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Life Cycle Cost And Carbon Credit Analysis For Solar Photovoltaic Powered Internet Of Things-Based Smart Street Light In Uyo

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Abstract— **This paper presents life cycle cost analysis and carbon credit analysis for solar photovoltaic (PV) powered internet of things (IoT)-based smart street light in Uyo Akwa Ibom State, Nigeria. The smartness of the street light entails its ability to control the light intensity depending on the availability or non-availability of human or vehicular presence on the street. Notably, the lighting system conserves energy by using various sensors to sense motion, darkness/light as well as traffic around the street light installations. However, in this work, the various circuit components that are used to realise the smart street light system are powered by a stand-alone solar power system and each of the components contributes to the system cost and energy demand. The life cycle cost of the stand-alone solar PV street lighting system captured all the components and their life cycle contribution to the system cost. Specifically, the life cycle cost includes the total capital cost, installation cost, replacement cost, cost of operation and maintenance throughout the entire life of the system. The overall cost of each of the stand-alone solar PV street lighting system for 8 years is estimated to be ₦249,000 while the total cost of using the diesel generating set per year is estimated at ₦15,040,430. Since only one of the diesel generating sets powers a number of lamps, about forty (40) lamps on an average stretch of obout 3Km, proper comparison would be to consider 40 stand-alone solar street lamp poles. Therefore, the overall cost of 40 stand-alone solar street light is ₦9,980,000. Hence, the payback period of the system is about 8 months. The energy cost of using the stand-alone solar street light per annum is ₦682,605 whereas the energy cost of using the diesel generating plant per annum is ₦15,040,430. This shows that by adopting the stand-alone solar smart and compact street lighting system, the energy cost is reduced by 4.5%. The carbon credits earned by each of the stand-alone installation were found to be ₦357.21k per annum, approximately, ₦14,288.40k per annum (considering 40 street lamp poles).**

Keywords— Life Cycle Cost, Photovoltaic (PV), Stand-alone, Payback Period, Energy Cost, Carbon Credits, Techno-economic Analysis, Internet of Things-based, Smart Street Light

I. INTRODUCTION

Life cycle cost analysis is a method used to analyze the total cost as well as a wide range of cost elements of a system throughout its life cycle [1,2,3,4,5,6]. The life cycle cost elements include; design, development and production costs, investment costs, operation and maintenance costs [5,7,8,9,10,11]. Analyzing these elements help to determine the cost-effectiveness of the option among different systems, technologies, services, processes and product alternatives [5,7,8,9,10,11]. LCCA is especially useful when there exist other alternatives that fulfill the same performance requirements, but differ with respect to initial, operating and maintenance costs [5,12,13,14,15].

In the last two decades, Akwa Ibom State, particularly Uyo, which is the State capital, has witnessed tremendous infrastructural development and growth in population [16,17,18,19]. In view of this, the government has consistently endeavoured to provide safe environment for the citizens and one of such strategies has been the provision of street lights to encourage safe operations and enhance the night life activities in the city. The government, in this wise, have installed a good number of street lights. However, most of these street light installations are being powered by diesel generators which incur a high cost of maintenance and emit Carbon dioxide (CO_2) fumes which is not healthy for the environment [20,21,22,23,24,25,26]. Solar Photovoltaic (PV) systems on the other hand, are less expensive in the long run, though initial cost of installation may be high. Apart from the fact that solar energy is abundantly available, it is a clean energy source, therefore solar PV systems are generally safer and environmentally friendly [27,28,29,30]. Generally, the capital cost of solar systems is quite high but since there is no fuel cost and the battery replacement cost is low, the general maintenance cost therefore, is low. In this work the cost of the stand-alone solar PV street lighting system which includes the total capital cost, installation cost, replacement cost, cost of operation and maintenance throughout the entire life of the system is estimated based on economic realities and other contingencies.

II. METHODOLOGY

The life cycle cost (LCC) of the stand-alone solar PV street lighting system captured all the components of the for the solar PV internet of things (IoT)-based smart street light and their life cycle contribution to the system cost. Specifically, the life cycle cost includes the total capital cost, installation cost, replacement cost, cost of operation and maintenance throughout the entire life of the system.
Notably, PV system sizing and circuit design are not covered in this paper. However, the information obtained from the PV system sizing and circuit design was used in the LCC analysis and to estimate the carbon credits earned by the system. Importantly, the LCC and carbon credit analysis used the solar PV system components that are sized based on the meteorological data of the case study area (Uyo) along with the circuit components that were obtained as part of the circuit design.

A. The Life Cycle Cost Analysis (with numerical computations)

The cost of the stand-alone solar PV street lighting system includes the total capital cost, installation cost, replacement cost, cost of operation and maintenance throughout the entire life of the system. The life time of LED is 25,000+ hours [31]. Assuming the street light is in use for an average of 9 hours a day (considering the hours they will be in the dim state), then the street light would last for approximately 8 years, all other factors being normal. In this work, lithium-ion batteries were uses for power storage. The life time of lithium-ion batteries is 2 to 3 years [32,33,34]. It is therefore expected that within the 8 years´ life time, new batteries will be bought four times (every two years). Table 1 shows the capital cost estimation per street light.

