SSRG International Journal of Electrical and Electronics Engineering
ISSN: 2348 – 8379 / https://doi.org/10.14445/23488379/IJEEE-V8I5P104
Volume 8 Issue 5, 16-24, May 2021

Original Article

Sustainable Smart Power Outlet Controller with Online Energy Management System for Public Charging Stations

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Received Date: 28 April 2021
Revised Date: 02 June 2021
Accepted Date: 06 June 2021

Abstract *- In developing countries, there are still problems of inadequate electricity supply. A major cause of electricity supply deficiency has been identified as energy theft, due to the insecure municipal electricity grid network and the perceptively high electricity tariffs. To solve these problems, this paper discusses a feasible solution by introducing solar powered charging stations with online management systems. This deployment would allow only authorized individuals to utilise power outlets for an assigned time limit. It also monitors and regulates the power demand to ensure that no high-power equipment is plugged in at any point in time. Having sized the solar station to cater for an uninterrupted 24hrs a day supply availability, the life cycle cost of operating the station for 20years is evaluated, considering three selected geographical locations in Nigeria (Kano, Ibadan and Port Harcourt). Subsequently, location appropriate tariffs of 3cents, 4cents and 6 cents were suggested bearing in mind a desirable breakeven point of 5 years. From the Environmental Impact Assessment, CO2 European Emission Allowance of £29,973.34 £37,498.82 and £44,638.11 can the accrued in the respective locations, over the period of 20years under view. As such, the viability, sustainability and profitability of the solar powered charging station is established.*

Keywords **—** *Control system, Energy management, IoT and system security, Smart power outlets, Sustainable energy system.*

I. INTRODUCTION

The generation, transmission and distribution of electrical power is one basic infrastructure required by all modern societies, with projected electrical energy needs continually rising. However, as the electricity demand figures continue to rise, there are still devastating records of power outages occurring even in some of the most reliable electricity grids. In fact, incidences of major blackouts are on the increase everywhere [1]. The United States continues to tussle with power outages and reports estimate a 285% increase in occurrence rate of outages since 1984 [2]. These lead to large economic losses. Estimated outage costs in the US and Canada alone is $75 Billion annually [1]. Due to power outages, in Africa, an average firm incurs a net loss of between $1,304 and $9,402 per kW annually [3].

In developing countries, another drawback to electricity supply is energy theft. This is due to improper accounting for electric units sold, possibly due to billing irregularities or stealing by illegal connections or by tampering with the meter [4]. An instance is Nigeria, where the power sector suffers huge revenue losses as a direct result of energy theft [4].

In spite of all these, the use of smart gadgets is getting more and more pervasive and widespread in the daily life of the average person [5]. As a direct consequence, the need to keep these devices powered at all times and all places has become significant. In cases of power outages, this might be a big problem considering the how important these gadgets are to the normal living of a daily life to several people. In developed countries where power supply is relatively stable, people still tend to engage in long outdoor activities or commuting and subsequently require recharging their devices at short stopovers in transit. Thus, the availability of public access, metered power outlets in certain strategic locations would be very beneficial to users, even with modest utility bills incurred. More significantly, in developing countries, such accessible outlets would be largely solutions from place to place.

A good number of solar charging stations (SCS) are already in use today. Initially, solar charging stations were centralised. As at 1997, these stations were few due to how expensive solar PV technology was and due to the short life span of batteries [6]. As at 2015, more than 45 solar charging stations were already running [6]. However, the main purpose of most of these stations were initially to provide electricity low-income populations that were off the grid [6].

General implementations involve a solar PV system and USB outlets for charging of phones. This makes the station streamlined to just mobile phones and as such, other equally or more important gadgets cannot benefit from the SCS. Some SCSs go further to provide outlets that can power multiple handheld devices at a particular time [7].

Frequent applications use IoT or Zigbee wireless technology with regards to energy efficiency, only few smart power outlets tackle vampire current and can disconnect devices on detection of it [8]. As few as they are, they boast ability to actively reduce standby power [9].

There are several solar charging station implementations in existence, but as at the time of writing this article, there is none documented that provides services for miscellaneous portable electronic devices. Also, public access billing methods for customer usage have not been incorporated into most implementations, thereby neglecting the revenue generation potential of such a setup. Similarly, there has not been any Solar Charging Station that utilizes internet-of-things enabled smart sockets that require online access code generation.

