African Journal of Science, Technology, Innovation and Development

ISSN: 2042-1338 (Print) 2042-1346 (Online) Journal homepage: https://www.tandfonline.com/loi/rajs20

Techno-economic viability of off-grid standalone PV-powered LED street lighting system in Lagos, Nigeria

M. O. Babatunde, T. O. Akinbulire, P. O. Oluseyi & M. U. Emezirinwune

To cite this article: M. O. Babatunde, T. O. Akinbulire, P. O. Oluseyi & M. U. Emezirinwune (2019): Techno-economic viability of off-grid standalone PV-powered LED street lighting system in Lagos, Nigeria, African Journal of Science, Technology, Innovation and Development, DOI: 10.1080/20421338.2019.1586112

To link to this article: https://doi.org/10.1080/20421338.2019.1586112

Published online: 23 Apr 2019.

African Journal of Science, Technology, Innovation and Development, 2019
https://doi.org/10.1080/20421338.2019.1586112

Techno-economic viability of off-grid standalone PV-powered LED street lighting system in Lagos, Nigeria

M. O. Babatunde *, T. O. Akinbulire , P. O. Oluseyi and M. U. Emezirinwune

Department of Electrical/Electronic Engineering, University of Lagos, Lagos, Nigeria
**Corresponding author email: mobabatunde@unilag.edu.ng*

The majority of the street lighting systems in Nigeria are predominantly composed of inefficient lighting fixtures powered either by the grid or diesel generators. Due to the epileptic nature of the grid and the fluctuations in diesel fuel pump prices, these methods for powering street lights are neither reliable nor sustainable. Use of energy-efficient lamps and photovoltaic (PV) panels has the tendency to reduce energy consumption and emissions. This study therefore presents a techno-economic analysis of deploying energy-efficient PV-powered street lighting systems using simple economic metrics. Environmental benefits of the proposed systems were also assessed by analyzing the reduction in CO_2 emission as well as the equivalent of oil saved. Relative to the existing grid-powered metal halide system, installation of LED PV-powered street light reduced energy consumption by at least 80%, while the grid-powered LED configuration reduced energy consumption by 80%. Economic analysis shows that the simple payback period (SPP) for the LED PV-powered technology was less than three years, while that of the grid-powered LED system was less than two years. The LED PV-powered technology had the highest CO_2 emission reduction of approximately 225 tonnes annually. Overall, street lighting using PV-powered and grid-powered LED is economically viable considering the payback time, net present value (NPV) and lifetime.

Keywords: LED, energy savings, street lighting, CO_2 emission, PV, energy efficiency

Introduction

Globally, lighting accounts for 10–38% of the total energy consumption in buildings in major cities (New York City Global Partners 2009). This lighting is either in residential buildings, commercial buildings and industrial buildings or public lighting such as street lighting. Street lighting is an important part of urban and rural infrastructure. Public street lighting is predominantly the responsibility of public authorities in most cities worldwide, and it has huge economic, social and security impacts on people (Jeremy, Paire, and Miraoui 2009; Masoud 2015). Provision of street lighting is imperative in the reduction of crime and road traffic related accidents in cities at night. The expenses of powering thousands of street lights for many hours of the night over the years add up and may become a burden on the authorities responsible for the payments. Though street light installation and operations are reported to be expensive (New York City Global Partners 2009), they have the advantage of making highways safer for drivers at night. For example, since night visibility decreases with an increase in human age (Owens, Wood, and Owens 2007), a certain category of people may not be able to drive comfortably at night without a quality street lighting system. Hence, the benefits of street lighting are evident.

Traditionally, utility companies apply a flat tariff rate for the electricity used by street lights because many of them are unmetered. However, with the emerging clamour for dynamic energy supply and pricing, street lights are now being metered. Consequently, the cost of powering street lights is on the rise. To reduce or control these costs, energy-efficient technologies are now being applied. By replacing traditional inefficient lamps with energy-efficient LED lamps, the operating costs can be reduced by up to 60%, as well as providing a better illumination level (New York City Global Partners 2009). These new lamps also last much longer than traditional bulbs, reducing maintenance costs significantly. Street light provision and maintenance is a large part of any municipality's budget, and the introduction of LED technologies can help free up funds for other programmes. Furthermore, these technologies coupled with the use of photovoltaic (PV) based power generation have the tendency to reduce emission by the same percentage as the reduction in energy consumed.

Street lighting models are usually simple if the pavement is a single dual carriageway only a few meters long. However, illumination becomes more complex to manage as the size increases. With urbanization fast transforming rural into urban communities, the number of streets has increased, and this has led to an increase in the number of street lights, energy consumption, CO_2 released, and costs associated with them. This is worsened by the use of an inefficient lighting system with a conventional power source. Inefficient lighting is a major cause of greenhouse gas emissions in many cities worldwide (Humphreys 2008). It increases energy consumption and, consequently, a significant financial resource is wasted annually on electricity tariffs.

Though causes of road accidents in Nigeria have been categorized broadly into factors which include vehicle operators or driver factors, vehicle factors, road pavement condition factors and environmental factors (Agbonkhese et al. 2013), driving at night is reported to account for at least 40% of fatal accidents and serious injuries in other parts of the world (Ward et al. 2005). In the case of Nigeria, there is still a lack of reliable data and information concerning night driving related traffic accident. However, it is believed that most night driving related traffic accidents occur because drivers and pedestrians suffer from reduced visibility caused by inefficient lighting (Murray et al. 1998; Schreuder 1988; Ward et al. 2005; Willis, Powe, and Garrod 2003). For instance, in a survey conducted in 2003 in the UK, it was found that road safety is the major advantage of street lighting improvement (Willis, Powe, and Garrod 2003). In the survey, 73% of respondents agreed that 'improved street lighting systems would improve the safety of children', while 63.8% agreed that 'efficient street lightings would reduce road accidents'. In Nigeria, many street lighting projects are poorly designed and inadequately maintained. For example, there are large numbers of burned-out lamps as well as inefficient lamps which consume enormous amounts of energy and financial resources with an increase in the carbon footprint, while often failing to provide standard quality lighting. Consequently, road accidents at night due to poor street lighting have been recorded in some part of Nigeria (Premium Times 2016).

Street lighting systems in Nigeria are mostly inefficient and usually powered by either the utility grid or captive diesel generators. These systems of powering the generator are usually unreliable due to the epileptic nature of the utility supply, fluctuations in the pump price of diesel, occasional scarcities of diesel fuel, and the emission of GHGs. This frequently leads to poorly lit streets and blackouts. Past studies have identified the technical and economic feasibility of adopting a solar PV system as an alternative to conventional powered systems (Akinbulire, Oluseyi, and Babatunde 2014; Akinyele and Rayudu 2016c; Akinyele, Rayudu, and Nair 2015). However, the general belief that PV-powered systems are expensive has limited their penetration (Monroy and Hernández 2008). This study therefore evaluates the techno-economic viability of deploying an energy-efficient street lighting system powered using the off-grid PV-battery system. Apart from supplying a constant power supply, it is believed that this alternative system will be cost effective and reduce CO_2 emissions. A road on the University of Lagos main campus, Nigeria, was selected as a case study.

