Usages in 2020 and 2021	The Prediction Model	Difference	
January	12,959	12,498	461	0.35
February	14,692	11,834	2858	2.18
March	14,516	13,251	1265	0.96
April	16,758	12,998	3760	2.86
May	16,602	18,122	−1520	1.16
June	9555	12,041	−2486	1.89
July	8414	9488	−1074	0.82
August	6461	12,573	−6112	4.65
September	14,922	17,331	−2409	1.83
October	17,734	16,165	1569	1.19
November	13,867	13,104	763	0.58
December	14,469	11,319	3150	2.40

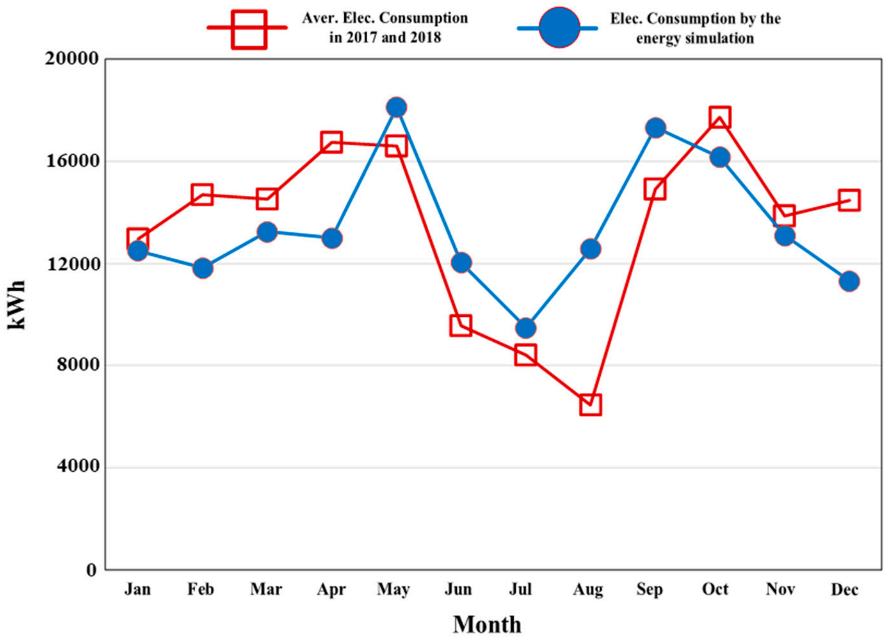
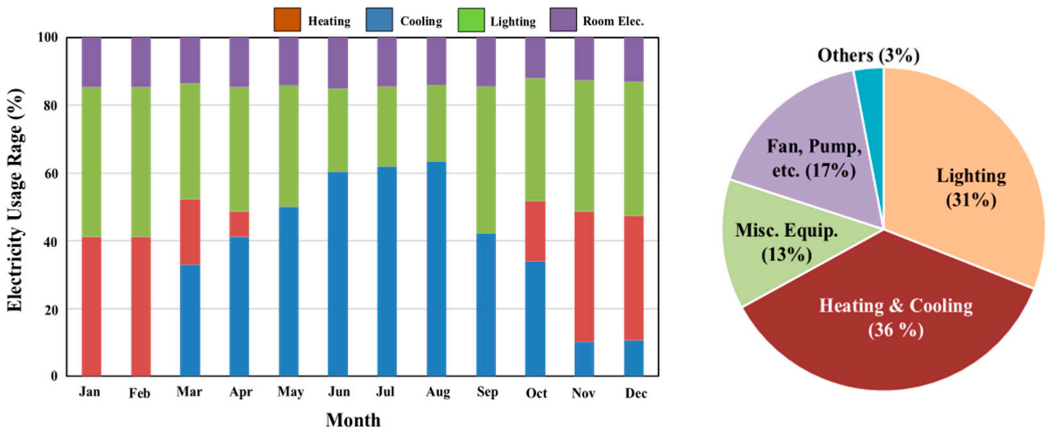


Figure 4. The energy consumption comparison between the energy usage and the energy simulation.