This paper proffers a plausible, unique and dynamic concept for providing a sustainable and realistic smartly controlled energy system that offers easily accessible, secure and affordable electrical energy units for multiple shared resource users.

II. GENERAL SYSTEM DESIGN

Every component and subsystem in the Charging Station system gets electrical energy supply from a solar-powered inverter. A subsystem controls the smart power outlet sockets and determines whether or not they are enabled. The same subsystem measures energy usage on each socket while they are powered on, in order to assess the proper and safe usage of the outlets. Before gaining access to use the charging station, the users need to register at a website, where they can buy single or multiple timeslots and energy quantities as desired. From the website, users are allocated access codes, which can be inputted, with the keypads at the system's control box, in order to unlock a particular socket for the allotted time. It is worthy of mention that the research in its implementation used twelve outlets but this number can definitely be adjusted to suit needs in further applications. The research thus consists of diverse components working together to achieve the desired aim. As shown in Fig. 1, the Charging Station can be classified into four distinct subsystems: Load, Power Supply Subsystem, Online Management Subsystem and Smart Outlet Control Subsystem.

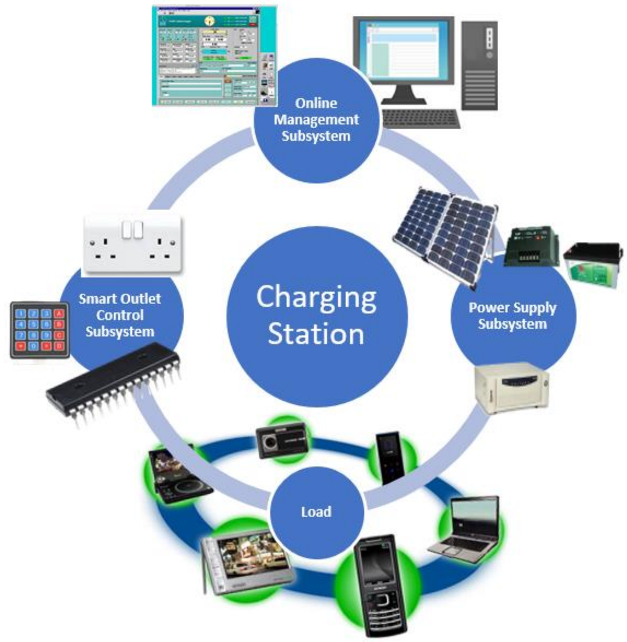

Fig. 1 Charging station general system overview

A. Energy Requirement at a Charging Station

From the foregoing, expected acceptable low power demand gadgets for use at the sockets include portable devices such as laptops, tablets, iPads, mobile phones, smart watches, etc. These electronic devices individually have relatively small power ratings. Nevertheless, the aggregate power requirement could be significantly high. A typical setup for the Charging station Power Supply Subsystem is shown in Fig. 2.

The charging station is expected to have an uninterrupted 24hrs a day system supply availability. Due to the varying duty cycles of equipment to be powered, the daily energy demand of equipment can be determined by considering the expected operating hours of each device.

$$WH_R = \sum_{i=1}^{N_d} (W_u \times O_h) \quad (1)$$

Where WH_R is the total daily energy requirement (in Watt-hours) for N_d energy dependent components in the system, W_u is the total power demand for the ith similar devices and O_h is the Daily duty cycle (h) for the ith similar devices. Table shows the ratings and anticipated energy demand for a hypothetical solar charging station using typical datasheet and load audit values.

To compensate for losses and possible vampire power in the system, a 20% allowance is adopted. Such that the total AC energy requirement, WH_{AC} is given by

$$WH_{AC} = 1.2 \times WH_R \quad (2)$$

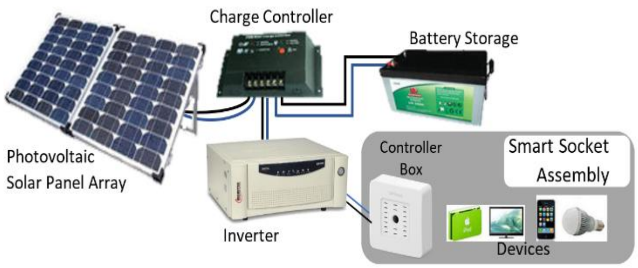

Fig. 2 Charging station power supply subsystem

B. Control Unit

The ATmega2560 microcontroller is used as the centre of control in this implementation, with the aid of an Arduino Mega 2560 development board. It controls all events relating to enabling or disabling the sockets in the charging station. It receives digital input from the keypad and measured variables from the current sensor as analogue input, to make decisions. Subsequently, information from the microcontroller are displayed on the LCD to give the user feedback at the point of using the keypad.