Energy-efficient street lighting

Inefficient lighting is mostly caused by the selection of inefficient lamps, poor design and installation, inadequate maintenance, poor operational practices, the inability to sustain power source for lamps, non-compliance with standards and codes, etc. On the other hand, an effective energy-efficient street lighting system is one which incorporates efficient lamp technologies, optimal pole height and placement, efficient light distribution, and aesthetics, while using the minimum energy in satisfying requirements for visibility and suitable light levels (Masoud 2015; New York City Global Partners 2009). With evolving technology, there are numerous opportunities to improve lighting quality. Some of the methods include retrofitting of inefficient lamps, improved operation and maintenance practices, automation of systems, and the use of renewable energy sources to power street lights. All these methods can also be merged to obtain a good lighting system. An efficient street lighting system must be efficient in both the quantity of energy it uses and the source of its energy. The addition of a renewable energy source to power street lights could in all likelihood enhance the system's efficiency and reliability.

Retrofitting involves the process of changing existing, less energy-efficient luminaries to more efficient ones. Retrofitting may be extended to existing lighting infrastructure based on the requirement of a particular roadway and the condition of the components. Therefore, the present state of the infrastructure dictates whether retrofits are needed or otherwise. Such infrastructure and components are grouped into structural (poles, substructures, trenches for cables), optical (luminaries) and electrical (lamps, ballasts, cables). During retrofitting, only part of the system is changed. Retrofitting is useful in energy savings and maintenance. Retrofitting involves partial removal of the existing lighting system and fitting new components, design or technology in areas they did not previously exist (e.g. replacement of either inefficient lamp or luminaries). This option gives the most efficient energy-technology design for street lighting. The fundamental aim when setting up a street lighting system is to design a system which returns the minimum net present value (NPV) that meets all appropriate lighting standards.

Energy-efficient technologies and design can reduce the costs of street lighting projects significantly, often by 25–60% (New York City Global Partners 2009). These savings can eliminate or defer the need for new generating plants while providing the capital for alternative energy solutions in rural or remote areas. These cost savings can also enable extension of street lighting to other areas, thereby increasing access to lighting in low-income and other off-grid communities. In addition, improvements in lighting quality and expansion in services can improve safety conditions for both vehicle traffic and pedestrians. A well-designed, energy-efficient street lighting system would enhance road users' visibility and safety, reduce energy consumption and operational costs, and enhance the appearance of neighborhoods. Other benefits include reduced energy consumption, reduced expenditure on the lifetime of the project and greenhouse gas emission reduction. To harness these aforementioned benefits, many methods are being adopted worldwide. Some of these methods include the following: changing to more efficient street lighting technologies, reduction in use of high power consuming high pressure sodium lights, and adaptive lighting controls to automatically switch off lights in off-peak periods (Akinbulire, Oluseyi, and Babatunde 2014). Apart from using these technologies, the application of renewable energy sources to power street lights will reduce greenhouse emissions as well as overall operational costs since there will be no cost of power generation after the initial capital cost at the beginning of the project.

Although the application of hybrid renewable energy system (HRES) such as photovoltaic-battery (PV/Bat), wind/PV/battery, wind/battery, etc. in residential and rural applications has increased over the years (Akinbulire, Oluseyi, and Babatunde 2014; Akinyele and Rayudu 2016b, 2016c; Ajayi and Ohijeagbon 2017; Ayodele 2016; Babatunde et al. 2018; Olatomiwa et al. 2015), its application in street lighting has been given limited consideration in municipal applications in developing economies. For instance, the majority of public street lights in Nigeria are either powered by the grid system or standalone diesel generators. A search through the literature, however, reveals a paucity of knowledge on the techno-economic and environmental viability of adopting an off-grid standalone PV-powered street lighting system in Nigeria.

Ajayi and Ohijeagbon (2017) evaluated the possibility and economic viability of solar and wind energy resources as sustainable electrical sources for off-grid rural settlements of 200 homes, a school and a health centre in Nigeria. The optimal system was selected based on net present cost (NPC). Akinyele and Rayudu (2016a) presented a comprehensive techno-economic and environmental impact assessment of a photovoltaic power system (PPS) for a small off-grid community. The system was planned to meet the community's energy demand of 63,900 kWh, with an annual load growth of 1% over a 25-year planning period. In a similar study, Akinyele and Rayudu (2016b) presented the development of a HRES for a small off-grid community in Kutunku, Gwagwalada, Nigeria, based on the socio-technical-economic approach. Furthermore, the embedded generation analysis indicated that five of the six configurations yielded profits over a 10-year project life as compared to the present utility tariff in Nigeria. In another study, the techno-economic and environmental effect of including DSM in HRES for a rural community was investigated (Akinbulire, Oluseyi, and Babatunde 2014). In order to ensure sustainability of PV projects, Akinyele and Rayudu (2016c) presented strategies for developing energy systems for off-grid communities, which are aimed at approaches to successfully deploy such energy systems in developing countries. Olatomiwa et al. (2015) evaluated the viability of adopting various HRES configurations comprising PV arrays, wind turbines and diesel generators in different locations within the geo-political zones of Nigeria. It is believed that solar-powered energy-efficient lamps provide a promising solution for energy savings and CO_2 mitigation (Abolarin et al. 2013; Adam and Apaydin 2016). These applications were limited to powering only basic loads in the rural community. However, for general adoption of this system for street lighting by governments, investors and decision-makers, it is necessary to determine the technical and economic viability of such technologies due to the high cost of PV system technologies and energy-efficient lamps.

It has also been reported that an off-grid solar system has an advantage of being generally cheaper than extending power lines in remote areas (Hall 2013). Furthermore, off-grid standalone PV-powered street light systems are self-sufficient. Since the street lights will only operate at night, adoption of an off-grid standalone PV-battery system will avoid sudden blackouts that may occur on the road due to a collapse of the grid system or diesel generators which is often experienced in many developing countries like Nigeria. Also, if these street lights are removed from the grid system, it will provide more energy that could be used to serve other consumers tied to the grid in an energy deficient power network. Using an off-grid standalone PV-powered street light system will also remove the future burden of electricity tariffs on the government's expenses since it can have a lifespan of up to 20 years. An off-grid standalone PV system generates clean energy and will also eliminate emissions that result from the use of conventional fuel (grid and diesel generators).

This work, therefore, seeks to evaluate the techno-economic and environmental viability of deploying an off-grid standalone PV system for energy-efficient street lighting in Nigeria.

Materials and methods

Technical consideration for lamp technologies

A light source solely defines visual value, cost and efficiency of the system and therefore it is the most significant component of a lighting system. Technically, lamp selection is dependent on the illumination level required by a particular road according to codes and standards, colour rendering properties of the lamp, lamp life and lamp efficacy (New York City Global Partners 2009). Efficacy of a lamp is the ratio of light output from that lamp to the energy it consumes, and it is measured in lumens per watt (lm/W). Efficacy estimates how well a light source produces visible light.

Although the use of light-emitting diodes (LED) permeates the street lighting markets, three types of lamps are commonly used in street light installations: metal halide (MH), mercury vapour (MV) and high pressure sodium vapour (HPS) (International Institute for Energy Conservation 2015; Leena et al. 2012). The technical characteristics of the various lamps used in street lighting are shown in Table 1. The industry has recognized HPS as a standard due to its high efficacy and lumen maintenance, but the major setback is with its colour rendition. The MH has the best colour rendering properties and its luminous efficacy is considerably high, but the major disadvantage is its low lamp life. The incandescent lamp also has high colour rendition but has poor efficacy and lamp life. The MV consumes high energy and has poor lamp life. The LED has the highest lamp life ranging from 40,000 to over 100,000 hours. It saves a lot of energy, but the cost of investment is high. For instance, compared to high irradiation diode (HID) lamps, the cost of procurement of LED lighting technology is high but its energy consumption is half that HIDs, thereby resulting in substantial energy savings, both in kilowatts and bills. While florescent and HID lamps require ballasts or capacitors, LEDs utilize an electronic arrangement that converts the supply voltage to low voltage DC. For the purpose of this study, metal halide (which is the existing technology at the site of study) and LED lamps were selected for consideration. Fluorescent lamps have high efficacy ranging from 55 to 100 lumens/watt as well as good colour rendering. Though florescent lamps have good lumen maintenance, they fail at the end of their useful life and contain mercury. The mercury powder found in fluorescent tubes pose significant health threats to plants, animals and humans exposed to it. A damaged fluorescent tube releases mercury into the environment, and the mercury could last for up to four hours in the air. This mercury is capable of causing asthma and other respiratory and diseases.