4.2. The Energy Use Breakdown

The energy end-use breakdown for the reference school building is shown in Figure 5. Due to the characteristics of school buildings, about 36% of the total energy consumption was used for artificial lighting. For maintaining thermal comfort, about 33% and 17% of the total energy was consumed for cooling and heating, respectively. As can be shown in b in Figure 5, the most electricity was consumed by heating and cooling equipment. For the lighting, slightly lower energy consumption was observed, which was about 5% less than that was consumed by heating and cooling equipment. Thus, it is required to reduce energy consumption by applying energy-efficient active design strategies, especially heating and cooling, and artificial lighting.



(**a**) (**b**)

Figure 5. Energy usage of the reference building. (**a**). Electricity usage rate. (**b**). Electricity consumption breakdown by mechanical systems.

4.3. Passive and Active Design Strategies

To develop the nearly zero-energy school building design, available passive and active design strategies were chosen and combined. In addition, the energy performance of these design strategies was assessed. The selected design strategies are presented in Table 3.

Table 3. Passive and active design strategies.

Design Strategy		
Passive design	Building envelopes	- External walls (U-value: 0.6 to 0.2 W/(m^2K)) - Roof (U-value: 0.7 to 0.13 W/(m^2K)) - Window system (single glazing to double low-E: 2.6 W/(m^2K))
Active system	Electric light bulb	- Replacing fluorescent lamps with LED
	Electric lighting control	- Daylighting
	HVAC system	- High-efficiency heat pumps (COP: 1.5 to 3.5)

Figure 6 shows the energy consumption of the reference school building by applying each design strategy. When replacing the fluorescent bulbs with LED lamps, about 29% of the total energy consumption was reduced. In addition, about 11% of the energy saving was achieved by the utilization of daylighting sensors. The use of high-efficiency heat pumps can reduce energy consumption by about 24%. While most active design strategies were effective in reducing energy consumption, the improved building envelopes had less impact on the energy consumption in the school building, which was less than 4%. It can be seen that the location of the reference building was under a mild climate. Moreover, about 43% of the energy consumption was reduced when all the combined active design strategies were applied.

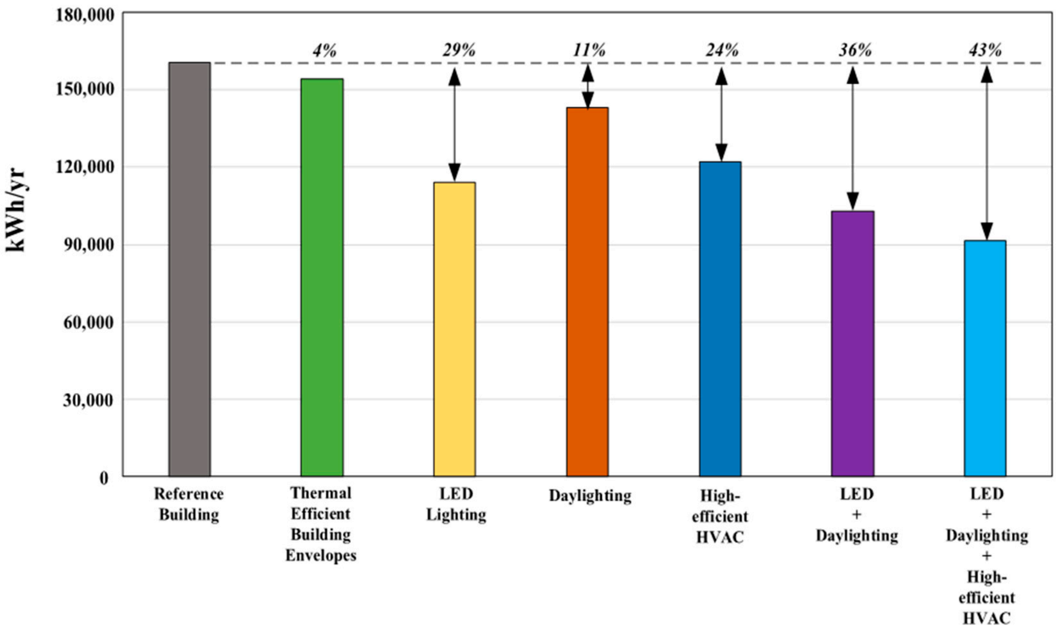


Figure 6. The energy consumption for each design strategy.