When the system is initialised, all sockets are disabled. Hence, when a user has generated an access code from the online platform, he/she will be expected to go to the allotted socket in desired charging station at the allotted time. On inputting the access code via the keypad, the code is acknowledged and validation is required from the online platform. Once the user authentication in successful, the relay enabling the respective socket is enabled and the user can proceed to use the socket for the allotted time frame. After which the relay will be trigger to open the circuit, which in turn disables the socket. AC power is obtained from the inverter output. The block diagram in Fig. 3 shows how the different components that make up the system interrelate to achieve the aim.

A very important aspect of the controlling system is ensuring that the power consumed is within the acceptable range. The system accurately performs this function using ACS712 current sensor. This sensor works based on the Hall Effect principle. The current measurement is used to ensure that energy, E does not exceed the prescribed energy limit, E^{max} as described by Equations (3) and (4).

$$E(t) = \int_0^t P \cdot dt \quad (3)$$

$$E^{max} = P^{max} \cdot t \quad (4)$$

Considering only the real power component P which is given as

$$P = i \cdot v.Cos\theta \quad (5)$$

Where θ is the power factor.

If we assume that we have a constant voltage level source, it implies that,

For

$$E^{max} \geq E(t) \quad (6)$$

$$\therefore P(t) < P^{max} \rightarrow i(t) < i^{max} \quad (7)$$

Thus, ensuring that the $i(t) < i^{max}$ guarantees that the energy usage is within the desired boundaries for any time duration.

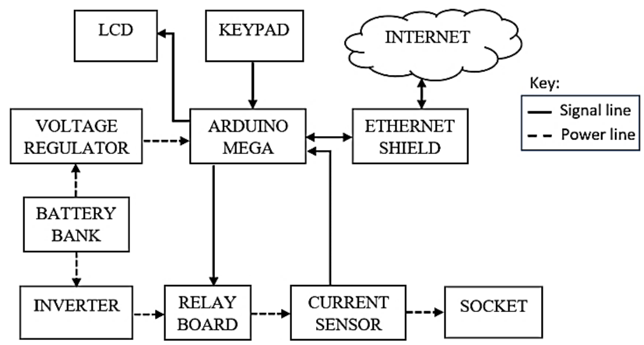

Fig. 3 Block diagram showing components interconnection

The Control unit, therefore monitors the system usage in real-time and sends updates to the online management system. Thus, the power expended on each socket is measured in real-time, ensuring that every kWh used up on each socket at the solar charging station is properly accounted for. As a result, every kWh can be billed for appropriately. This puts at bay energy theft and hence, revenue loss. More so, whenever a socket is activated but is not in use for over 10 minutes, that socket is powered off.

Table 1. Energy and power demand of each component in the charging station

Gadgets	Average power consumption (W)	Number of Units	Daily Duty Cycle (h)	Total AC Load (W)	Daily Energy Demand (Wh)
Phones	6	12	24	72	1728
Tablets	10.5	12	24	126	3024
Smartwatches	2.5	6	24	15	360
Laptops	35	12	24	420	10080
Light Bulbs (indoor)	15	4	24	60	1440
Light Bulbs (outdoor)	100	2	12	200	2400
TOTAL				893	19032

This is done to prevent vampire current and as a result, save energy on each socket. The microcontroller detects when infinitesimal electrical current (i.e. approximately zero) is observed to flow to a socket over time. This operational function also benefits the user in that it helps them to save purchased time in the event of little or no power consumption. The user can then re-log in whenever he/she is ready to resume use of the socket.

Summarily, the controller monitors the energy consumed on each socket and the duration for which it has been powered on relative to the purchased time slot. It then makes informed decisions based on accurate measures of these two facts. A flow diagram illustrating the controller operation is shown in the Fig. 4.