Induction lighting is similar to fluorescent fittings but differs because it has no electrode and thus has a long

Table 1: Technical details of street lamp technology.

Lamp type	Colour Rendering Index (CRI)	Luminous efficacy (lm/W)	Lifetime (hours)
High pressure sodium (HPS)	30	50–150	15,000–24,000
Low pressure sodium (LPS)	5	100–190	18,000–24,000
Mercury vapour (MV)	50	50	10,000.00
Metal halide (MH)	70–95	70–130	8000–12,000
Fluorescent	60–90	40–100	6000–45,000
Compact fluorescent lamp (CLF)	60–90	50–75	6000–15,000
Incandescent	90–100	5–25	1000
Induction	50–90	60–90	100,000
Light emitting plasma (LEP)	50–90	60–90	100,000
Light emitting diode (LED)	70–90	Up to 160	100,000+

Source: International Institute for Energy Conservation 2015; Leena et al. 2012

life (over 100,000 hours). It possesses a good colour rendition index (CRI) with good efficacy of around 60–90 lm/W. Light emitting plasma is the newest light source technology. Being an electrode-less light source, it has a long life (over 100,000 h). It also has good CRI and good efficacy and thereby has a tendency to minimize energy cost.

PV-powered lighting system sizing

The steps involved in the sizing of a PV-powered lighting system are shown in Figure 1. The PV-powered lighting system process starts with determining the needs and the standard requirements for the particular road. The codes regarding street lighting are usually given in standards such as; BIS 1981, BS 5489-1 or as may be applicable in the region under consideration. These standards and codes provide recommendations on the overall principles of road and street lighting. Such provisions include the aesthetic, technical and statutory provisions on operation and maintenance of road lighting fixtures. The recommended level of illumination for street lighting for different road types is given in standards (*Road Lighting Part 2: Performance Requirements* 2003). For the purpose of this study, the BS 5489-1:2013 is adopted. This was used because engineering designs specifications in Nigeria follow the BS codes. The next step involves the identification of suitable energy-efficient lamp and computation of the number of lamps that would meet the illumination requirements for the road. This is used in the estimation of the energy demand of the lamp under specified operational hours. To obtain the energy demand E_a, the total power in kW of the lamps and other energy consuming devices is obtained and multiplied by the total hours for which the lamps are expected to operate. The next stage is the component size estimation. These include the size of the PV module, charge controller and battery. Using the lowest monthly average solar irradiation data of the year, the amount of solar radiation the PV panel needs to trap each day to meet the load requirement is also estimated. The total Watt-hours per day expected from the PV modules is divided by the day-hours sun radiation and the number of PV panels for the system is obtained by dividing the result from the previous step by the rated output of the PV modules available from the manufacturer. After the sizing of the entire system, measurement and evaluation of the system are carried out to determine the total cost of the system. Measurement and evaluation involve the material take off with the associated economic analysis of the system. In order to evaluate the viability of the system, the NPV, which is regarded as the total discounted cost of the system over its lifetime, is usually used to evaluate its economic advantage. Furthermore, other economic indices such as simple payback period (SPP), internal rate of return (IRR), return over investment (ROI), and cost of conserved energy (CCE) can also applied to evaluate the viability of the project. Finally, the CO_2 emission and oil equivalent of energy saved with deployment of energy-efficient lamp are appraised. The project may be re-evaluated to search for more improvement opportunities.

Component sizing

PV sizing

Depending on the manufacturer, various sizes of PV modules produce different amount of power. The peak Watt (Wp) generated is dependent on the PV module size and system location. The size of PV module that is required to meet the load demand for each standalone system (pole, lamp) is expressed as Equation 1. The value of η_{sys} (overall system efficiency) is expressed as Equation 2.

$$P_{pv} = \frac{E_a}{\eta_{sys} \times SH} \quad (1)$$

$$\eta_{sys} = \eta_{inv} \times \eta_{pv} \times \eta_{batt} \quad (2)$$

where P_{pv} is the area of the PV module, E_a is the energy demand, SH is day-hours sun radiation, η_{inv} is the inverter efficiency, η_{pv} is PV module efficiency, η_{batt} is battery efficiency, and η_{sys} is the system efficiency. For this analysis, the overall system efficiency selected was 70%.

The solar irradiation and day-hours sun radiation are generally dependent on location, weather, and season of the year (Dazhi, Jirutitijaroen, and Walsh 2012; Dizqah, Maheri, and Busawon 2012). Depending on the application, surrounding structures can also affect the level of solar irradiance received by PV modules. Highrise buildings, trees, snow, dust, etc. may also reduce the efficiency of solar incident on PV modules. As compared to other areas, low level of solar irradiance is received by regimes farther from the equator. Cloudy conditions in some months of the year also reduce the solar irradiance incident on the earth surface. The assumption in this study is that the lighting system will operate for at least

