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Economic Analysis of Replacing HPS Lamp with LED Lamp and Cost Estimation to Set Up PV/Battery System for Street Lighting in Oman

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Abstract: In this paper, two aspects related to streetlight systems are considered. In the first part, the economic analysis of replacing existing HPS lamps with light-emitting diode (LED) and discrete LED lamps for street lighting is performed using actual data from Oman. The street lighting system inside Sultan Qaboos University is considered for the case study. The discounted payback period, which is calculated to study the practicability of implementing the system, is found to be 1.01 years, making the system financially appealing. Moreover, the estimated reduction of a carbon footprint shows that tonnes of CO_2 emissions are reduced, which makes it environmentally attractive. The second part of the paper considers optimal sizing of PV/battery system for a new streetlight system with LED lamps. The life cycle cost analysis was performed and the related cost of energy generated per kWh is estimated as 0.097 \$/kWh which proves the economic viability of the system to be implemented in Oman besides minimizing the CO_2 emissions to zero.

Keywords: street lighting; HPS; LED; optimal sizing; discounted payback; CO_2 emissions; life cycle cost; PV/battery

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1. Introduction

The Greenhouse gases produced from fossil fuel–charged energy generation cause global warming and harm the environment. In the context of lighting, these greenhouse gases can be reduced by decreasing electric energy consumption using energy-saving lamps. Zero greenhouse gas emission is possible through the use of renewable energy resources for power generation. Globally, 19% of the total electricity generated is used for lighting purposes, which results in the emission of 1900 Mt of CO_2 per year, equivalent to emissions ejected from 70% of the world's light passenger vehicles [1]. Street lights, which enhance safety and comfort for road users, are one of the major sources of electricity consumption and account for 3.19% of the electricity generated globally [2]. In the UK, streetlights consume about 40% of a city's total electricity cost [3], causing huge amounts of CO_2 emissions.

The highest level of energy consumption per luminaire is for outdoor lighting [4]. The lamps used for street lighting are classified broadly into three categories: incandescent, discharge, and solid-state lamps (SSL). Presently, the most commonly used lamp among these is the high-pressure sodium (HPS) lamp [5]. The main reasons for the popularity of the HPS lamp compared with the discharge and incandescent lamps are its high lumen/watt, smaller size, and lower cost. Lately, increasing fuel prices and environmental issues have stressed the need to replace existing lamps with more energy-efficient and environment-friendly lamps.

A much better alternative for energy saving (also given its superior features) is the light-emitting diode (LED) lamp, which can replace the existing HPS lamps. These lamps possess high luminous efficacy and more accurate distribution of luminous flux compared with HPS lamps [6]. It was initially manufactured in the 1960s to be smaller and reduce energy consumption and has now become vital for electronic applications [7]. An LED light fixture is composed of a housing, a lens, a driver, and PCBs along with the LEDs [4]. It is a rather complex system with several components at different levels with optical, thermal, and electrical functions [8]. CO_2 emissions caused by electricity generation from fossil fuels can be minimised in street lighting systems by converting the most widely used HPS lamps to energy-efficient lamps, and these emissions can be reduced to zero by using solar-powered streetlights with battery backup.

This paper shows a detailed analysis of the characteristics of LED lamps that make it more appealing compared with HPS lamps and emphasizes the importance of replacing these lamps. It also considers a new street light system powered by PV/battery system, with optimised values for the number of photovoltaic (PV) panels and batteries using genetic algorithm. The related life cycle cost and cost per kWh of generated energy is evaluated. The street lighting system inside Sultan Qaboos University, Oman, is considered a case study for estimation and cost analysis. This paper is organised as follows. The first part deals with the conversion of HPS lamps into LED lamps, with a literature review in Section 2, the design of a streetlight system with LED lamps and discrete LED lamps in Section 3, economic analysis in Section 4, and CO_2 emission reduction in Section 5. The second part deals with optimising the number of panels and batteries for new street light system, with Section 6 covering the models for the panels and batteries, Section 7 the objective functions and constraints, Section 8 the life cycle cost analysis followed by the conclusion.

2. Literature Review on LED Lamps

The SSL uses LEDs as its light source. A single LED produces less light output compared with incandescent or compact fluorescent lamps (CFL), which use multiple diodes to produce the required light output. The first SSL was reported in 1994, when the first high-brightness blue LED was developed [9]. LED lamps are composed of LEDs, a solid-state device with a driver circuit, a cooling system, and optics [10]. LED lamps are gaining popularity for their high luminous efficacy, low energy consumption, long life, and absence of harmful chemicals. Several research papers have emphasized various aspects related to LED lamps, which include the behavior of LEDs under various conditions as well as their converter circuits, luminous efficacy, driver circuits, and color-rendering properties. Research done by the JSC Federal Research Institute [11] presents the intermediate results of their project which aimed at organizing the fabrication of highly efficient and reliable LEDs with high luminous efficacy and a lifetime of 100,000 h. Another study [12] involving the measurement of road lighting luminance and an analysis of the energy efficiency, glare properties, and life cycle costs of LED installations suggests that more energy savings can be attained in mesopic dimensioning. A paper published by the Nitride Semiconductor Research Laboratory [13] details the fabrication of three types of white LEDs with high luminous efficacy of 249 lm/watt and a high luminous flux of 14.4 lm. A literature survey on LED lamps as energy-efficient lamps as well as developments in driver technology is presented [14], along with technical issues related to thermal properties and LED array configurations.

The U.S. Department of Energy published reports based on a study of LED lamps in three parts focused on various aspects of LED lights. This comprehensive life cycle assessment (LCA) study explains in detail how lighting affects the environment. The first part [15] covers an analysis of life cycle energy consumption comparing different types of lamps, the second part [16] focuses on the manufacture and performance of LED, and the third part [17] discusses the environmental testing of LED lamps. The results show that LED lamps are the least harmful to the environment compared with incandescent lamps and CFLs.

A white paper published by USAI Lighting [10] describes in detail the savings in energy and maintenance in LED lamps as well as the superior features of LED lamps compared with those of other types of lamps. The return on investment (ROI) of LED lamps is calculated in [18] to decide whether sodium vapor lamps can be replaced with LED lamps. The variety of driver circuits that can be used in LED lamps is discussed in [19], which suggests avoiding the use of an electrolytic capacitor, which has a very short lifetime, in driver circuits to improve the life of these circuits. The use of an integrated double buck-boost converter with LED lamps in street lighting was investigated in [20], showing that these converters can provide high power factor, high efficiency, and low costs. Energy saving in the transition from HPS lamps to LED lamps for greenhouses requiring additional heating is presented in [21], which uses the 'greenlight' simulation model and considers the climatic conditions of fifteen regions around the world. The energy savings were found to increase by 10–25% through the transition, but the increase in demand for heating during winter and the energy loss caused by the transpiration of crops were higher in HPS lamps.

A techno-economic analysis of LED luminaires is presented in [4], considering the technologies, global supply chain, and comparative cost analysis, which showed that the local manufacture of luminaires was economically more viable. Rapid advancements in the field of LED technology and considerable energy savings as a result of such technology make it more appealing. An experimental study on the influence of illuminated crosswalks on drivers' behavior and pedestrians' safety in Rome [22] showed the promising impact of LED lighting on drivers' behavior and the improved safety of pedestrians. The conversion of HPS lamps to LED lamps in street lighting is investigated in [6], which shows that a useless luminous flux causes electricity loss. The luminous flux distribution is optimized, and the results prove that converting HPS lamps to LED lamps with the same total luminous flux resulted in reduced light trespass, higher illuminance, higher uniformity of traffic lines, and higher levels of vertical illuminance.

Light pollution, which affects humans and the environment, is considered for public lighting in [23]. The comparison of a scattered flux with consumed electricity showed that luminaires with LEDs which emit white light are more precise for weakly illuminated roads. The study also emphasizes the advantages of white light for sustainability in the global problem of light pollution. An economic analysis on converting high energy-consuming sodium lamps to LED lamps and 'part night' lighting is presented in [24]. The conversion of 29,701 existing sodium lights to LED lights results in the reduction of CO_2 emissions by 38% and energy savings of 44%. A study on energy savings and CO_2 emission reduction for outdoor lighting [25] in a university campus considered four different scenarios: (i) switching off the lamps early; (ii) dimming the lamps; (iii) converting metal-halide lamps to LED lamps; and (iv) combining Cases (ii) and (iii). The results showed annual energy savings of 762 MWh and a reduction of 251 tonnes of carbon emissions annually for Case (iv).