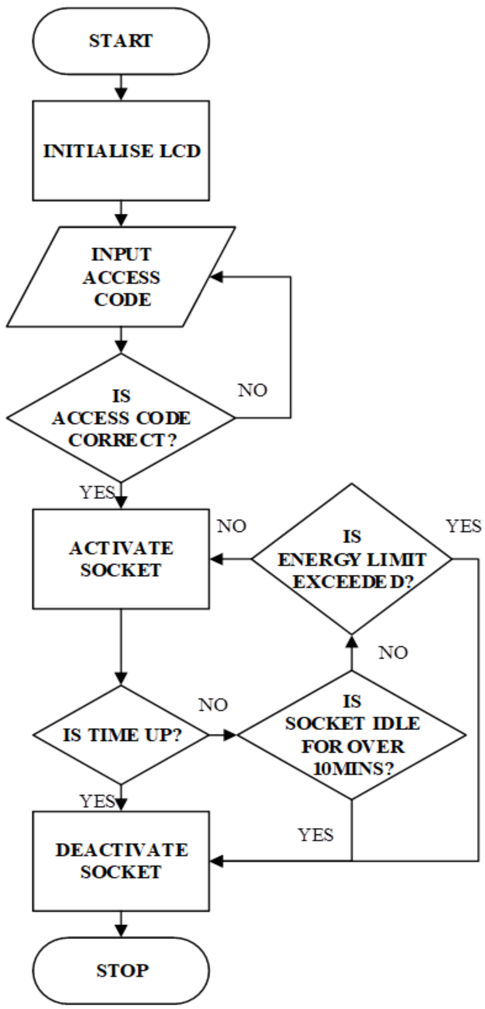

Fig. 4 Flow chat of the smart socket control operations

C. Installation Requirements in Three Nigerian Cities as a Case Study

Considering possible implementations of the solar charging system across different locations in Nigeria, there will definitely be variations in the cost and amount of power available for use in each station. Nigeria is located in the tropical region of West Africa with a total area of 923,768 Km^2, with a mean geographical location at latitude 9°04′90"N and longitude 8°40′38.84"E.

Three geographically dispersed cities in Nigeria are picked for consideration as case studies: Ibadan, Port Harcourt and Kano. It is manifest from the solar resource map of Nigeria produced by SolarGIS and published by World Bank Group, that the average Global Horizontal Irradiation (GHI) is about 5 kWh/m^2 in Ibadan, about 4.3 kWh/m^2 in Port Harcourt and about 6.1 kWh/m^2 in Kano State.

Table 2. Solar pv system specific requirements for various locations

Location	Kano	Ibadan	Port Harcourt
θ (°)	11.76	7.37	4.82
β_{max} (°)	36.76	32.37	29.82
I (kW/m^2)	6.1	5	4.3
$I_{S(AV)}$ (kW/m^2)	7.269	5.808	4.881
A_{PV} (m^2)	22.37	27.99	33.31
P_{PV} (kW)	3.803	4.758	5.663
N_M (Modules)	14	17	20
I_{CC} (Amperes)	316.91	396.53	471.89
Nc (Days)	0.6	1.0	2.0
Br (Ampere-Hour)	310.69	647.92	1542.13
N_B (Batteries)	2	4	8

III. ECONOMIC ANALYSIS OF SOLAR CHARGING STATION

This section presents an analysis on the economic implication of the implementation of a Solar Charging Station.

A. Life Cycle Cost of Solar Charging Station

The life cycle cost (LCC) of the PV system is critical to determining the feasibility and sustainability of the charging station. The life cycle of the PV module is computed over a period of 20 years. The life cycle cost of a PV system is calculated using the formula [10] in equation (8).

$$LCC = C_{BATT} + C_{CC} + C_{INV} + C_{INS} + C_{PV} + C_{BATTs} + C_{MP} + C_{SB} + C_{SBS} + C_{CO} + C_{INT} + C_{MI} \quad (8)$$

Where C_{BATT} is the present-day cost of the battery, C_{CC} is the cost of the charge controller, C_{INV} is the cost of the inverter, C_{INS} is the cost of the installation of the PV system, C_{PV} is the cost of the PV module, C_{BATTs} is the cost of a subsequent batteries, C_{MP} is the present cost of maintenance, C_{SB} is the cost of wall sockets and bulbs, C_{SBS} is the subsequent cost of wall sockets and bulbs, C_{CO} is the cost of the control circuit, C_{INT} is the cost of the internet and C_{MI} covers the miscellaneous expenses.