Table 1. Capital cost estimation per street light

Component	Quantity	Unit price (₦)	Total amount (₦)
Arduino Wi-Fi module	1	5500	5500
LDR	1	2000	2000
PV module	1	20000	20000
Li-ion Battery	9	2500	22500
IR module	2	3000	6000
LM2596	2	2000	4000
LM317	1	2500	2500
ULN2003 driver IC	1	2500	2500
Wireless router	1	15000	15000
Cost of fittings and casing	1	15000	15000
Cost of programming		45000	45000
Other components(wires, resistors, copper cloud board and so on)		10000	10000
Total			**150000**

The cost of other components like resistors, capacitors, cables, and so on is estimated to be ₦10,000. One wireless router serves many street lights in a particular area hence only one router will be considered in this work. PV systems require minimal maintenance because it has no fuel cost, no movable parts that may be damaged in the process [32]. Thus, maintenance cost of the system per year is estimated to be 0.1% of the system's capital cost [32]. Since the batteries will be replaced every two years, the routine maintenance will be every two years. Maintenance cost of the system bi-annually = cost of battery + cost of labour, where the cost of labour is assumed to be ₦2,000 per street light. Maintenance cost hence is:

Maintenance cost = 22,500 + 2000 = ₦24,500

Therefore maintenance cost over its life time (8 years) = 24,500 x 4 = ₦98,000.

The cost of the system has been estimated based on economic realities but there is a need of contingency cost [35,36]. Contingency cost here means the cost that has not been accounted for in the course of cost estimation. Therefore the contingency cost is assumed to be 1% of the capital cost [32]. That is; contingency cost = 1% x 150,000 = ₦1,500.

The overall cost of the stand-alone solar PV street lighting system for 8 years is the sum of capital cost, maintenance cost and contingency cost which is given in the expression as follows:

$$LCC = CP + CM + CC \quad (1)$$

Where:
LCC = life cycle cost
CP = the purchase price or capital cost
CM = the cost of maintenance
CC = contingency cost

CC = 150,000 + 98,000 + 1500 = ₦249,000.

B. Energy Cost Estimation of Using Diesel Generating Set per Year (with numerical computations)

This stand-alone system is being compared to the conventional diesel powered street lights currently being used in Uyo Metropolis. The current market price of a litre of diesel in Nigeria is approximately ₦230. The diesel generating sets being used in some parts of Uyo city is the FG Wilson sound proof type. According to [34], the approximate fuel consumption of a 75KVA generator at a quarter load is 5.4 litres/hour and 9.4 litres/hour at half load. For the sake of this analysis, the half load consumption is considered being that high pressure sodium lamps are being used in most of the street lights and these consume more energy. Assuming the street lights stay on from 7pm in the evening, to 6am the next morning without dimming, the number of hours used per day is 11 hours. The cost analysis for the diesel powered system is as follows:

Cost of FG Wilson sound proof generator (65KVA) (₦) = 5,300,000

Hours of use per day = 11

Litres of diesel consumed per hour = 9.4

Litres of diesel consumed per day (11 hours) = 103.4

Total number of litres consumed per year = 103.4 x 365 = 37,741

Cost of diesel per year (₦) = 8,680,430

Assuming the maintenance cost of the generating set per year is 10% of its original cost [1], then maintenance cost (₦) = 0.1 x 5,300,000 = 530,000

Cost of installation includes cost of wires, clips, and labour. In this study, the installation cost is estimated to be 10% of the generator cost [32].

Hence Installation cost (₦) = 0.1 x 5,300,000 = 530,000.

The total cost of using the diesel generating set per year, is the sum of generator cost, fuel cost, cost of installation and maintenance cost given as:

The total cost of using the diesel generating set per year = 5,300,000 + 8,680,430 + 530,000 + 530,000 = ₦15,040,430.

C. Payback Period (with numerical computations)

In Uyo City, one of these diesel generating sets powers all the lamps on a long stretch of over 5 Km. Along this stretch, about 40 lamps could be connected and powered by one diesel generating set. However, the cost analysis of the stand-alone solar PV street light is for only one lamp pole. Now, in a proper comparison, 40 stand-alone solar street lamp poles are equally considered. Therefore, the overall cost of the stand-alone solar street light is:

The overall cost of the stand-alone solar street light = 40 x 249,000 = ₦9,980,000.

The payback period can be calculated thus [32]:

$$P_b = \frac{overall\ cost\ of\ PV\ system\ for\ its\ life\ time}{total\ cost\ of\ using\ diesel\ generator\ for\ the\ first\ year}$$

Where P_b is the payback period

$P_b = \frac{9980000}{15040430}$ = 0.66 year(s) = 0.66 x 12 months = 7.9 months (approximately 8 months).