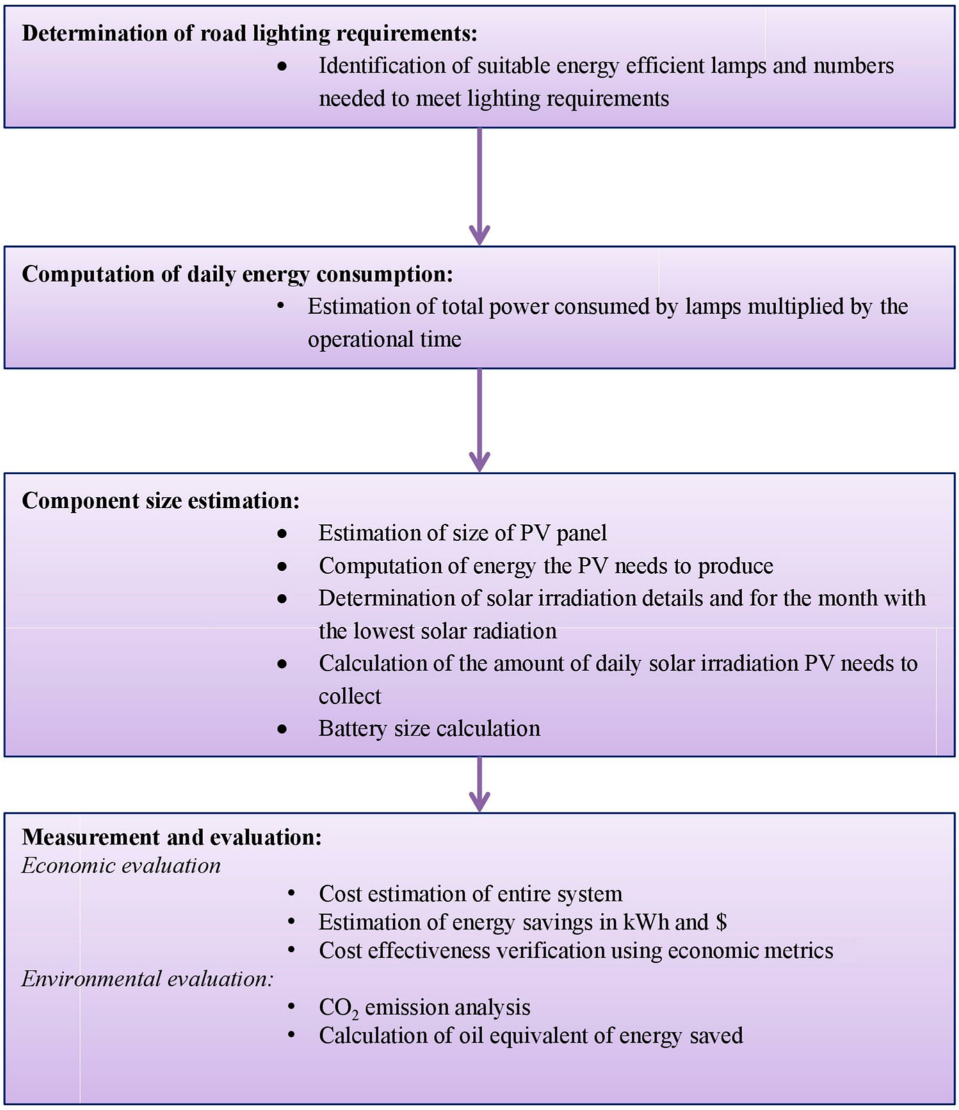

Figure 1: Flowchart for PV-powered street lighting system sizing.

12 hours per day and the day-hours sun radiation is five hours.

Battery sizing

Generally, battery size in PV applications is dependent on factors such as local solar irradiation, autonomy and load connected. However, it is worth noting that batteries come only in standard ratings and consequently selection of the next larger size is recommended. To evaluate the size of battery (kWh or Ah) Equations 3 and 4 are considered.

$$M_{\mathrm{batt1}}(\mathrm{kWh}) = \frac{A_b \times E_a/365}{DoD} \tag{3}$$

$$M_{\mathrm{batt}}(\mathrm{Ah}) = M_{\mathrm{batt1}} \times \frac{1000}{V_s} \tag{4}$$

where A_b is the autonomy, E_a is the energy demand, DoD is the depth of discharge, and V_s is the battery voltage. For the purpose of this study, battery autonomy (battery duration at a specified load level) of one day was chosen, while the selected battery voltage and DoD were 24 V and 90% respectively. The solar charge controller was selected to match the voltage of PV system and batteries. The controller must have enough capacity to withstand the current from the PV system. Typically, the size of the solar charge controller is estimated by multiplying the short circuit current of the PV module by a factor of 1.3. The value of the short circuit current of the PV module is based on the work of Babatunde et al. 2018.

Economic consideration for lighting technologies

The economic performance of energy-efficiency improvements can be evaluated from several perspectives. A policymaker's perspective should capture all costs and benefits experienced by different parties in a society (e.g. consumers and utilities). Economic metrics used in this study include the cost of conserved energy (CCE), the simple payback period (SPP), the internal rate of return (IRR), the return on investment (ROI), and the net present value (NPV). The CCE is evaluated by using Equation 5:

$$\mathrm{CCE} = \frac{d/1-(1+d)^{-n} \times \mathrm{IN_V}}{\Delta \mathrm{EN_a}} \tag{5}$$

where d is the discount rate, n is the number of years over which the investment is amortized, IN_V is the initial investment and ΔEN_a is the annual energy savings.

Individual consumers usually evaluate cost effectiveness and benefits differently from policymakers, because while policymakers consider the societal angle, consumers want relatively more realistic and easily comprehensible methods to view return on their investment. Thus, the consumer perspective is often represented by a simple payback period (SPP). SPP is a technique used to determine the specific time in years it takes for an investment to be paid off or recovered. This is evaluated by using either present value amounts or cash flow amounts. Most consumers and investors expect a quick payback. The SPP measures the risk and not the return and does not account for the time-value of money, risk, opportunity cost or financing. It is however easy for most individuals to understand and apply, regardless of academic training or field of application. When applied to compare related investments, it can be quite useful. SPP is given by Equation 6:

$$\mathrm{SPP} = \frac{\mathrm{NP_C}}{A_\mathrm{S}} \tag{6}$$

where NP_C is the net project cost and A_S is annual saving.

The NPV is the present value of future cash flows less the present value of the investment cost. This is generally regarded as the best method of analyzing the economic viability of setting up long-term projects such as a photovoltaic (PV) lighting system (Bowlin, Martin, and Scott 1990; Dixion 1994). NPV analysis comprises the time-value of money and estimates the present worth of all costs anticipated. This can be obtained by using Equation 7:

$$\mathrm{NPV} = -C_0 + \sum_{i=1}^{T} \frac{C_i}{(1+r)^i} \tag{7}$$

where C_0 is the investment at year zero is, C_i is cash flow at year i, r is the appropriate interest rate (discount rate), and T is the lifespan of the project. For the purpose of this study, a discount rate of 10% was used.

The internal rate of return (IRR) on an investment or project is the annualized effective compounded return rate that makes the net present value of all cash flows from a particular investment equal to zero. The IRR is an indicator of the profitability, efficiency, quality, or yield of an investment. This is in contrast to the NPV, which indicates the total value or magnitude added by making an investment. Usually, most investors prefer the use of IRR in capital budgeting to compare the profitability of various projects based on the rate of return. For instance, an investor will compare an investment in a PV-powered street lighting to a grid-powered street lighting based on the IRR of each project. To maximize returns, the project with the higher IRR is preferred in terms of investment. If all projects require the same up-front investment cost, the project with the highest IRR would take the highest priority. Though the NPV has gained preference among academia, research shows that investors prefer the use of IRR over NPV for the determination of profitability (Pogue 2004). Investors find it easier to compare investments of various magnitudes in terms of percentage rates of return than by NPV. However, NPV has been reported to be a better reflection of worth to business profitability (Pogue 2004). IRR, as a measure of investment efficiency, may give enhanced perceptions in capital constrained circumstances. In contrast, when comparing mutually exclusive projects, NPV is the appropriate index. Return on investment (ROI) is the profit to an investor resulting from an investment of some resource. A high ROI is an indicator that the investment's gains compare satisfactorily to its cost. As an evaluation metric, ROI is used to estimate the efficiency of an investment or to compare the efficiencies of several different investments. In business, the ROI metric is used to estimate, per period, rates of return on money invested in an economic entity in order to choose whether or not to accept an investment. It is also used as an indicator to compare different investments within a portfolio. In a survey carried out in carried out in 2010, 77% of senior marketing mangers interviewed reported that they found the 'return on investment' metric very useful (Farris et al. 2010). Hence, we adopted the ROI as part of the economic metrics in this study. cost of conserved energy (CCE) is a powerful performance metric used especially by policymakers for evaluating societal cost effectiveness of energy efficiency technologies. The CCE calculates the cost of conserving one kWh of electricity. If retrofitting with energy-efficient technology results in a CCE which is less than the price paid for a kWh of electricity, the project may be labelled as cost effective (Mills and Piette 1993; Rosenfeld et al. 1993; Stefano 2000).

Generally, both a PV lighting system and a grid-powered lighting configuration require a luminaire (lamp inclusive) and a pole. In addition to these, a PV lighting system also requires the installation of a PV panel, a battery and other electronic components such as a controller (Figure 2). Depending on the manufacture and technology, the battery usually requires replacement every five years. A grid-powered lighting system requires wiring to connect the system to the grid. The maintenance cost of PV lighting is higher because the surface of the solar panels requires dusting.