The replacement of several types of high-intensity discharge lamps with LED lamps in street lighting considering economic indicators based on 'company benefits' and 'national benefits' is presented in [26], which showed the highest national economic value through the conversion of HPS lamps to LED lamps. The total payback period was found to be about nine years, and the annual ROI was found to be 11.55%. A review of several possible failure mechanisms in LED lamps caused by the degradation of materials used for LED lamp manufacture is presented in [8]. An energy-maintenance optimization model to determine the dimming level and number of LED lamps to be replaced is presented in [27] to maximize energy savings and minimize maintenance costs considering the degradation of luminous flux with the case study of an open-plan office. Annual energy savings of about 3 MWh and a reduction of 30% in maintenance costs were achieved with the proposed model.

A cost-optimal analysis for selection of best retrofit considering two educational buildings in Italy is presented in [28] adopting the net present value (NPV) index to analyze the economic feasibility considering seven different scenarios. Replacement of lamps with energy-efficient lamps considering daylight autonomy and visual comfort applying lighting control is considered. Total return (TR) of between 20–25 years was shown for the different scenarios considered, due to which the authors conclude the economic infeasibility of lamp replacement. An optimal decision tool to maximize energy savings and allocate the retrofit optimally for urban smart streetlight system in Italy with a pre-defined budget is presented in [29] with quadratic integer programming based formulation. Replacement of HPS lamps and installation of energy harvesting units, which can store and supply energy based on requirement are considered in this work. A similar study is presented in [30] based on dynamic programming for existing streetlight systems in Italy with proven efficacy to be adopted in large-scale streetlight systems. Optimal allocation of retrofits considering the cost parameter and energy savings accounting the light pollution levels, dimming control and drivers' comfort is a challenge in smart streetlight systems.

Street lighting design based on measurements and user survey for maximum energy savings, considering the comfort of users is presented in [31], with a case study of a campus outdoor lighting system. HPS and mercury vapor lamps were replaced with LED lamps and a commercial software was used for remote management and control. Results showed energy savings of about 70% with 3–4 years investment return time. Techno-economic analysis for replacement of HPS lamps with LED lamps/LED corn bulbs and replacement of HPM(high-pressure mercury) lamps with HPS lamps/LED lamps/corn bulbs considering several scenarios with/without dimming control for street lighting system in Serbia is presented in [32]. Replacement of HPS and HPM lamps along with dimming control showed maximum energy savings, replacement with LED lamps showed longer payback period and replacement with LED corn bulbs gave the shortest payback period, which was 2.15–2.83 years.

Through analysis of existing research, it is evident that replacement of energy-inefficient lamps with energy-efficient lamps in street lighting is a very important criterion to be followed to minimize the energy cost as well as CO_2 emissions. Streetlight systems powered by renewable energy units is the next step, which can result in zero emissions. Nevertheless, techno-economic analysis of the above-mentioned aspects is vital to investigate the possibility of practical implementation. Existing literature has done a lot of work related to the manufacture, replacement of energy-inefficient lamps with energy-efficient lamps and economic analysis/optimal sizing of PV/battery systems. However, under the context of depletion of fossil fuels, increase of electricity cost and increase of CO_2 emissions, it is imperative to analyze the practicality of lamp replacement and enhancing the use of renewable energy resources in street lighting with actual data considering every detail, to be adopted in streetlight systems worldwide. Existing research has not incorporated all the essential factors in lamp replacement which includes the methodology of lamp replacement from scratch, with existing streetlight systems, real data and techno-economic analysis under a single study. Moreover, optimal sizing of PV/battery system for a new street lighting system, evaluation of the related life cycle cost and cost of generated energy based on actual data is never investigated.

Based on the literature review, there are research gaps to be addressed, related to replacement of energy-inefficient lamps with energy-efficient LED lamps.

1. Although studies consider the techno-economic analysis of converting energy-inefficient lamps with energy-efficient LED lamps, to the best of authors' knowledge, the replacement of lamps in existing streetlight system with methodology from square one using actual measurements of roads, poles, etc. has not been addressed in any work.
2. Replacement of HPS lamps with customized discrete LED lamps for additional energy savings with basic design and calculation is never considered.
3. The payback period with reference to the topic is high, which is available in literature, provides an inaccurate assessment for readers, resulting in the withdrawal from projects that actually require replacement of energy-inefficient lamps with energy-efficient LED lamps for cost savings as well as minimizing CO_2 emissions. The authors considered real data for accurate and practicable results.

4. Optimal sizing of renewable energy system for street lighting is considered in countable number of papers, but optimal sizing of PV/battery system for street lighting with design methodology for street lighting considering a new area deprived of streetlight and the related life cycle cost is never investigated.
5. This study is the first of its kind conducted in Oman.

Materials and Methods

The methodology adopted for conversion of HPS lamps to LED and discrete LED lamps and the related steps for techno-economic analysis is presented in Figure 1. The design of a new streetlight system with optimal sizing of PV/battery system and the related life cycle cost analysis is presented in Figure 2.

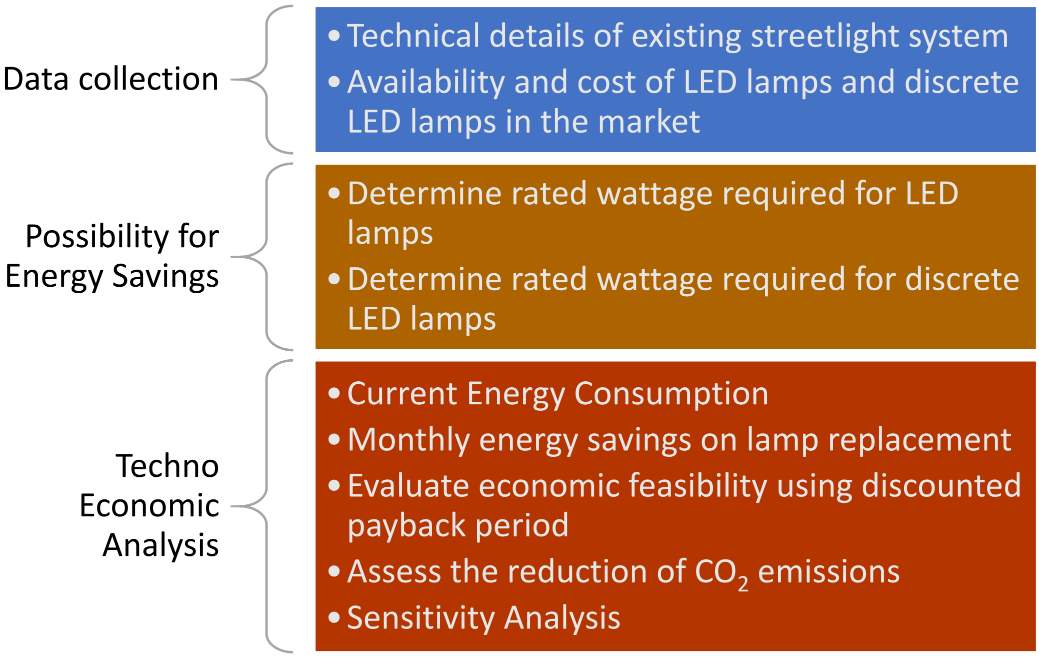


Figure 1. Steps involved in the techno economic analysis of replacing HPS lamps with LED and discrete LED lamps.

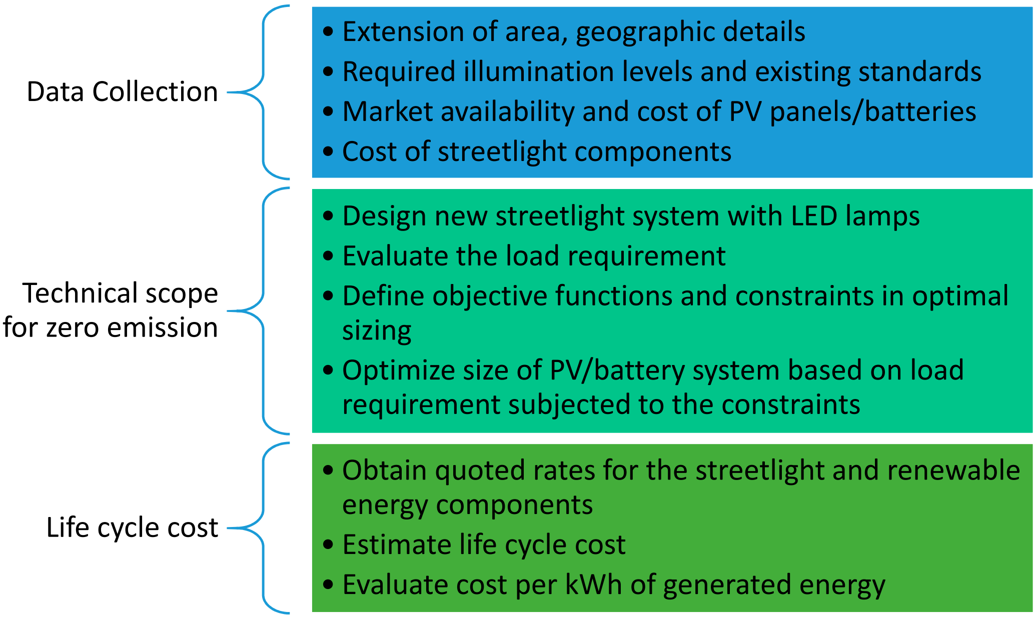


Figure 2. Methodology for economic analysis to set up new streetlight system powered by PV/battery system for zero emissions.