Within these 20 years, only the battery is required to regularly be replaced. A batch of batteries is expected to have depreciated enough for replacement every 4 years. Hence, a batch of batteries will be purchased 4 times within the life cycle of the PV system apart from the initial purchase. Equation (9) is used to obtain the cost of purchasing batteries subsequently.

$$C_{BATTS} = \sum_{i=1}^{n} C_{BATT} \cdot \left(\frac{1 + R_{INF}}{1 + R_{INT}}\right)^{L} \quad (9)$$

Where n depicts the number of assemblies of batteries to be purchased during the lifecycle of the system, R_{INF} is the rate of inflation, R_{INT} is the rate of interest and L is the lifetime of each assembly of batteries.

The wall sockets and bulbs also get changed along the lifetime of the station. An LED bulb has a life expectancy of 50000 hours that is, about 11 years if used 12 hours daily [11]. The socket would rationally be changed every 10 years as well as a result of public use. Consequently, both the socket and the bulb will be changed once in the 20-year lifespan of the station. The subsequent cost of changing both is then calculated as given in Equation (10).

$$C_{SBS} = \sum_{i=1}^{n} C_{SBS} \left(\frac{1 + R_{INF}}{1 + R_{INT}}\right)^{L} \quad (10)$$

Where L is their lifetime.

The cost of maintenance, C_{MP} can be calculated as follows,

$$C_{MP} = C_{MY} \times \left[\left(\frac{1-\left(1+\frac{R_{INF}}{1}+R_{INT}\right)^{N}}{1-\left(1+\frac{R_{INF}}{1}+R_{INT}\right)}\right)\right] \times \left(\frac{1+R_{INF}}{1+R_{INT}}\right) \quad (11)$$

Where C_{MY} is the cost of maintenance every year of the PV module and N is 20 years.

Every other cost that accrues to the LCC is gotten from market survey.

The entire cost of the project is assessed and then a discussion of the findings is also made. Assessment of the cost is to ensure that this online management solar charging station is not only ground breaking but also self-sustaining and significantly profitable for investors. A system that can sustain itself will definitely be a source of revenue and not a liability to the government or any private body that decides to adopt the system. Equally, intending users should be able to access electrical power at cheaper rates than already exist power supply offers, in order to give them a motivation to have preference for this system.

From a thorough market survey, the cost of equipment needed at the booth required to calculate the LCC are shown in the Table 3.

Table 3. Estimate unit costs of the solar charging station

Item	Unit Cost ($)
Solar Panel (per Wp)	0.59
Inverter (per 500W)	116
200Ah Deep Cycle Battery	380
Charge Controller (12V 80A)	80
Control Circuit	120.6
Bulbs and sockets	14
Internet	20
Miscellaneous	80

B. Tariff Estimation

The solar tariff rates in developed countries range from 7 cents per kWh in the United states to 17 cents per kWh in Germany [12]. These tariff rates proved cheaper than the average tariff rates in the world, as at the same year 2016, the average global electricity rate was 18.8 cents per kWh [13]. In 2018, the average electricity prices in the United states and Germany were recorded as 13 cents per kWh and 33 cents per kWh respectively. Thus, the solar tariffs have a significantly lower rate, at approximately half the price of the regular municipal electricity price.

However, due to the fact that the standard of living in Nigeria is much less compared to these developed nations, such electric tariff pricings cannot be applied to Nigeria directly. Taking a look at the average electricity tariff pricing across different zones in Nigeria, the cheapest price is at 6.67 cents per kWh while the most expensive is at 7.5 cents per kWh [14]. This emphasizes the difference in the standards of living between Nigeria and developed nations.

An investigation of the relationship between Human Development Index and the electricity tariff could be explored. The Human Development Index (HDI) is a composite statistic of life expectancy, education, and income per capita indicators. It is used to distinguish whether the country is a developed, a developing or an underdeveloped country. Using the data of Global electricity prices in 2018 for 26 selected countries (in U.S. dollars per kilowatt hour) and the Human Development Index of the same countries, a correlation analysis, yielded a value of 0.59137366. This moderate positive correlation implies there are yet other significant factors that affect tariff selection, which will include: Fuel type, power plant operation and maintenance costs, transmission and distribution system, weather conditions and government regulations or subventions.