CO_2 emission and oil equivalent saved

CO_2 emission reduction related to retrofitting grid-powered MH street lighting system with PV-powered LED and grid-powered LED street lighting was also estimated. It was assumed that in generating a kilowatt-hour of electric energy using fossil fuel, 1.25×10^{-3} tonnes of CO_2 is emitted and 12,000 kWh of energy is equal to 1 tonne of oil (Babatunde et al. 2018; British Petroleum 2017). Based on the emission data of an earlier research study conducted at the University of Lagos, the annual CO_2 emission (EM_{CO2}) and the annual oil equivalent of energy saved (OEES) are estimated using Equations 8 and 9 respectively and the information in Appendix A

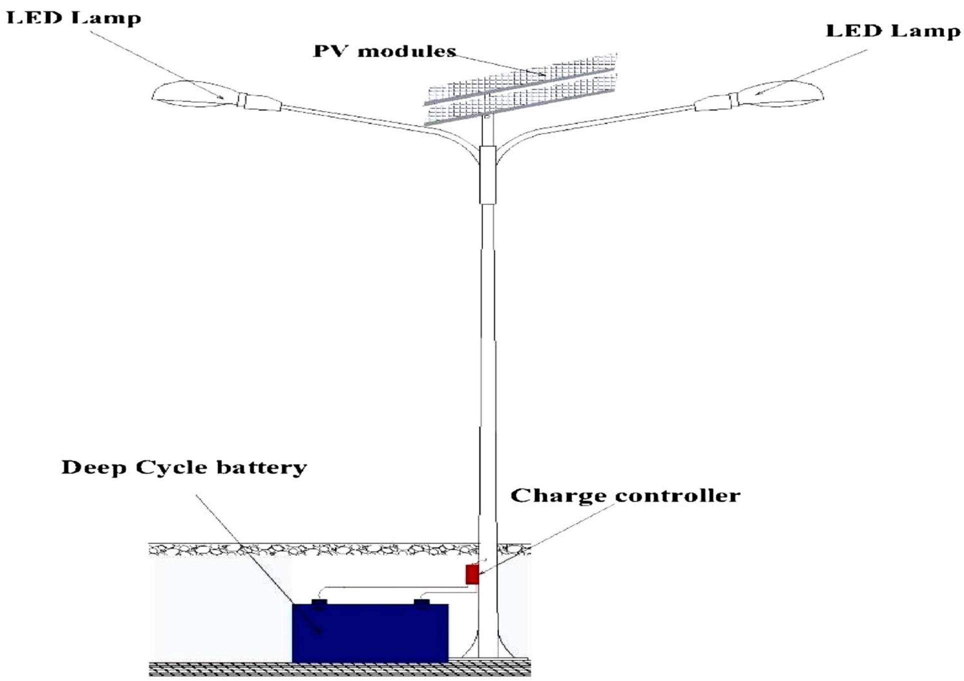

Figure 2: A typical solar street lighting system.

(Babatunde et al. 2018; British Petroleum 2017).

$$\mathrm{EM}_{\mathrm{CO2}} = \frac{E_{\mathrm{se}}(\mathrm{kWh}) \times 1.25 \times 10^{-3}}{1\,\mathrm{kWh}} \quad (8)$$

$$\mathrm{OEES} = \frac{E_{\mathrm{se}}(\mathrm{kWh}) \times 1\ \text{tonne of oil equivalent}}{12,000\,\mathrm{kWh}} \quad (9)$$

where E_{se} is the annual energy saving in kWh. Inputs to the equations are given in Table 2.

Results and discussion

The site of the case study is the main campus of the University of Lagos, Nigeria. The University of Lagos was identified as a case study because its street lighting system is a representative of comparable configurations in most Nigerian cities. A survey of the main campus shows that the present street lighting system is grid/diesel powered MH lamps spanning 2.5 km (Table 2). The total number of lamps and other details for the case study (road) are given in Table 2. In Nigeria, the annual average solar irradiance is estimated to range from approximately 12.6 MJ/m^2/day in coastal regions to 2.52 MJ/m^2/day in the extreme northern part of the country (Akinbulire, Oluseyi, and Babatunde 2014). The solar irradiance for the area under study was extracted from NASA data and is shown in Figure 3. The month of August recorded the lowest insolation level while the month of April had the highest irradiance. Usually, the period of lowest solar irradiance represents the worst case scenario and is utilized in the design (Akinyele and Rayudu 2016c; Akinyele, Rayudu, and Nair 2015).

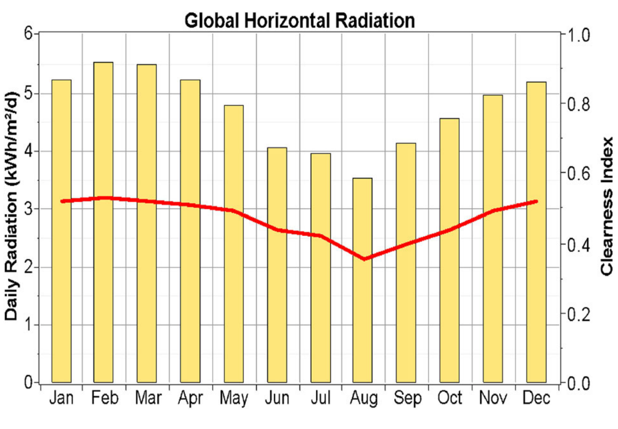

Figure 3: Average monthly solar irradiation data for Lagos.

The present 500 W MH lamps were replaced with 100 W LED lamps of an equivalent illumination level. LED has the tendency to reduce energy consumption in lighting systems because of the absence of a heating filament and consequently reduce losses due to heating of the filament. This implies that the cable current carrying capacity will also be reduced, resulting in a reduction in the initial cost of investment. This is a major advantage of a PV-powered solar street lighting configuration as it also reduces losses. Based on Equations 4–9, the technical configuration of the solar powered LED lighting system was estimated. Each complete unit of PV-powered 100 W LED lighting system consisted of a 300 Wp PV module and a 120Ah-24V battery with a rated 8 A charge controller and a 500 W rated inverter. The economic comparison for three configurations of street lighting (grid-powered MH, grid-powered LED and PV-powered LED lamp) for the 140 lamps was considered and cumulated.

The summary of initial installation costs of the three systems are shown in Table 3. The installation cost for the grid-powered MH was estimated at US$278,190, while grid-powered LED street lighting installation cost was US$329,978. The total installation cost for the PV-powered LED configuration was $424,050. The additional

Table 2: Survey data and technical parameters of the case study street.

Technical inputs			Road survey data	
Parameter	Value	Unit	Parameter	Value
r	10	%	Road length	2.5 km
SH	5	hours	Height of pole	10
V_s	24	V	Number of lamps	140
A_b	1	day	Type of lamp	MH
DoD	90	%	Voltage rating	Single-phase 240 V, 50 Hz
η_{sys}	70	%	Lamp power	500 W
I_{sc}	5.498	A	Required illumination level	8 Lux (BS 5489-1:2013)

investment related to PV was due to the PV module battery, charge controller and LED lamp costs. Due to the utilization of LED, saving on solar-powered LED installation system was achieved on the power cable cost. Table 4 shows that the SPP for the solar-powered LED is 4.2 years and 1.6 years for the grid-powered LED system over a period of 20 years. Results of other economic indices such as IRR, CCE and ROI are also shown in Table 4. The grid-powered LED lamp has an IRR of 19% as compared to PV-powered technology at 16%. The cash flow for both systems shows that the initial investment in the PV-powered LED systems exceeds that of the grid-powered LED system in the first year of investment because of the high initial capital costs involved in the purchase of the PV module and LED lamps. At year 5, 10, and 15 respectively, there would be additional investment for the PV-powered LED system due to the purchase of batteries. After the initial year of investment, the PV-powered LED alternative would save $19,622.4 annually, while the LED grid-powered alternative would save $13,981 per annum when both systems are compared to the MH grid connected system.