3. Design of Street Light System with LED Lamps

3.1. Technical Details of Street Light System in Sultan Qaboos University

The street lighting system inside the university consists of the main road lighting system and the side road lighting system; this study considers the former. The technical details of the main road lighting system are shown in Table 1.

Table 1. Technical Details of Street Lighting System inside University.

No. of Lamps	Type of Lamps	Wattage Rating	Width of Road	Required Lux Level	Spacing between Poles
285	HPS	400 W	6 m	60 lux	30 m

3.2. Methodology to Calculate Rated Wattage for LED Lamps

The existing lamps used inside the university are HPS lamps of 400 W rating. To replace these lamps with LED lamps, the first step is to calculate the illumination level required from the new LED lamps. The flux of LEDs decreases with time, but the human eye hardly notices a decrease of less than 30% over the operating period. Hence, a margin of acceptance for the decrease in flux and extended lamp life is considered [33]. As described in [34], the required illumination in lumens is:

$$LL = \frac{S \times E \times W}{CoU \times Mf} \tag{1}$$

where,

S = distance between poles (30 m)
E = required lux level for the selected road (30 lux)
W = width of the road (6 m)
CoU = coefficient of utilisation of the selected lamp
Mf = maintenance factor = LLD × LDD (0.85)
LLD = lamp lumen depreciation factor (0.9)
LDD = luminaire dirt depreciation factor (0.95)

The CoU of the LED lamp depends on the type of lamp used and is considered to be 0.77 as in [35]. Using the values mentioned, the lamp illumination required is obtained as $8250.573 \approx 8251$ lumens.

Over the past 25 years, the efficacy of LED lamps has improved from 25 lm/watt to 160 lm/watt [36]. As per the illumination requirement, a 70 W LED lamp with luminous efficacy of 120 lm/W will be sufficient for replacement. However, a 70 W lamp will provide illumination very close to the required value, and the illumination may drop below requirement with lamp aging. Therefore, an 80 W led lamp is chosen for the replacement to provide the required lumens over the lifetime of the installation. With the luminous efficacy of 120 lm/watt, an 80 W lamp can produce 9600 lumens (80 W × 120 lm/W), which is well above the requirement.

The 400 W HPS lamps inside the university can be replaced with new 80 W LED lamps To reduce energy consumption and maintenance costs. The economic feasibility of implementing the LED system can be determined using the discounted payback period.

3.3. Design of Street Lighting Using Discrete LED Lamps

The standard wattage lamps cannot be customized and therefore provide fixed lumens. Based on the illumination requirement and the luminous efficacy of the lamp, the wattage rating of the lamp is calculated, and the nearest wattage rating is usually selected. The lamp used may therefore be overrated and result in excess energy consumption.

The discrete LEDs available in [37] can be used to create customized LED lamps. Vendors provide housing that can be used to install discrete LED lamps as per the requirement. As these are customizable, the users can choose the precise wattage of LED lamps to suit their requirements and reduce the excess energy consumption from the standard overrated lamps. The lamps can be designed to match the wattage requirement using several discrete LEDs. LEDs require driver circuit comprising of a power source along with the control circuitry, which have several functions of converting line voltage to low voltage and current levels, AC to DC conversion, color correction and dimming purposes [1].The process for designing the discrete LED lamps for a street lighting system inside the university is provided next.

As calculated in Section 3.2, the required illumination level for the lamp is 8251 lumens. The data of the commercially available discrete LED lamps for street lighting are obtained from Cree Lighting [37]. The data for different discrete LEDs is available which includes their maximum rated power and corresponding lumen output. Using the optical efficiency $\eta_{optical}$ and thermal efficiency $\eta_{thermal}$, the required lumens from the LED lamps can be obtained using Equation (1),

$$\text{Actual lumens required} = \frac{\text{Target lumens}}{\eta_{optical} \times \eta_{thermal}} \tag{2}$$

From the literature, $\eta_{optical}$ and $\eta_{thermal}$ are found to be 95% [16] and 85% [35], respectively. Therefore the actual lumens required is 10,218 lumens. The number of LEDs required in the customized lamp is obtained from Equation (2),

$$\text{No. of LEDs} = \frac{\text{Actual lumens}}{\text{Lumen rating of each LED}} \tag{3}$$

The wattage of the customized LED lamp is calculated from Equation (3),

$$\text{Lamp Wattage} = \text{No.of LEDs} \times \text{Rated wattage of each LED} \tag{4}$$

The monthly energy savings possible with the use of LED lamp is given in Equation (4),

$$\text{Monthly energy savings} = \text{Difference in wattage} \times T \times D \tag{5}$$

where, T is the daily ON time of the lamp in hours, and D is the total number of days in the month. For calculation, it is assumed the lamp is ON for 12 h a day for a total of 31 days in the month. Table 2 shows the wattage and energy savings possible using different commercially available discrete LEDs. The maximum rated power and the maximum light output of the LEDs specified in the table are provided by the manufacturer [37]. The number of LEDs required in the customized lamp and monthly energy savings are calculated using this data.

Table 2. Design of discrete LED lamps with the corresponding energy savings.

Sl. No:	Max.Rated Power (W)	Max.Light Output (lumens)	No: of LEDs	Total Wattage (W)	Difference in Wattage	Monthly Energy Savings (kWh) (Approx)
1	3	283	36	108	292	108,624
2	6	777	13	78	322	119,784
3	10	1175	9	90	310	115,320
4	5	629	16	80	320	119,040

It is evident from Table 2, the maximum energy savings while satisfying the illumination requirements is possible using the 78 W customized LED lamp (row 2). For further calculations relating to the discrete LED, these specifications are used.

4. Economic Analysis Using Discounted Payback Period

To study the cost-effectiveness of any system before implementation, the payback period must be calculated to examine the feasibility of implementing the system under study. The results of calculating the payback period assist in deciding if the system is financially viable.

To calculate the payback period, the initial investment and the annual savings in energy and maintenance must be determined. The energy consumption level of a street lighting system differs based on the season and the type of lamp used. Figure 1 shows a comparison of energy consumption levels for HPS and LED lamps. During the winter months, the streetlight works for 12 h a day, whereas for the summer, with longer days, it works for only 10 h a day. The energy cost, therefore, is to be calculated separately for the summer and winter months. Table 3 and Figure 3 show the load consumption of each month separately for 400 W HPS and 80 W LED lamps.

Table 3. Monthly load consumption of HPS lamp and 80W LED lamp.

Month	No: of Days	Load (kWh) HPS Lamp	Load (kWh) LED Lamp
Jan	31	42,408	8481.6
Feb	28	38,304	7660.8
Mar	31	42,408	8481.6
Apr	30	34,200	6840
May	31	35,340	7068
Jun	30	34,200	6840
Jul	31	35,340	7068
Aug	31	35,340	7068
Sep	30	34,200	6840
Oct	31	42,408	8481.6
Nov	30	41,040	8208
Dec	31	42,408	8481.6
	Annual kWh=	457,596	91,519.2

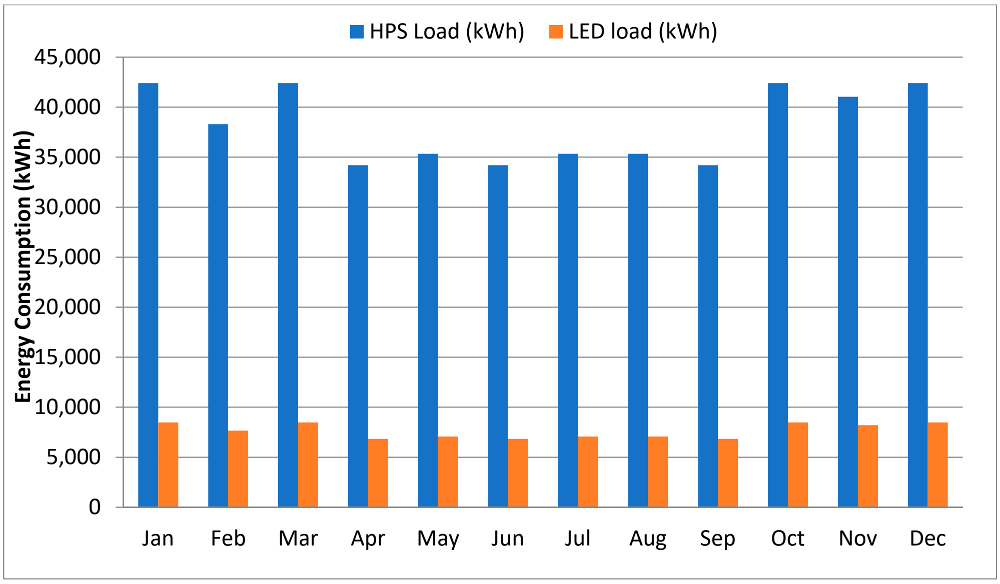


Figure 3. Monthly load consumption of HPS and LED lamps.