This means that if the government of Akwa Ibom State prefer the option of using diesel powered street lights, they will spend the same cost of the stand-alone solar PV street lights (₦9,980,000) in just 8 months, whereas, that could have been spent over 8 years if the stand-alone solar PV street light system is embraced.

D. Carbon Credits Earned by the System (with numerical computations)

The total energy consumption of the stand-alone solar PV street light was calculated to be 44.5KW based on the power consumption of the different components making up the street light and the number of hours they will be in use per day. The total power produced (W_P) of the solar PV module is 20W as specified by the manufacturer. Assuming an average 7 hours of sunshine per day in a typical dry season in Akwa Ibom State, the total power produced per day is given as:

The total power produced per day= 20 x 7 = 140Wh

Assuming three (3) months of high rainfall (this is typical in Akwa Ibom State for the months of June, July and August), which equals approximately 90 days, then an average of 275 days of clear sky is being considered. Therefore, the total power produced per annum is given as:

P_{annum}= P_{total} x number of clear sky days per annum

140 x 275 = 38,500 Wh = 38.5KWh.

Where P_{annum}= total power produced per annum (140Wh)

And P_{total} = total power produced per day (275)

Akinlabi*et al*. [37] developed a model for determining the unit cost of electricity using diesel generators. For a 65KVA generating set (which is what is mostly used in Akwa Ibom State to power the street lights), Akinlabi*et al.* [37] determined the unit cost of electricity to be ₦17.73/KWh. Therefore, cost of energy produced by the stand-alone solar street light is given as [37]:

$Cost_{energy}$ = P_{annum}x Unit cost of electricity

Where $Cost_{energy}$ = cost of energy produced by the system

And P_{annum} = 38.5KWh = 38500Wh

$Cost_{energy}$ = 38500 x 17.73 = ₦682,605

Hence, the energy cost of using the stand-alone solar street light is ₦682,605. Whereas, from the cost analysis, the energy cost of using the diesel generating plants per annum is ₦15,040,430. Therefore, the use of the solar PV powered IoT-based street light reduces the cost of energy by 4.5% thus: $\frac{682605}{15040430} x\, 100 = 4.5\%$.

A compilation of Carbon Dioxide (CO_2) reduction by solar PV power plants all over the world has been carried out by Denis Lenordic [38]. According to Denis Lenordic, data of electricity produced in MWh and CO_2 emission reduction per annum in the top 100 solar PV power plants is given as 0.932 tons of CO_2 emission reduction per MWh of electricity produced [38]. Therefore, CO_2 emission reduction by the stand-alone solar street light system per annum is as follows:

CO_2 emission reduction (tons) = P_{annum} x CO_2 emission reduction

Where 38.5KWh = 0.0385MWh,

CO_2 emission reduction (tons) = 0.0385 x 0.932 = 0.03588 = 0.0359 tons

Presently, CO_2 emission reduction is being traded at USD 27.5/ton. Therefore, CO_2 reduction by the stand-alone solar PVstreet light system per annum is as follows [38]:

$$ERs = ER\ (tons) \times ERTV$$

Where ERs = CO_2 emission reduction by system

ER = CO_2 emission reduction (tons) (0.0359 tons)

And, ERTV = CO_2 emission reduction trade value (USD 27.5)

$$ERs = 0.0359 \times 27.5 = UDS\ 0.99.$$

Going by the present Dollar to Naira exchange rate in Nigeria which is ₦362/USD, this amounts to ₦357. 21k per street light. Therefore, each stand-alone solar street light system earns ₦357. 21k on carbon credits per annum. Considering about 40 street lamp poles on a stretch of about 5km, the system earned ₦14,288.40k on carbon credits per annum.

III. CONCLUSION

A life cycle cost (LCC) analysis along with carbon credit analysis of a solar PV powered PV IoT-based smart street light is carried out. The energy cost for powering the street light with diesel generator was also presented. The analysis was based on the solar PV power system that is sized based on the meteorological data in Uyo. Also, the system components considered are as specified by a prior circuit design for the system. However, the study in this paper did not cover the sizing and circuit design. Rather, the overall life cycle cost of the system was analysed. The energy cost of using the solar PV powered IoT-based street light was compared with the energy cost of using the diesel powered street lights. From this comparison, the payback period was estimated. Finally, the carbon credits earned by the solar PV powered IoT-based street light was calculated.

The result of the LCC analysis shows that the use of the solar PV IoT-based Street light reduced the energy cost demand by 4.5%. The study also shows that carbon credits can be earned by the system, indicating that the solar PV street light is eco-friendly. Hence, the solar PV street light reduces the hazards caused by CO_2 being emitted into the atmosphere when the diesel generator is used to power the street lights. It is therefore highly recommended that the government adopt the solar PV IoT-based street lights for a cleaner and safer environment. Apart from the health benefits, the analysis shows that in the long run the overall cost of running the solar PV street lights is lesser than that of the diesel powered street lights.

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