The environmental benefit comparison of the entire system configuration is presented in Table 4. Utilization of the PV-powered LED street lighting system reduced CO_2 emission by 307 tonnes annually, while approximately 21 tonnes of oil equivalent of energy would be saved annually. On the other hand, the grid-powered LED alternative would save about 15 tonnes of oil equivalent annually and CO_2 emissions would be reduced by 219 tonnes per annum.

Sensitivity analysis

This present study only considered a small scale of a 2.5 km road with only 140 lamps at the University of Lagos, Nigeria. Meanwhile, Lagos state government powers about 400 km of street lighting on conventional fuel sources. In order to examine the economic implication of the proposed design on an urban scale, a sensitivity analysis was carried out to show the effects of an increase in the number of lamps (which will normally be directly proportional to the length of the road) to be retrofitted on the overall NPV, CCE, IRR, and SPP. The number of lamps was varied from 140 to 1000. Figure 4 shows that as the number of lamps increases, so does the SPP. At 140 lamps, the SPP for a PV-powered LED street light system is a little above six years, while that of a grid-powered LED system is slightly above two years. This is three times less than that of the PV-powered LED street light system. Shown in Figure 5 is the effect of change in the number of lamps on the CCE. It can be seen that as the number of lamps increases, so does the CCE. The difference between the CCEs as the number of lamps increases is also shown on the chart (Figure 5). As the number of lamps increases, the difference in the CCE decreases. Since it

Table 3: Initial cost comparison of street lighting technologies at the University of Lagos, Nigeria.

Design configuration	Grid-powered MH lamp		Grid-powered LED lamp		Off-grid PV-powered LED lamp	
Item	Unit price	Subtotal	Unit price	Subtotal	Unit price	Subtotal
Lamp cost US$	120	16,800	800	112,000	800	112,000
Grid connection cost /generation cost US$		28,000		5600	0	0
Power cable cost US$	0	60,800		44,800		10,000
Conduit and piping cost US$		18,000		18,000		4500
Switch yard cost US$		3300		580	0	0
Light pole cost US$	300	21,000	300	21,000	0	0
PV panel cost (/W LED, Wp) US$	0	0	0	0	2.4	
Total PV installation, (kWp) US$	0	0	0	0	33.6	
PV price US$/Wp	0	0	0	0	5	
Total PV module cost, US$	0	0	0	0	950	133,000
Deep cycle battery cost, US$	0	0	0	0	200	28,000
Controller cost US$	0	0	0	0	150	21,000
PV modules poles US$	0	0	0	0	300	21,000
Civil constructions and installations cost US$	750	105,000	700	98,000	400	56,000
Subtotal (US$)		252,900		299,980		385,500
Miscellaneous (10%)		25,290		29,998		38,550
Total installation cost US$		278,190		329,978		424,050

Table 4: Potential economic and environmental benefits of street lighting technologies at the University of Lagos, Nigeria.

Item	Grid-powered MH Lamp	Grid-powered LED lamp	Off-grid PV-powered LED lamp
Power rating per lamp (W)	500	100	100
Total power connected (kW)	70	30.1	14
Initial installation cost (US$)	278,190.00	329,978.00	424,050.00
Maintenance and item replacement times			
Lamp replacement time (yr)	2	10	10
Battery replacement time (yr)			5
Charge controller replacement time (yr)			5
PV module replacement time (yr)			20
Lamp replacement cost (US$)/yr	16,800.00	112,000.00	112,000.00
Battery replacement cost (US$)/yr	0	0	28,000.00
Charge controller cost (US$)/yr	0	0	21,000.00
PV module replacement cost (US$)/yr	0	0	0
Annual maintenance cost (US$)/yr	7841.70	6539.34	9361.50
Total maintenance savings (US$)/yr		18,102.36	15,280.20
Overall saving/economic index			
Hourly power saving (kW)		39.9	56
Lighting hours (hr)	12	12	12
Electricity price US$/kWh (X1 tariff)	0.09		
Annual total energy savings kWh/yr		174,762	245,280
Annual total energy savings US$/yr		13,980.96	19,622.4
Total maintenance saving US$/yr		18,102.36	15,280.20
Total annual savings US$/yr		32,083.32	34,902.60
Additional investment for LED US$/yr	Reference	51,788.00	145,860.00
Simple payback period (yr)		1.6	4.2
NPV		US$ 100,876.13	US$ 65,883.69
IRR		19%	16%
CCE		0.040	0.080
ROI		279%	190%
Environmental benefits			
CO_2 emission reduction tonnes/yr		218.5	306.6
Oil equivalent of energy saved (tonnes)		14.6	20.4

has been reported that an energy-efficient technology that results in a CCE which is less than the price paid for a kWh of electricity is cost effective (Stefano 2000), all grid-powered LED street lights for lamps up to 1000 lamps are cost effective, whereas the PV-powered LED street light system is only effective for between 140 and 400 lamps. In order to make PV-powered LED street lighting more cost effective, there is a need for the government to subsidies PV technology and LED lamps to reduce the initial cost of purchase of the technologies. In Figure 6, it is observed that as the number of lamps increases, so does the NPV. Initially, the difference between the PV-powered LED and the grid-powered LED street light systems was high, with the latter having the advantage. However, as the number of lamps increases, the difference decreases, and the PV-powered LED street light system has a higher value compared to the grid-powered LED street light system. In the context of work done on the economics of adopting solar street lighting (Masoud 2015; Nunoo, Attachie, and Abraham 2010; Wu et al. 2009), this study was able to identify that the grid-powered LED street lighting system has a lower payback period than the PV-powered configuration. This study however shows that at a lower lamp number, the NPV of the grid-powered street light is higher, but as the number of lamps increases, the NPV of the PV-powered system becomes higher than that of the grid-powered street light system. From the foregoing, it can be seen that implementation of the proposed off-grid PV-powered street light design on an urban scale will result in considerable economic benefit as well as emission reduction.