Based on the data from the maintenance department, the annual savings in energy and maintenance is estimated, which is detailed in Table 4. The initial investment for the project depends on the cost of the LED lamp and the labour cost. The former is obtained by a quotation from the JR lighting company from China, and the shipping costs are obtained from a logistics company in Oman.

Table 4. Economic analysis of replacing HPS lamps with LED lamps.

	Parameter Considered	Value
Annual Energy Savings	Electricity Cost	$0.078 per kWh
	Annual energy cost with HPS lamp	Total kWh consumed per year × cost per kWh = 457,596 × 0.078 = $35,692.488
	No. of HPS lamps replaced per year	100
	Replacement/maintenance cost of 1 HPS lamp	$65.80
	Annual maintenance cost of the HPS lamps	= 100 × 65.80 = $6580
	Annual energy consumed by LED lamp	91,519.2 kWh
	Annual energy cost with LED lamp	= 91,519.2 × 0.078 = $7138.5
	Annual savings in energy cost possible by the replacements of HPS lamps with the LED lamps	= 35,692.488 − 7138.5 = $28,554
	Maintenance cost of the LED lamps	0
	Annual savings in the maintenance cost on lamp replacement	$ 6580
	Total saving in the energy and maintenance cost	= 28,554 + 6580 = $35,134
Initial Investment	Cost of LED lamp with 80 watts (120 lm/watt)	$81.8
	Cost of 285 LED lamps	$23,313
	Shipping charges from China to Oman	$300
	Labour cost for replacement per lamp	$32.51
	Labour cost for replacing 285 lamps	$9265.35
	Initial investment	= Cost of lamp + shipping cost + labour cost = $32,878.35

The discounted payback period is the number of years it takes to break even from undertaking the initial expenditure by discounting future cash flows and recognising the time value of money [18].

$$\text{Discounted cash inflow} = \text{Actual cash inflow}/(1+i)^N \tag{6}$$

i = discount rate
N = period to which cash inflow relates

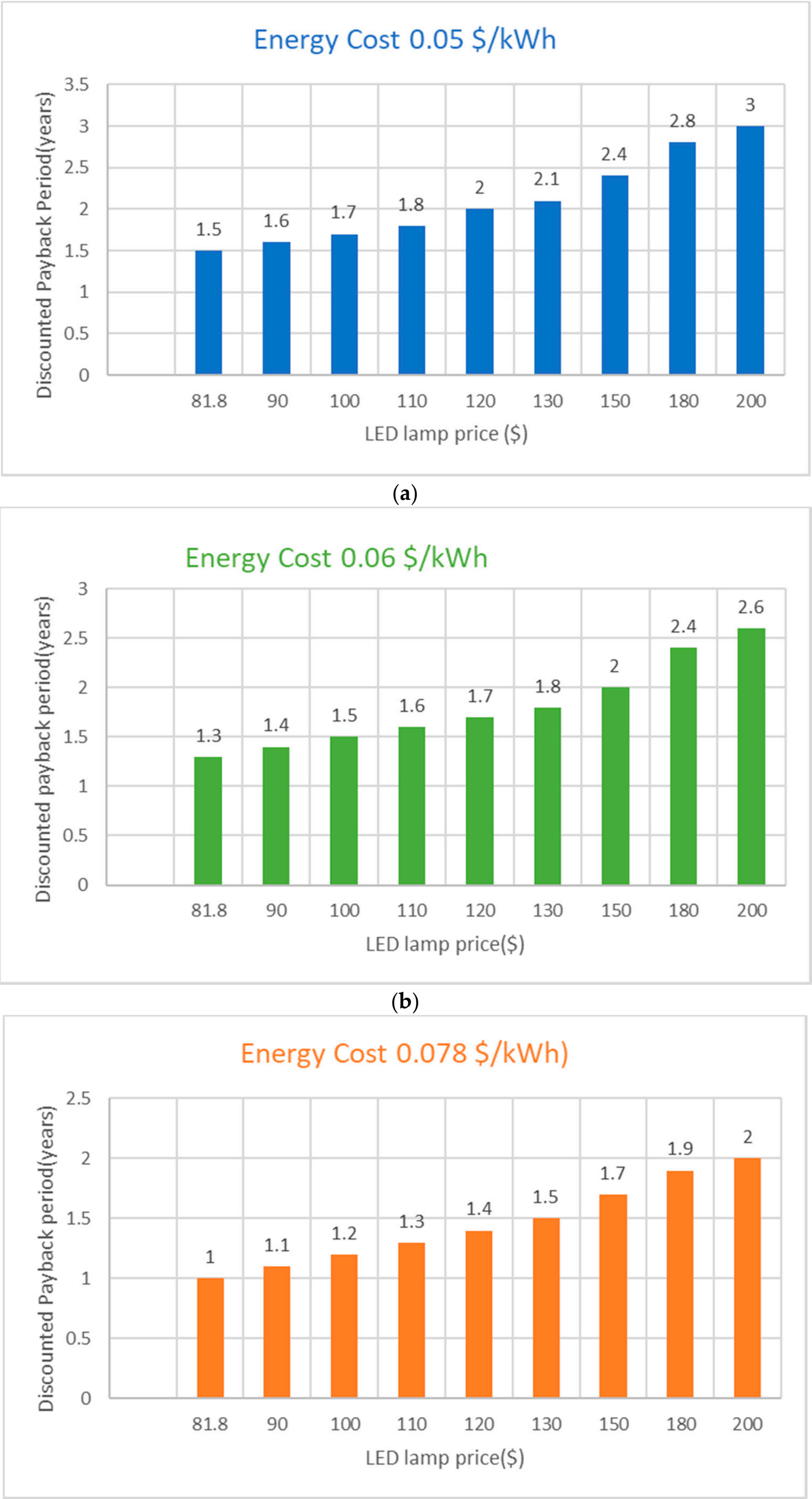
$$\text{Discounted payback period} = A + B/C \tag{7}$$

A = last period with negative discounted cumulative cash flow
B = absolute value of discounted cumulative cash flow at the end of A
C = discounted cash flow during the period after A
Discount rate = 8% [38]

The discounted payback period can be calculated with an Excel sheet, as shown in Table 5.

In Table 5, A = 1, B = 346.86, and C = 30,121.742. The discounted payback period is calculated using Equation (7) and is equal to 1.01 years.

Due to fluctuating oil prices and as the availability and price of LED lamps varies from place to place, the authors performed a sensitivity analysis with varied prices of electricity and LED lamp cost to check the economic feasibility of replacing HPS lamps with LED lamps. The results of sensitivity analysis are presented in Figure 4.