C. Break-even Point

The breakeven point for the charging station is the number of years before the system begins to generate profit within its life cycle. To factor in the time value of money, the discounted payback period method is used. The discounted cash inflow, D_{CI} is gotten using the formula in Equation (12) [15].

$$D_{CI} = \frac{C_I}{(1+d)^n} \quad (12)$$

Where, C_I is the calculated cash inflow, d is the discount rate and is 12% here and n is year that the cash flow represents. The depreciated breakeven point, D_{pp} can then be calculated as in Equation (13).

$$D_{pp} = N_r + \frac{C_U}{C_I(N_r+1)} \quad (13)$$

Where, N_r is the year prior to full recovery, C_u is the cost that is yet to be recovered as at that year and $C_I(N_r+1)$ is the cash inflow of the next year.

IV. ENVIRONMENTAL IMPACT ASSESSMENT AND FUEL COST SAVINGS

The carbon dioxide reduction due to a PV power station implementation is 0.932kg per kWh [15]. As a result, the carbon dioxide saved, S_{CO_2} in this station can be calculate as,

$$S_{CO_2} = 0.932 \times P_{PV} \quad (14)$$

The global warming potential can be estimated, according to [16], 1 gram of NOx has been considered equivalent to 298 grams of CO2 and 1 gram of CO equivalent to 3 grams of CO_2. Thus,

$$S_{CO} = S_{CO_2} \times 0.3333 \quad (15)$$

It should however be noted that an accurate analysis of carbon emission saved cannot be discussed in this paper as an accurate analysis is only derived from "cradle to grave" study of each components in the charging station that is, from manufacturing to dismantlement and recycling.

From the consumer perspective, the use of a solar charging station would attract some form of reduction in expense on electricity. The difference in the Government regulated electricity tariff or the solar charging station tariff as compared with the use of fossil fuel generators is evaluated. Subsequently, the amount of money saved when operating the charging station on PV system as opposed to running it on fossil fuel-based petrol generator can be determined using the expression [16] in equation 16.

$$F_s = K_1 P_{PV} + K_2 P_G \quad (16)$$

Where K_1 and K_2 are constants on the fuel consumption curve and have varying values such as 0.246L/kWh and 0.08145L/kWh, P_G is the rated power of the generator in kW and P_{PV} is the power rating of the PV system in kW. As such the fuel savings, F_s is calculated in Litres per hour.

V. RESULTS AND DISCUSSION

The results of the Economic and Environmental analysis considered for the implementation of the Solar Charging Station in three locations in Nigeria are presented and discussed in this section.

A. Life Cycle Cost

Inflation rate and interest rate in Nigeria as at October, 2018 according to [17] were at 12.78% and 14% respectively.

Using these rates and the formulas for accruing the LCC, Table 4 is formed showing the cost of each element in $ for an implementation in Kano, Ibadan and Port Harcourt. The ratio of the initial cost and the operation & maintenance cost is graphically presented in Fig. 5.

Table 4. Life cycle cost of the solar charging station for various locations

Location	Kano	Ibadan	Port Harcourt
C_{BATT}	760	1520	3040
C_{CC}	320	400	480
C_{INV}	928	1160	1392
C_{INS}	850	850	850
C_{PV}	2244	2807	3341
C_{BATTs}	2732.96	5466.04	10932.07
C_{MP}	1790	1790	1790
C_{SB}	108	108	108
C_{SBS}	11.3	11.3	11.3
C_{CO}	120.6	120.6	120.6
C_{INT}	20	20	20
C_{MI}	80	80	80
LCC ($)	9964.86	14332.94	22164.97