Future research

Although Nigeria is blessed with good solar irradiation across the country, many solar installations are recorded to have failed in the past (Akinboro, Adejumobi, and Makinde 2012; Ohunakin et al. 2014). Just like other solar PV-based projects, the solar street lighting application is also experiencing a lot of challenges. Some of the factors responsible for the failure and challenges include: grid unreliability, lack of awareness and information, inadequacy of technically skilled personnel, lack of proper government policy and incentives that favour solar-based projects, ineffective quality control of products, theft and vandalization, and, most importantly, an inadequate maintenance culture (Akinboro, Adejumobi, and Makinde 2012; Ohunakin et al. 2014). In order to mitigate these barriers and make solar street lighting sustainable in Nigeria, the government and relevant regulatory agencies will need to formulate and implement favourable policies backed up with strong political will at all levels of government. Although the cost of maintaining the proposed solar street lighting has been considered in this study (Table 4), decision-makers should also give priority to periodic maintenance of solar street lighting facilities so as to mitigate system failure and ensure that the facilities last their entire lifespan. In line with this, future research will be conducted on the sustainability of solar street lighting facilities. For

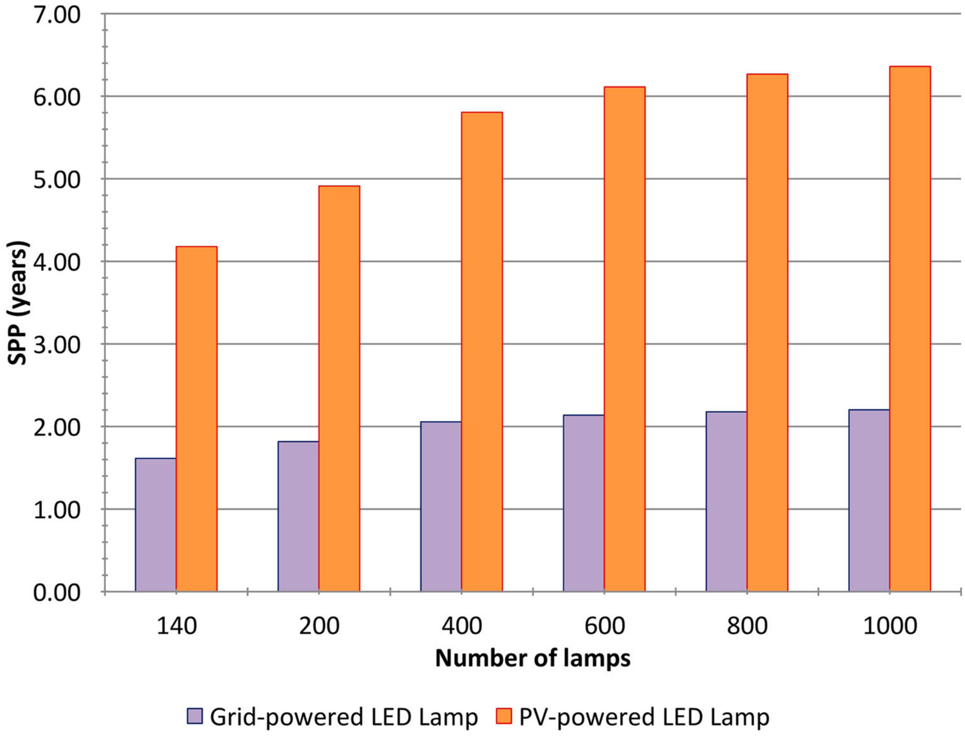

Figure 4: Sensitivity analysis of SPP with number of lamps.

example, research on solar street light maintenance decisions based on multi-criteria decision-making (MCDM) which involves key stakeholders (facility managers, investor and government) needs to be carried out. Such a study would determine the most suitable maintenance strategy for street lighting facilities by considering the four main maintenance strategies (preventive, corrective, condition-based and predictive). The selection process will be based on sustainability criteria (economic, technical, social and environmental).

Conclusions

The techno-economic and environmental analysis of replacing the metal halide grid-powered street lighting system with a LED grid-powered and LED PV-powered street lighting system has been presented in this study.

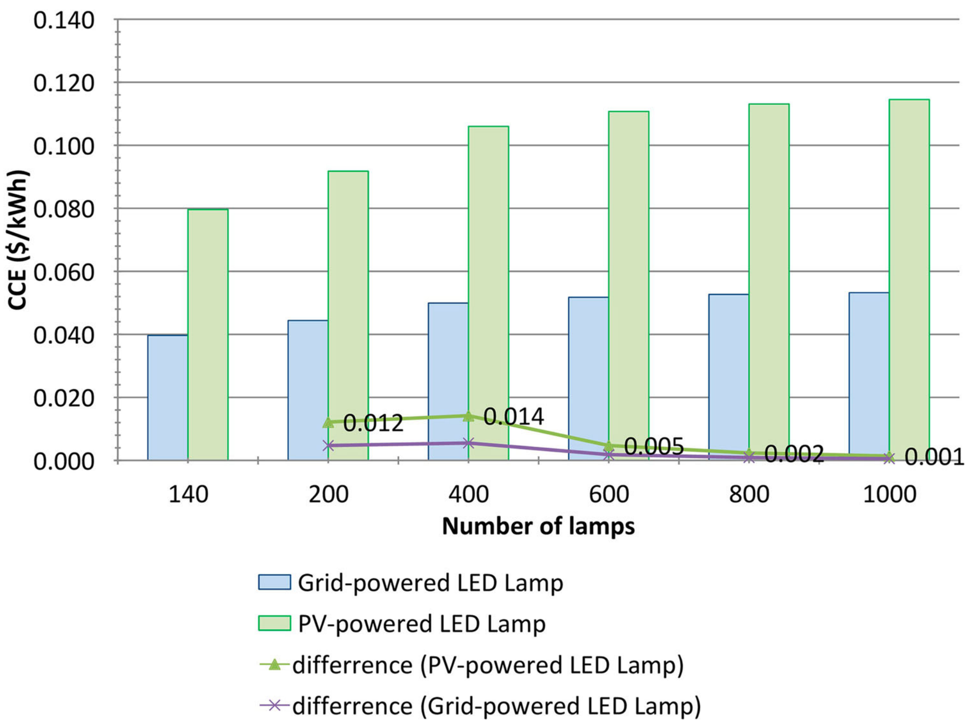

Figure 5: Sensitivity analysis of CCE with number of lamps.

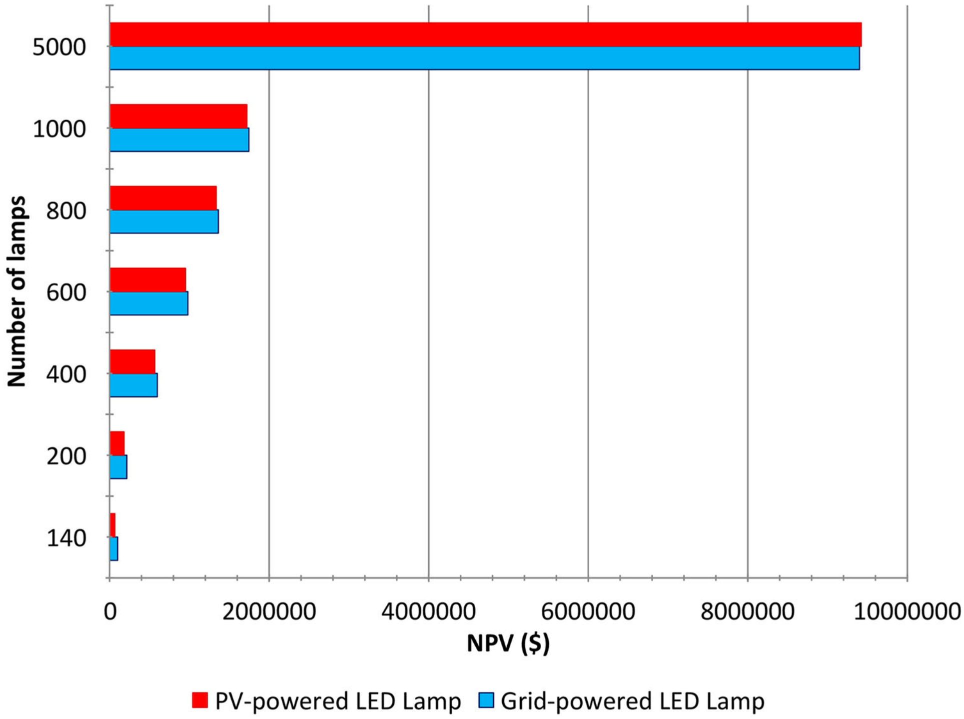

Figure 6: Sensitivity analysis of NPV with number of lamps.