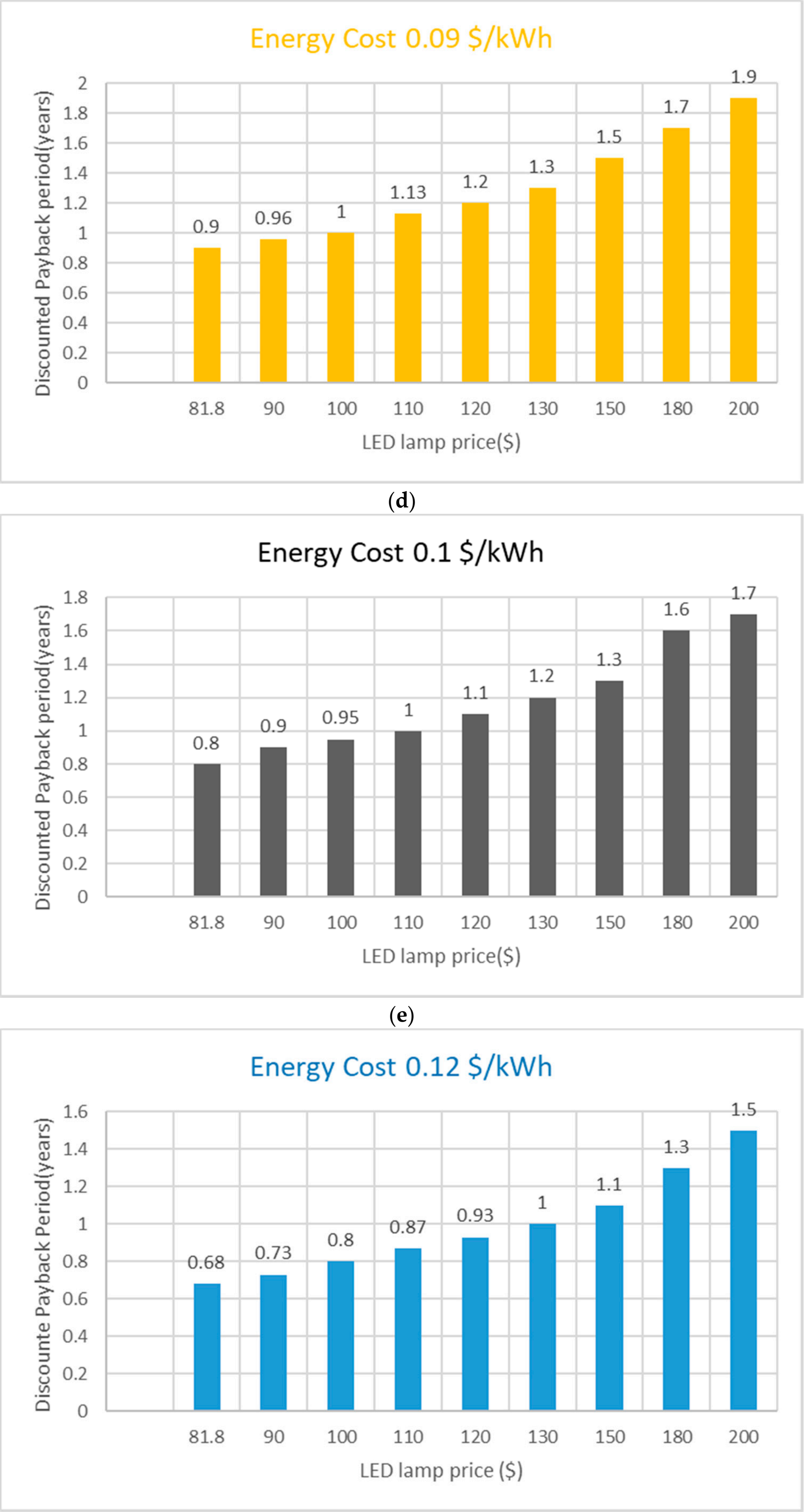


(**a**)

(**b**)

(**c**)

Figure 4. *Cont.*



(**d**)

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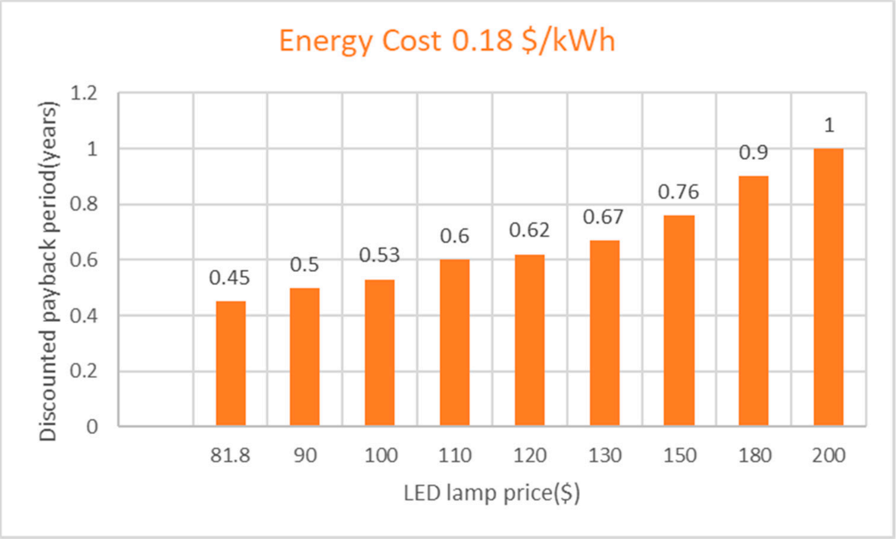
Figure 4. *Cont.*



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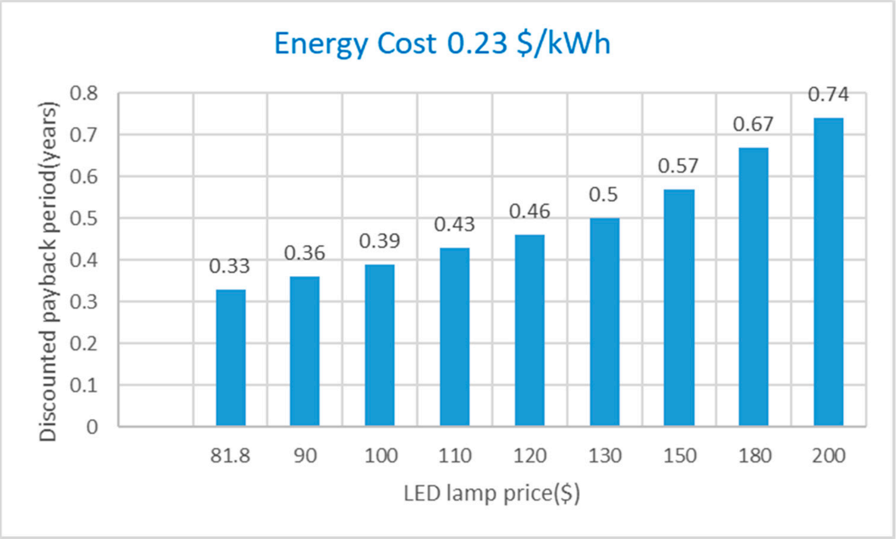

(**h**)

Figure 4. Effect of varied prices of electricity and LED lamp on the discounted payback period: (**a**) Energy cost 0.05 $/kWh (**b**) Energy cost 0.06 $/kWh (**c**) Energy cost 0.078 $/kWh (**d**) Energy cost 0.09 $/kWh (**e**) Energy cost 0.1 $/kWh (**f**) Energy cost 0.12 $/kWh (**g**) Energy cost 0.18 $/kWh (**h**) Energy cost 0.23 $/kWh.

Table 5. Calculation of discounted payback period. The color shows the transition from negative to positive value and the parameters selected.

Year	Amount	Discounted Cash Flow	Cum.Sum
0	−32,878.35	−32,878.35	−32,878.35
1	35,134	32,531.48148	−346.8685185
2	35,134	30,121.74211	29,774.87359
3	35,134	27,890.50196	57,665.37555
4	35,134	25,824.53885	83,489.9144
5	35,134	23,911.61004	107,401.5244
6			
7		Payback=	1.011515553

Sensitivity analysis shows that in regions with high electricity prices, it is highly recommended to replace the energy-inefficient lamps with energy-efficient LED lamps, as the discounted payback period is very short. In regions where the electricity prices are low, it is still economically viable to replace the energy-inefficient HPS lamps with LED lamps, even with the high investment cost of LED lamps. With a low electricity price of 0.05 \$/kWh and high cost of LED lamp (\$200 per lamp), the discounted payback was only three years, which proves the economic feasibility besides the reduction of tonnes of CO_2 emissions.

5. Reduction in CO_2 Emissions When the HPS Lamp Is Replaced with the LED Lamp

In Oman, 97.5% of the electricity generated is from natural gas [39]. According to the International Energy Agency, electricity generated from natural gas results in the emission of 400 g of CO_2 per kWh of generated electricity [40]. In Oman, both the open-cycle gas turbine (OCGT), which has an efficiency of 30%, and the combined-cycle gas turbine (CCGT), with an efficiency of roughly 45%, are used. Based on a seven-year statement of power generation in Oman by the Oman Power and Water Procurement Company [35], the CCGT generates 8390 MW, and the OCGT generates 1945 MW. Based on this, the reduction in CO_2 emissions is analyzed for the streetlight system under study, which is presented in Table 6.