4.4. Renewable Energy System—Solar Photovoltaic Generation

Based on the energy consumption of the passive and active design strategies, it is imperative to use renewable energy systems for achieving a nearly zero-energy school building design. Among available renewable energy systems, solar photovoltaic (PV) generation was chosen due to its great energy-saving potential and worldwide use in the area of net/nearly zero-energy building design [39–43]. Based on the reference model provided by NREL's PVWatts Calculator, the default PV system size was 2 kW with 16% efficient PV modules, which corresponds to an array area of approximately 25 m^2 [44]. The annual electricity production by different coverages of the total roof area was also calculated using solar resource data from Riyadh, Saudi Arabia. The specifications of the PV system and the different annual electricity productions are presented in Table 4.

Table 4. Application of solar PV design alternatives.

Solar Resource Data Site	PV System Size (kW)	Module Efficiency (%)	PV System Losses (%)	Coverage of the Total Roof Area (%)	Annual Electricity Production (kWh/Year)
Riyadh, Saudi Arabia	2	16	14.08	10	44,594
				15	67,431
				20	89,908
				25	112,386
				30	134,863
				40	179,817

Figure 7 shows applications of passive and active design solutions with PV systems. Initially, about 4% of the total energy consumption was decreased by the thermally advanced building materials for all five cases. For nearly zero-energy school building design, different PV system alternatives were utilized. When LED light bulbs or energy-efficient HVAC systems are used, the PV system covering 25% of the roof area can be chosen. With all the design solutions, about 50% of the total energy consumption was decreased. For this case, the PV system covering 15% of the total roof area can be selected. When only daylighting control was applied, the PV system covering about 35% of the roof area was used.

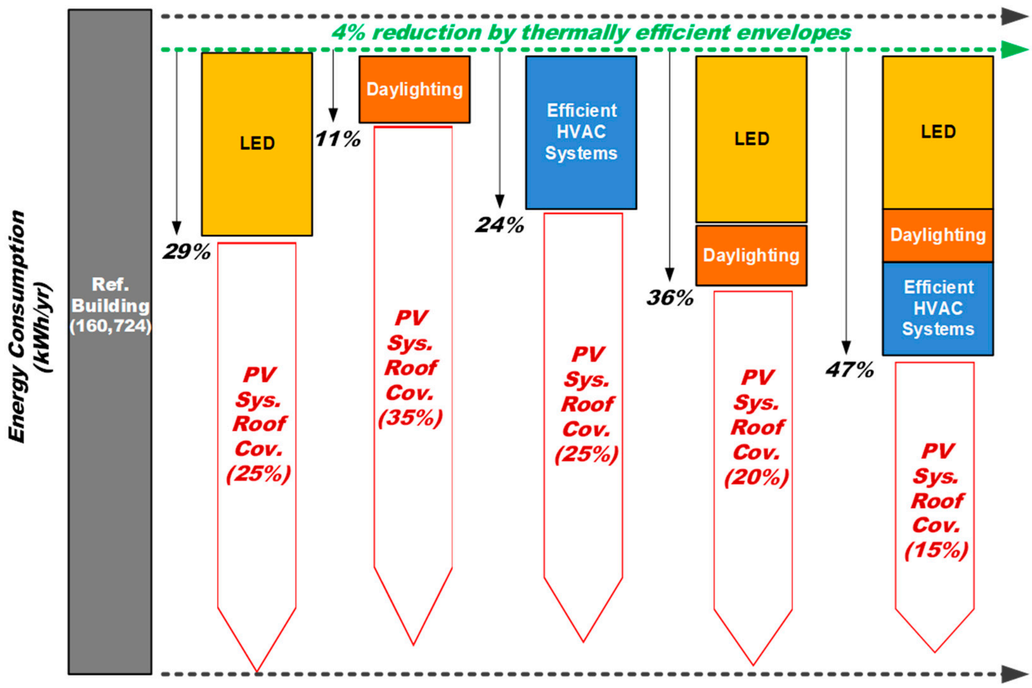


Figure 7. The energy consumption reductions by passive and active design solutions with PV systems.