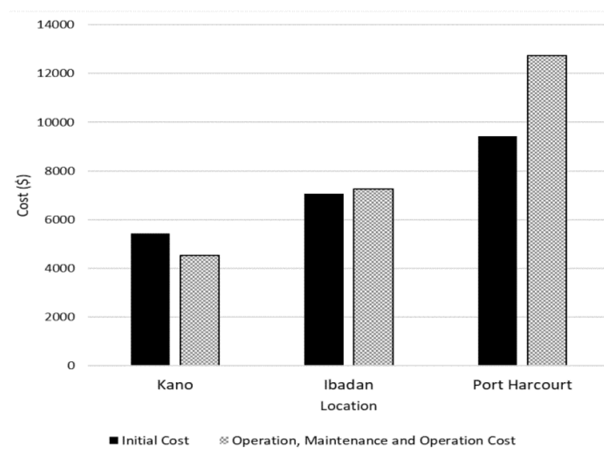

Fig. 5 Comparison of the initial cost with the operation and maintenance cost for the various locations

B. Tariff Estimation

Since a cheaper tariff rate gives the solar charging station a bigger nod from multiple users, the reference for pricing at this SCS is subject to the site of implementation. As a result, in a developing country like Nigeria is 3 cents per kWh can be considered a suitable price. This makes the tariff rate not just cheaper than grid rate but also affordable to the average Nigerian considering the standard of living in the country. This could be as cheap as ₦10 on conversion to local currency depending on exchange rate. It is nevertheless useful to indicate that a flat rate tariff scheme is applied in the Solar Charging Station billing system design. As such, further analysis on the sustainability and profitability of the tariff selection per hour, as against per kilowatt-hour can be made considering the break-even analysis.

Fig. 6 shows the cumulative present values of the income accrued from operation of the solar charging station over the period of 20years, for different tariff options, assuming an average of 12 sockets are in use for 24hrs a day.

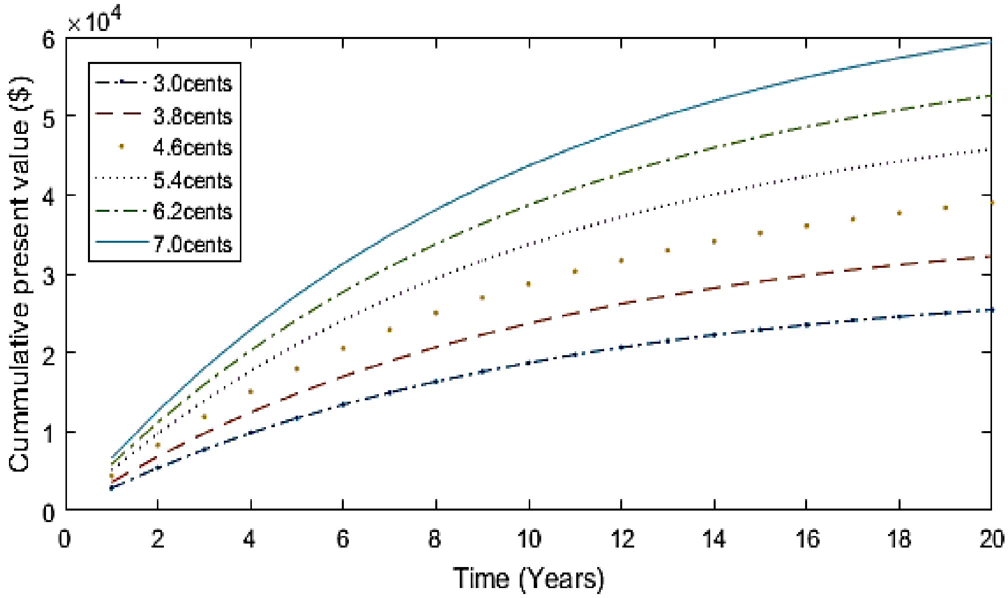

Fig. 6 Variation in cumulative present value with tariff

From the graph in Fig. 6, it is obvious that slight increases in the electricity tariff can yield significant increases in the cumulative income.

C. Breakeven Point

A graph of the variation in Depreciated Break-even point with Tariff Variation is shown in Fig. 7. As expected, due to the abundance of solar irradiance experienced in Kano, and the corresponding requirement of fewer batteries for replacement, the breakeven point is much lower than that of Port Harcourt for all tariffs.