Table 6. Estimation of CO_2 emission reduction.

Parameter Considered	Value
CO_2 emission per kWh from CCGT	$= \frac{\eta_{OCGT}}{\eta_{CCGT}} \times 400$ $= 0.30/0.45 \times 400$ g =267 g/kWh
Total MW generated	10,335 MW
OCGT contribution	18.8%
CCGT contribution	81.18%
Annual energy consumption for the HPS lamp	457,596 kWh
Annual energy consumption for LED lamp	91,519.2 kWh
Difference in kWh when HPS lamp is replaced with LED lamp	366,076.8 kWh
CO_2 emissions reduced	$= 0.188 \times 366,076.8 \times 400 + 0.8118 \times 366,076.8 \times 267$ = 106,876,341.4 g

The resulting reduction in CO_2 emissions per year upon replacing the HPS lamp with the LED lamp will be 106.876 tonnes, thus saving millions of dollars and huge amounts of emissions.

In the section to follow, a new streetlight system with PV/battery sources and LED lamps is designed for an area deprived of streetlights using optimized values for the number of PV panels and batteries. The cost estimation for this new streetlight system is presented based on real data in Oman.

6. Optimization of PV/Battery System for the New Street Light System

PV energy is one of the most important, clean [41], abundant, sustainable, and environment-friendly [42] energy sources to meet the challenges in the shortage of fossil fuel and the harm it causes to the environment. However, the intermittent nature of PV energy causes challenges in the design and implementation phase, such as supply imbalance, reverse power flow, and voltage/frequency variations [43], thereby reducing reliability. Battery storage is necessary to store the excess energy generated by PV resources to compensate for the intermittency of such resources, thereby improving their reliability. The optimization of the number of panels and batteries required is necessary for the hybrid system to work with the highest reliability and fetch economic benefits.

In the literature, several studies considered the optimization of hybrid renewable energy systems considering several aspects of objective functions and constraints. The optimal sizing of the PV/battery system is presented in [44], considering battery degradation, various tariffs, and PV panel orientation. The accuracy of the PV model is improved by considering the effect of ambient temperature on generated solar energy. The optimal sizing of a PV/diesel/battery off-grid system is presented in [45] using a hybrid optimization technique in which the geographic information system (GIS) is used to find the optimal location considering techno-economic, environmental, and social factors. A PV/wind/battery system is optimized using the 'loss of load' probability (LOLP) for reliability in [46]. A PV/battery/fuel cell system was optimized for a street lighting system using a genetic algorithm (GA) to minimize the loss of power supply probability (LPSP) and cost of energy (COE) for controlled and uncontrolled load [47].

The HSWSO model, an optimum-sizing tool, is developed to optimize the PV/wind/battery system using the loss of power supply probability(LPSP) and levelized cost of energy (LCOE) concepts [48]. A case study in Australia [49] calculated the optimal battery sizing for the residential PV/battery system to minimize the total annual cost, which includes COE as well as battery degradation. The economic feasibility of installing a battery storage system based on the current market prices and the added benefits of the operational optimization of the battery storage system compared with battery operation based on self-consumption maximization are investigated. The optimization of a PV/battery-based residential micro-grid to determine the optimal number of panels and batteries, the depth of discharge of the battery, and the tilt angle to minimize the LCOE are presented in [41] considering battery lifetime and long-term daily grid blackout.

The optimal sizing of the residential PV/battery system aimed towards minimizing the operation cost using a two-stage adaptive robust optimization technique is presented in [43] considering the uncertainties of the PV resource and the load. Different scenarios considering different parameters for uncertainty are presented. A similar study was conducted [42] for the PV/battery residential off-grid system to determine the number of panels and batteries for reduced operation costs considering the intermittency of renewable energy resources. Based on the forecasted solar irradiance, the daily usage of appliances is prescheduled and then executed using a Monte Carlo simulation to account for uncertainties. The optimal sizing of the PV/battery-based hybrid system to minimize the total life cycle cost is proposed in [50] considering LPSP to account for reliability. An improved harmony search algorithm is adopted to find optimal values, which are proved to be robust compared with the two other state-of-the-art methods. Multi-objective–based optimal sizing for the standalone PV/battery-based system is presented in [51] to determine the best among three types of batteries in terms of reliability and cost. Lead acid batteries can best be applied in real-world applications compared with lithium ion and AGM batteries, showing an annual energy deficit of only 16.6 h.

The optimal sizing of the PV/battery-based grid-connected system is proposed in [52] to minimize the total net present cost considering greenhouse gas emission and reliability, adopting a novel method based on teaching–learning optimization. Compared with conventional energy generation, the efficiency of the net present cost and the COE were improved by about 16% and 17%, respectively, with the proposed method.

In the literature, various parameters are used to gauge the reliability of the RE system. These are the loss of power supply (LPS), the LPSP or deficiency of power supply probability (DPSP), and the LOLP. The LPS is the extra power required to meet the load or the power deficit [53,54]. In this paper, the LPS is considered to gauge reliability.

6.1. Design of New Street Light System with PV/Battery System and LED Lamps

The streetlight system of Sultan Qaboos University comprises 285 lamp posts, each 30 m apart, which covers a total distance of 8.55 km. A new streetlight system has been designed for this distance using LED lamps. One of the factors to be considered while designing the streetlight system is the space-to-height ratio, i.e., the space between two light poles should be roughly two and a half to three times the height of the pole. Consider the following:

Pole height = 12.5 m

Spacing between poles = 35 m

Space/height ratio <3

Considering the parameters of Sections 3.1 and 3.2 and substituting those in Equation (1), the lamp lumens required is calculated as 9625.68 lm. An 80 W LED lamp with a luminous efficacy of 130 lm/watt can produce a lumen output of 10,400 lm to meet the requirement.

No. of poles required for a distance of 8.55 km = 8550/35 ≈ 245 poles

Assume that the load during summer is 10 hrs and that during winter is 12 h.

Summer load = 80 W × 245 × 10 hrs/day = 196 kWh/day

Winter load = 80 × 245 × 12 = 235.2 kWh/day

The optimum values for the number of PV panels, N_{module}, and the number of batteries, $N_{battery}$, are found using the genetic algorithm (GA) tool in MATLAB for each month. The LPS will be used to gauge the reliability of the PV/battery system used for the streetlight system [31].

6.2. System Modelling

Several terms are used to gauge the reliability of the PV/battery systems. In this paper, the *LPS* is used to gauge the reliability of the PV/battery system used for the streetlight system, as shown in Equation (8) [53].

$$LPS(t) = Load(t) - E_{total}(t) \tag{8}$$

$Load(t)$ represents the load demand, and E_{total} represents the energy generated by the PV system. The equation for E_{total} is expressed in Equation (9):

$$E_{total}(t) = \left\{ E_{PV}(t) + E_b(t-1) \times N_{battery} - W_{Bmin} \right\} \times \eta_{inv} \tag{9}$$

where,

$E_{PV}(t)$ = energy generated by the PV system during the time interval $[(t-1), t]$

$E_b(t-1)$ = initial stored energy in a single battery $[(t-1), t]$

W_{Bmin} = minimum permissible battery energy level (kW)

$N_{battery}$ = number of batteries

η_{inv} = inverter efficiency

The current streetlight system inside the university is an AC system, which is supplied from the grid. A PV system that can supply AC for the existing system without making any major changes to the system is considered. Hence, an inverter is necessary to convert the generated DC to AC.

6.2.1. Model for Panel

The energy output from the PV system is [53]:

$$E_{PV}(t) = N_{module} \times E_{module}(t) \tag{10}$$

where, N_{module} represents the number of PV modules, and E_{module} represents the instantaneous generated PV energy (kW) calculated as [55]:

$$E_{module}(t) = A_{PV} \times E_{sun} \times \eta_{PV} \times \eta_{wire} \tag{11}$$

where,

A_{PV} = area of solar panel (m^2)

E_{sun} = daily solar irradiation (Wh/m^2)

η_{PV} = PV panel efficiency

η_{wire} = wiring efficiency

The effect of the temperature on the conversion efficiency of the PV module [55] is expressed in Equation (12):

$$\eta_{PV} = \eta_{PV,ref}\left[1 - \beta\left(T_c(t) - T_{c,ref}\right)\right] \quad (12)$$

where, $\eta_{PV,\,ref}$ and $T_{c,\,ref}$ are the reference values for the efficiency of the PV module and the cell temperature; β is the temperature coefficient for efficiency; and, $T_c(t)$ is the cell temperature calculated using [56]:

$$T_c(t) = T_A(t) + \left(\frac{NOCT - 20}{800}\right) \times G(t) \quad (13)$$

where, $T_A(t)$ is the ambient temperature, $G(t)$ is the solar radiation (W/m^2), and $NOCT$ is the nominal operating cell temperature. $NOCT$ is defined as the cell temperature when the irradiance is 800 W/m^2, the ambient temperature is 20 °C, and the wind speed is 1 m/s [56].