4.5. Cost-Effectiveness of Design Strategies with PV Systems

Concerning the PV panel price ranging from USD 300 to USD 400 based on 250 W panels, the payback time was calculated for five cases in Section 4.4 (Table 5). As shown in Table 5, the most expensive design solution was Case 2 due to the highest roof coverage by the PV system, while the cheapest design solution was Case 5 even though all the possible passive and active design strategies were used. Without any solar PV panels, the capital costs of all cases are varied, and the most expensive design solution is Case 5. This point was also reflected in the payback time calculation. The longest and the shortest payback times were observed for Case 2 and Case 5, which were 9.5 years and 2.6 years, respectively. Combining two or more design strategies can have more energy performance than that of the sole design solution in the reference school building. This can thus lead to choosing the PV system covering a smaller roof area. Therefore, Case 5 was chosen for a nearly zero-energy school building design solution considering the energy performance and cost-effectiveness.

Table 5. The payback time for 5 cases.

Case		Investment Cost ($, USD)	Annual Maintenance Cost (% of Investment Cost)	PV Generation (kWh/Year)	PV Degradation Rate (%)	Payback Time (Year)
Case 1	LED lamps	4702	1			6.1
	PV system (roof coverage: 25%)	155,319	1	112,386	0.5	
Case 2	Daylighting sensors	32,670	2			9.5
	PV system (roof coverage: 35%)	217,446	1	157,340	0.5	
Case 3	Energy-efficient heat pumps	118,620	1			6.1
	PV system (roof coverage: 25%)	155,319	1	112,386	0.5	
Case 4	LED lamps + daylighting sensors	36,742	2			4.3
	PV system (roof coverage: 20%)	124,255	1	90,910	0.5	
Case 5	LED lamps + daylighting sensors + energy efficient heat pumps	155,362	2			2.6
	PV system (roof coverage: 15%)	93,191	1	67,432	0.5	

5. Discussion

The present study presented the procedures for developing a nearly zero-energy school building by assessing energy and economic performance. To achieve the goal, a typical public school building was chosen as a reference building considering the climates and other situations. The energy performance of the reference school building was assessed by using energy simulations. As a result, most of the energy used in the reference school building was consumed by mechanical systems, especially artificial lighting due to the mild climate conditions. Most studies about nearly/net-zero-energy building design including commercial, school, and other mixed-use buildings under hot and humid climate conditions have implemented thermally improved building envelopes, natural ventilation, and energy-efficient lighting and controls [45–48]. Even though most of those studies have implemented more passive design features than active or renewable energy systems, the present study had to deal first with active design strategies because of the energy-inefficiency of passive design strategies in which the energy-saving by the use of passive design features was less than 3% of total energy consumption. Although the reference building is located under a mild climate, where the highest air temperature is above 30 °C, the impact on the energy consumption by passive design strategies did not change when all passive design variables were sensitized. It can be seen that school buildings have a different schedule in which severe hot and cold seasons can be avoided and that cooling and heating energy can be reduced. Thus, the main energy was used for artificial lighting and equipment such as computers, screens, etc., in classrooms.

As shown in Figure 5, the second contributor to energy consumption was equipment in the reference school building. For example, there were computers, screens, copy machines, etc. By managing the plug loads of that equipment, such as applying high energy-efficient equipment, the energy performance of the school building can be improved. However, it was difficult to consider all the energy-efficient equipment because of the large variety of equipment. Moreover, the high-efficiency heat pump was solely considered. Because more than 80% of buildings in Saudi Arabia have implemented air source heat pumps, the use of ground source heat pumps or thermal storage tanks using PCMs is necessary in the beginning stage. Due to the regional characteristics of Saudi Arabia, the energy consumption by mechanical systems has become the main concern and the energy and economic assessment of highly advanced mechanical systems should be further analyzed. Still, the concern of energy use is not the main issue, but it has become more important in Saudi Arabia. Even though energy prices in the market can have seasonal variation and future fluctuation, the price difference was not taken into account. While it is not a critical variable in the long term, it requires considering fully the seasonal and future energy price fluctuations for more accurate economic analysis.