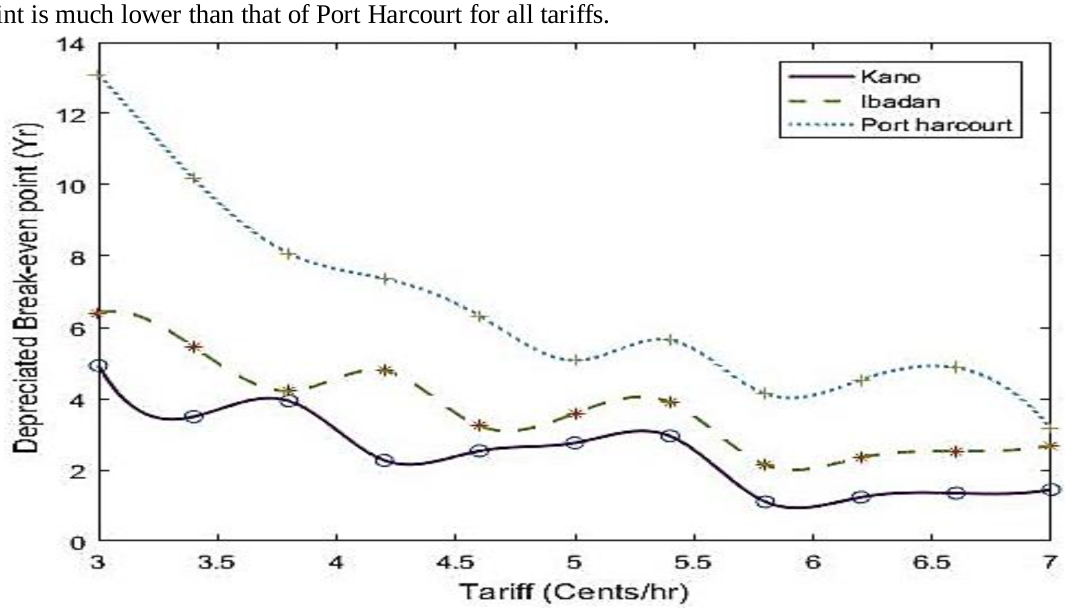

Fig. 7 Variation in depreciated break-even point with tariff

Hence, considering a reasonably desirable breakeven point of 5 years (out of the anticipated 20years life cycle), it can be observed that the different locations would be required to be assigned different tariffs, as stated in Table 5. Fortunately, the literacy enlightenment level and economic purchasing power of the average residents of the respective locations correspond with the tariffs, thereby assuring the expected patronage.

Table 5. Estimated tariff assigned for each location

Location	Kano	Ibadan	Port Harcourt
Tariff (Cents/h)	3.0	3.5	5.0

D. Environmental Impact Assessment and Fuel Cost Savings

A summary of the amount of greenhouse gas effect avoided, and the subsequent possible carbon credits can be seen in Table 6. While Table 7 shows the cost saved by not making use of a conventional fossil fuel generator.

Table 6. Carbon credit estimation over life cycle

Location	Kano	Ibadan	Port Harcourt
S_{CO2} (kg/h)	3.544	4.434	5.278
S_{CO2} (tons/annum)	31.05	38.84	46.24
Lifecycle S_{CO2} (tons)	620.91	776.84	924.71
S_{CO} (kg/h)	0.9569	1.1971	1.4251
S_{CO} (tons/annum)	8.38	10.49	12.48
Lifecycle S_{CO} (tons)	167.65	209.73	249.67
Carbon credit for the system lifecycle*($)	29973.34	37498.82	44638.11

*CO_2 European Emission Allowance of EUR 23.40/ton 12/17/2018

Table 7. Cost of fuel savings evaluation

Location	Fs (L/h)	Fs (L/year)	Cost of Fs per annum in $ **
Kano	1.245	10906.2	5151.1
Ibadan	1.558	13648.1	6446.2
Port Harcourt	1.854	16241	7670.8

**at $0.472 per litre using conversion of $1 = ₦307 [18]

VI. CONCLUSION

Blackouts and billing problems have been plaguing developing nations for centuries. Indeed, commuters in developed countries have had their own fair share of the problem. The Solar Charging Station concept tendered assuredly delivers a unique, sustainable and feasible smartly controlled energy system. The station is set-up to provide adequate and green power supply for all connected devices at all times. Whilst at this, the facility both uses clean energy and also protects itself from waste and misuse. while keeping the solution unique. Providing power for multiple handheld devices, the socket control system realizes intelligent power outlet control using Internet of Things. The tariff rates are well selected at affordable rates. Most importantly, the system is not only eco-friendly and self-sustaining but also can be a very good source of revenue for agencies adopting it.

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