6.2.2. Model for Battery

The energy stored in the battery E_b is subject to the following constraint:

$$E_{bmin} \leq E_b \leq E_{bmax}$$

Assuming that, at the end of the day, the battery is fully charged, the energy stored in the battery is [53]:

$$E_b = E_{bmax}$$

where,

$$E_{bmax} = \text{Ah rating} \times \text{Voltage rating} \quad (14)$$

During the night, streetlights consume the energy stored in the battery. Hence, at the beginning of the day, when the energy starts getting stored in batteries through the PV system, the energy stored in the batteries, E_b $(t-1)$, will be the following:

$$E_b(t-1) = \left(E_{bmax} \times N_{battery} - Load\right)/N_{battery} \quad (15)$$

E_{bmin} = minimum permissible battery energy level

$$E_{bmin} = (1 - l) \times E_{battery} \times N_{battery} \quad (16)$$

l = maximum depth of discharge.

6.2.3. Specifications of Panel and Battery

The specifications of the panel considered in this study are provided in Table 7.

Table 7. Panel Specifications.

NOCT (°C)	T_c ref (°C)	β (%/K)	η_{pv} ref (%)	Area PV (m^2)	η_{inv} (%)	η_{wire} (%)
45	25	0.38	20.1	2.162	95	98

The specifications of the battery considered in this study are as follows:
Battery Specifications: 12 V, 200 Ah
DOD max: 80%.

6.2.4. Meteorological Data

The data required for the calculations were extracted from various sources. The energy generated from the solar panel depends on the solar insolation, with varied values every day. The monthly solar energy data, required to evaluate the number of panels and batteries for each month, are taken from [57], which studies the effect of a tilt angle on incident solar radiation and optimizes the surface tilt angles and directions to collect maximum solar radiation in Muscat. The ambient temperature (T_a) and the sunshine hours are obtained from the website of NASA. The meteorological data used in the calculations are presented in Table 8.

Table 8. Meteorological data.

Month	E_{sun} **(Wh/m^2/day)**	***Ta*** **(°C)**	**Sunshine hrs**
Jan	6210	20.6	10.8
Feb	6630	21.3	11.4
Mar	6290	24.3	12
Apr	6500	28.3	12.7
May	6370	32.1	13.2
June	7310	33.9	13.5
July	6370	33.8	13.4
Aug	6120	32.9	12.9
Sep	6440	30.8	12.3
Oct	6700	28.2	11.6
Nov	6970	24.9	11
Dec	6320	22.2	10.7

The meteorological data and the panel specifications are used to evaluate the E_{module} for each month using the equations in Section 6.2.1. The monthly values of E_{module} and the various calculated parameters for the panel are presented in Table 9.

Table 9. Monthly E_{module} and related parameters for panel.

Month	$G(t)$ **(W/m^2)**	$Tc(t)$ **(°C)**	ηpv	***Emod*** **(KW)**
Jan	575	34.975	0.193381095	2.54441168
Feb	581.5789	39.47434	0.189944498	2.457214931
Mar	524.1667	40.68021	0.189023457	2.319899904
Apr	511.811	44.29409	0.186263171	2.362344594
May	482.5758	47.18049	0.18405854	2.287695959
June	541.4815	50.8213	0.181277694	2.585619681
July	475.3731	48.65541	0.182931998	2.273693966
Aug	474.4186	47.72558	0.183642201	2.192940314
Sep	523.5772	47.16179	0.184072826	2.313014989
Oct	577.5862	46.24957	0.184769579	2.41550629
Nov	633.6364	44.70114	0.185952272	2.528932091
Dec	590.6542	40.65794	0.189040462	2.331174316

7. Objective Functions, Constraints, and PV/Battery System Configuration

LPS is the deficiency of energy during a time interval, which is the difference between the energy available (sum of the PV and battery energies at the start of the interval) and the load demand.

$$LPS(t) = Load(t) - E_{total}(t) \tag{17}$$

A value of zero for $LPS(t)$ denotes that the load is met by the PV/battery combination. Our objective is to minimize the *LPS*, resulting in maximum reliability for the system, the number of modules, N_{module}, and the number of batteries, $N_{battery}$, as the decision variables. The constraints are related to the requirements of the panel and battery: (i) the generated PV energy should satisfy the load demand; and (ii) the deficiency in energy should be met by the stored energy in the battery during the previous interval. In a study that considers the optimization of the number of panels and batteries for the PV system [53], the number of autonomous days is not considered; hence, an additional constraint is added considering this variable. It can be summarized as follows.

Minimize the following objective function:

$$LPS = Load(t) - E_{module}(t) \times N_{module} + \left(E_b(t-1) \times N_{battery} - E_{bmin}\right)) \times \eta_{inv} \tag{18}$$

Subject to the following constraints:

$$E_{module}(t) \times N_{module} \times \eta_{inv} \leq Load(t) \tag{19}$$

$$E_b(t-1) \times N_{battery} - \left(\frac{Load(t)}{\eta_{inv}}\right) + (E_{module}(t) \times N_{module}) = E_{bmin} \tag{20}$$

The *LPS* is minimized after being subjected to the given constraints using the genetic algorithm(GA) optimization tool in MATLAB to optimize the size of the PV and batteries in the system. Considering the objective functions and constraints and plugging in the parameters, the optimized values for the number of panels and batteries are obtained, as presented in Table 10 and Figure 5.

Table 10. Optimized values for number of panels and batteries.

Month	N_{panel}	$N_{battery}$
Jan	97	123
Feb	101	123
Mar	106	124
Apr	88	102
May	89	104
June	80	102
July	89	105
Aug	95	102
Sep	90	102
Oct	103	122
Nov	98	123
Dec	105	124

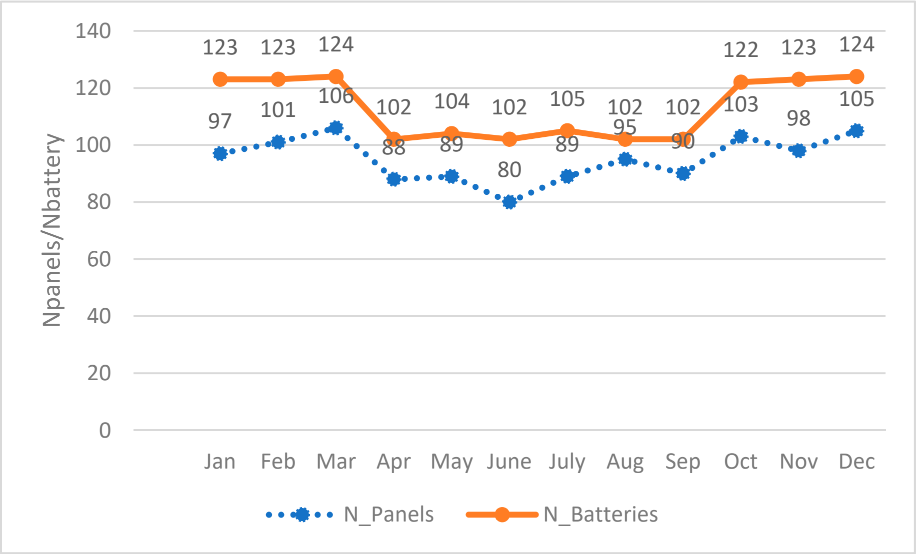

Figure 5. Optimized values for number of panels and batteries.

The maximum N_{panel} and $N_{battery}$ values were found to be 106 and 124, respectively, which will be used in the following economic analysis. Economic analysis is necessary to study if the system is economically viable to be implemented. Economic analysis using life cycle cost (*LCC*) is one of the best methods to analyze the economic profitability of the system [58].

The results of optimization of N_{panel} and $N_{battery}$ are used in the economic analysis of the PV/battery system under study for the calculation of the life cycle cost. The cost per kWh of the generated energy is evaluated thereafter.