In Section 4.5, the payback time for all cases was calculated. For further analysis, the quality of the life-cycle cost was verified through a sensitivity analysis. As shown in Figure 8, a 25% increase, a decrease in capital costs, and a 5% increase in electricity costs were used. The life-cycle costs for each design strategy reflecting two different capital costs and the 5% increased energy costs were presented. With the variation in the capital costs, the economic order of the base design strategies was similar. Specifically, the difference among the design strategies became larger as the capital costs were increased compared to the base designs and the design strategies with the decreased capital costs. In addition, the sole use of the high-efficiency heat pump can have the worst result with the increased capital cost. In the case that the electricity costs were increased, there was little difference from the base design strategies.

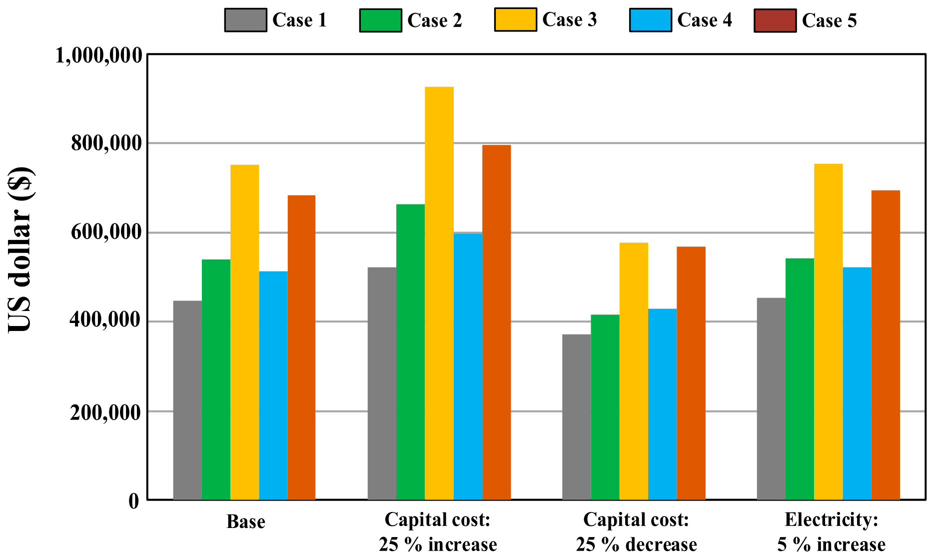


Figure 8. Sensitivity of the life-cycle costs of design solutions for the nearly zero-energy school building design.

6. Conclusions

The use of nearly zero-energy buildings has been significantly growing in developed countries [45]. Even though this concept is in the beginning stage in developing countries, building energy efficiency has become one of the biggest issues in Saudi Arabia. In the current decade, the number of studies of energy efficiency in buildings including net-zero-energy building design has rapidly increased in Saudi Arabia. However, most studies have focused on residential or commercial buildings. The present study showed the assessment of the energy and economic performance of government buildings such as school buildings in Saudi Arabia to develop a nearly zero-energy school building design.

For the study, a public school building in Abha City in Saudi Arabia was chosen as a reference school building. Energy simulations were performed by adopting the conditions of the school building. For the energy breakdown, the energy was mainly consumed by artificial lighting. To reduce energy consumption, available passive and active design solutions were applied. When light bulbs were replaced with LED lamps, about 30% of total energy consumption was reduced. In addition, LED lamp replacement with daylighting sensors can have a 36% reduction in total energy consumption, while the improvement of building envelopes was 4% of total energy reduction. The remaining energy was offset by the renewable energy system, especially solar PV panels. Except for the passive design features, the other active design solutions with proper solar PV panels were in the economic analysis to find the best design solutions for the nearly zero-energy school building. Comparing the payback time of each combination of active design solutions with solar PV panels, all active design solutions with the PV system covering 15% of the total roof area were chosen as the best design solution for the nearly zero-energy school building design. This present study has revealed the challenges of achieving a nearly zero-energy school building design under the climate conditions in Saudi Arabia. Moreover, the outcome of the study shows the possibility of a nearly zero-energy building concept for buildings in Saudi Arabia. Suggested further work will include the energy performance analyses of various active design solutions such as ground source heat pumps and thermal storage tanks.

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