8. Life Cycle Cost Analysis

Life cycle cost analysis is a modelling tool to study the economic feasibility of renewable energy systems which covers all the RE system life stages, including initial cost and costs of operation and maintenance [59]. The life cycle cost is defined as the sum of the present worth of all the components that constitute the hybrid system [60]. *LCC* includes the original price of purchasing the equipment along with the cost of replacing, maintenance and operation, which is expressed as,

$$LCC = \text{capital } \cos t + \text{operations and maintenance } \cos t + \text{replacement } \cos t - \text{salvage value} \quad (21)$$

The costs of various components, expressed in $(USD) are based on quoted rates, literature review and internet survey, which is presented in Table 11.

Table 11. Data required for evaluation of Life Cycle Cost.

Parameter Considered	Value
Maximum number of panels from the optimized results	106
Cost per panel, quoted ($0.268 per watt)	$ 117.92
Cost for 106 panels, including shipping	$ 13,050
Optimized no. of batteries	124
Cost per battery, quoted	$ 160
Cost for 124 batteries, including shipping	$ 20,440
Inverter rating	1.2 × 80 × 245 = 23,520 W
Inverter cost, quoted	$ 2170.5
Inverter cost, including shipping	$ 2320.5
Battery charge controller cost, quoted	$ 1123
Battery charge controller cost, including shipping	$ 1373
Auxiliaries cost	$ 7488.6
Total cost of PV system	$ 44,072

The installation cost of PV system is taken as 10% of the PV system initial cost [61] and annual operation and maintenance cost is 1% of the initial capital cost [62]. Auxiliaries cost is taken as 20% of the initial cost of PV system as the distance considered for streetlight system here is 8.55 km and cost of cables/accessories are to be considered.

Inverter rating is taken as 120% of the total wattage of the load.

The lifetime of the PV system is 25 years except for the battery with a replacement period of seven years and the inverter with a replacement period of 13 years. The *LCC* is calculated using equation [61] with the salvage value included as,

$$\begin{gathered} LCC = \text{Initial cost of PV system} + \text{installation cost} + \text{cost of the replaced batteries} \\ + \text{cost of replaced inverter} + \text{maintenance and operation cost} - \text{salvage value} \end{gathered} \quad (22)$$

$$\text{Inverter Rating} = 1.2 \times 80 \times 245 = 23{,}520\ W \quad (23)$$

$$\begin{gathered} \text{Initial cost of PV system} = \text{PV array cost} + \text{cost of first set of batteries} \\ + \text{cost of battery charge controller} + \text{inverter cost} + \text{ auxilliaries cost} = \$\ 44{,}072.15 \end{gathered} \quad (24)$$

The present worth (PW) of components, which are replaced, can be obtained from the relation [63],

$$PW = \frac{Ini}{(1+d)^p} \tag{25}$$

where Ini represents the initial cost of the component

d = discount rate

p = the period of replacement in years.

The inflation rate is not considered and the real discount rate is considered as 8% in the further calculations. The components to be replaced are the battery and inverter.

The present worth of batteries, inverter and salvage value is to be calculated.

Salvage value is taken as 15% of the total initial purchasing cost = 6611 $(USD) [64].

Plugging in these values to Equation (22), the life cycle cost (LCC) is calculated.

LCC = 81,658 $(USD)

$$\text{Annualized capital } \cos\text{t} = LCC \times CRF \tag{26}$$

CRF represents the capital recovery factor, given in Equation (27).

$$CRF = \frac{d(1+d)^L}{(1+d)^N - 1} \tag{27}$$

d = discount rate (8%)

L = Lifetime of the PV system (25 years)

CRF = 0.09368

Annualized capital cost = 7650 $(USD)

$$Cost\ per\ kWh\ of\ generated\ energy = \frac{Annualized\ capital\ cost}{Annual\ kWh\ generated} \tag{28}$$

Annual kWh generated = 78,674.4 kWh

Cost per kWh of generated energy = 0.097 $(USD)

The cost per kWh of energy generated from PV/battery system for the streetlight system is considered in only $0.097, which proves the economic feasibility of implementing the system in Oman besides minimizing the CO_2 emissions to zero.

9. Conclusions

The replacement of energy-inefficient lamps with energy-efficient LED lamps—especially in street lighting—is a subject matter that gained great attention in recent years. However, the requirement for huge investment is a limitation faced by local governments for its practical implementation. This paper studies the economic feasibility of replacing HPS lamps with LED lamps for street lighting in the premises of Sultan Qaboos University in Oman, with actual data from the maintenance department of the university. Based on the quoted rates of LED lamp and existing costs of labour and electricity in Oman, the discounted payback period was found to be 1.01 years, which shows that the replacement of HPS lamps with LED lamps is an economically attractive choice. Generally, projects with a payback of less than five years are highly recommended; in this case, it is just 1.01 years. Based on sensitivity analysis considering varied prices of LED lamps and electricity cost, the authors highly recommend the replacement of HPS lamps to LED lamps in regions with the high cost of electricity as the discounted payback period is even less than a year. Even in places with low electricity costs and high cost of LED lamps, it is still economically feasible with a payback period less than three years. Furthermore, replacing HPS lamps with LED lamps in a small streetlight system, as shown by this study, results in the reduction of 106.876 tonnes of CO_2 emissions. This shows the high significance of replacing energy-inefficient streetlight lamps with energy-efficient LED lamps to reduce millions of tonnes of CO_2 emissions worldwide.

The second part of the paper considers optimal sizing of PV/battery system for a new streetlight system with LED lamps. Based on the optimized sizes of panels/batteries, the life cycle cost of PV/battery system required to power the new streetlight system extending a stretch of 8.55km is $81658. The cost per kWh of generated energy is estimated to be 0.097 $/kWh which proves that the system is economically feasible to be implemented in Oman where the existing energy cost is 0.078 $/kWh. With increasing cost of energy prices and decreasing the cost of renewable energy components, the proposed methodology will prove to be more promising and economically appealing besides minimizing the CO_2 emissions to zero.

To study the practicality of implementing energy-efficient methods in street lighting system, local governments can adopt the presented methodology. This depends on the geographic features of the location, availability/cost of LED lamp, cost of renewable energy components and electricity price. The methodology is comprehensive and adoptable by any location, considering the various aspects existing in the selected region. More research is required in the control side of LED lamps including the housing and driver circuit with detailed analysis of LED lamps. Smart streetlight systems considering light pollution and driver comfort is another technical aspect to be considered in the methodology for more energy savings and CO_2 emission reduction.

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Nomenclature

SSL	Solid-State Lamp
HPS	High Pressure Sodium
LED	Light emitting diode
PCB	Printed circuit board
PV	Photovoltaic
CFL	Compact Fluorescent lamp
ROI	Return on investment
NPV	Net present value
TR	Total return
S	Distance between poles
E	Required lux level
W	Width of road
CoU	Coefficient of utilization
Mf	Maintenance factor
LLD	Lamp lumen depreciation factor
LDD	Luminaire Dirt depreciation factor
$\eta_{optical}$	Optical efficiency
$\eta_{thermal}$	Thermal efficiency
T	Daily ON-time of the lamp in hours
D	Total no: of days in a month
i	Discount rate
N	Period to which cash inflow relates
$OCGT$	Open cycle gas turbine
$CCGT$	Combined cycle gas turbine
GA	Genetic Algorithm
LPS	Loss of power supply
E_{total}	Energy generated by the PV system
$E_{PV}(t)$	Energy generated by the PV system during the time interval [(t−1), t]
$E_b(t{-}1)$	Initial stored energy in a single battery [(t−1), t]
W_{Bmin}	Minimum permissible battery energy level (kW)
N_{module}	No: of PV modules
$N_{battery}$	No: of batteries
η_{inv}	Inverter efficiency
E_{module}	Instantaneous generated PV energy (kW)
A_{PV}	Area of solar panel (m^2)
E_{sun}	Daily solar irradiation (Wh/m^2)
η_{PV}	PV panel efficiency
η_{wire}	wiring efficiency
$\eta_{PV,\ ref}$	Reference value for efficiency of the PV module
$T_{c,\ ref}$	Reference value for efficiency of cell temperature
β	Temperature coefficient for efficiency
$T_c(t)$	Cell temperature
$T_A(t)$, T_a	Ambient temperature(°C)
$G(t)$	Solar radiation (W/m^2)
$NOCT$	Nominal operating cell temperature
E_b	Energy stored in the battery
E_{bmin}	Minimum permissible battery energy level
E_{bmax}	Maximum permissible battery energy level
Ah	Ampere-hour
$E_b\ (t{-}1)$	Initial energy stored in the battery
l	Maximum depth of discharge
DOD	Depth of discharge
E_{module}	Energy generated by PV module(kW)
LCC	Life Cycle Cost
RE	Renewable Energy
CRF	Capital recovery factor
PW	Present Worth
P	Lifetime of PV system

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