The street lighting system at the University of Lagos, Nigeria was used as a case study. For the case study, the configuration of the system that will adequately serve the street light is 100 W LED lamps powered with 300Wp module and a 120Ah-24V battery. For the present case study, the costs of CCE for both grid-powered and PV-powered LED technologies are lower than the present tariff. Hence, they are both economical. Considering installation costs, the MH grid-powered technology installation ranks best followed by the grid-powered LED and then the PV-powered LED technology. This cost is compensated for by the quantity of energy saved and CO_2 reduction level by the LED solar-powered technology, thereby making it the best. From the sensitivity analysis, it is seen that the higher the number of lamps to be replaced, the higher the savings and NPV.

Furthermore, grid connected LED lamp technology showed a payback period of less than two years, while the payback period of the PV-powered LED lamp technology is 4.2 years. Based on the results obtained, utilization of PV-powered LED technology for street lighting of the university community was energy efficient. The PV-powered LED lighting system achieved 80% savings in energy consumption. However, initial costs are approximately 52% higher than those of the grid-powered metal halide technology currently utilized. The NPV for the PV-powered LED lighting configuration is $65,883. Annual oil equivalent savings of about 307 tonnes is achievable through the use of PV-powered LED. This study serves as a pivotal study for policymakers in making informed choices to enhance sustainable street lighting systems utilizing a combination of energy-efficient lighting technology and standalone PV systems. This study emphasizes the possibilities of the penetration of renewable energy sources in street lighting. It also shows that the carbon footprint can be reduced using RES and energy-efficient lamps. In the meantime, this study is a further contribution to the potential of renewable energy systems and energy efficiency as means of improving electricity supply and reducing energy consumption without resulting in huge economic cost differences or environmental degradation.

Acknowledgements
The authors thank the University of Lagos for the conducive environment and information provided during the survey.

Conflict of interest

The main author and all co-authors (listed as authors) met authorship criteria and certify that they have participated sufficiently in the work to take public responsibility for the content, and participation in the concept, design, analysis, writing, or revision of the manuscript. Furthermore, each author certifies that this material or similar material has not been and will not be submitted to or published in any other publication.

ORCID
M. O. Babatunde http://orcid.org/0000-0001-6533-7171
T. O. Akinbulire http://orcid.org/0000-0003-0747-7023
P. O. Oluseyi http://orcid.org/0000-0002-1164-7630
M. U. Emezirinwune http://orcid.org/0000-0001-6601-6337

References

Abolarin, S. M., A. O. Gbadegesin, M. B. Shitta, A. Yussuff, C. A. Eguma, L. Ehwerhemuepha, and O. Adegbenro. 2013. "A Collective Approach to Reducing Carbon Dioxide Emission: A Case Study of Four University of Lagos Halls of

Residence." *Energy and Buildings* 61: 318–322. doi:10.1016/j.enbuild.2013.02.041.

Adam, Aminu Dankaka, and Gokhan Apaydin. 2016. "Grid Connected Solar Photovoltaic System as a Tool for Green House Gas Emission Reduction in Turkey." *Renewable and Sustainable Energy Reviews* 53: 1086–1091.

Agbonkhese, O., G. L. Yisa, E. G. Agbonkhese, D. O. Akanbi, E. O. Aka, and E. B. Mondigha. 2013. "Road Traffic Accidents in Nigeria: Causes and Preventive Measures." *Civil and Environmental Research* 13: 90–99.

Ajayi, Oluseyi O., and O. D. Ohijeagbon. 2017. "Feasibility and Techno-Economic Assessment of Stand-Alone and Hybrid RE for Rural Electrification in Selected Sites of South Eastern Nigeria." *International Jouranl of Ambient Energy* 38 (1): 56–68. doi:10.1080/01430750.2015.1035799.

Akinboro, F. G., L. A. Adejumobi, and V. Makinde. 2012. "Solar Energy Installation in Nigeria: Observations, Prospect, Problems and Solution." *Transnational Journal of Science and Technology* 2 (4): 73–84.

Akinbulire, Tolulope O., Peter Olabisi Oluseyi, and Olubayo Moses Babatunde. 2014. "Techno-Economic and Environmental Evaluation of Demand Side Management Techniques for Rural Electrification in Ibadan, Nigeria." *International Journal of Energy and Environmental Engineering*. doi:10.1007/s40095-014-0132-2.

Akinyele, D. O., and R. K. Rayudu. 2016a. "Comprehensive Techno-Economic and Environmental Impact Study of a Localised Photovoltaic Power System (PPS) for off-Grid Communities." *Energy Conversion and Management* 124: 266–279.

Akinyele, D. O., and R. K. Rayudu. 2016b. "Community-Based Hybrid Electricity Supply System: A Practical and Comparative Approach." *Applied Energy* 171: 608–628. doi:10.1016/j.apenergy.2016.03.031.

Akinyele, D. O., and R. K. Rayudu. 2016c. "Strategy for Developing Energy Systems for Remote Communities: Insights to Best Practices and Sustainability." *Sustainable Energy Technologies and Assessments* 16: 106–127. doi:10.1016/j.seta.2016.05.001.

Akinyele, D. O., R. K. Rayudu, and N. K. C. Nair. 2015. "Development of Photovoltaic Power Plant for Remote Residential Applications: The Socio-Technical and Economic Perspectives." *Applied Energy* 155: 131–149. doi:10.1016/j.apenergy.2015.05.091.

Ayodele, Raphael. 2016. "Feasibility Study of Stand-Alone Hybrid Energy System for Rural Electrification in Nigeria: The Case Study of Ala-Ajagbusi Community." no. February.

Babatunde, O., Akinyele, D., Akinbulire, T., and Oluseyi, P. 2018. "Evaluation of a Grid-independent Solar Photovoltaic System for Primary Health Centres (PHCs) in Developing Countries." *Renewable Energy Focus* 24: 16–27.

Babatunde, Olubayo M., Peter O. Oluseyi, Tolulope O. Akinbulire, Henry I. Denwigwe, and Tolulope J. Akin-Adeniyi. 2018. "The Role of Demand-Side Management in Carbon Footprint Reduction in Modern Energy Services for Rural Health Clinics." In *Environmental Carbon Footprints*, 317–363. Oxford, United Kingdom: Elsevier.

Bowlin, D. O., D. J. Martin, and D. F. Scott. 1990. *Guide to Financial Analysis*. 2nd ed. New York: McGraw-Hill.

British Petroleum. 2017. *BP Statistical Review of World Energy*. London: British Petroleum.

Dazhi, Yang, Panida Jirutitijaroen, and Wilfred M. Walsh. 2012. "Hourly Solar Irradiance Time Series Forecasting Using Cloud Cover Index." *Solar Energy* 86 (12): 3531–3543. doi:10.1016/j.solener.2012.07.029.

Dixion, R. 1994. *Investment Appraisal—A Guide for Managers*. Revised ed. London: Kogan.

Dizqah, Arash M., Alireza Maheri, and Krishna Busawon. 2012. "An Assessment of Solar Irradiance Stochastic Model for the UK." no. 2: 670–675.

Farris, Paul W., Neil Bendle, Phillip Pfeifer, and David Reibstein. 2010. *Marketing Metrics: The Definitive Guide to Measuring Marketing Performance*. Upper Saddle River, New Jersey: Pearson Education.

Hall, Kenneth L. 2013. "Out of Sight, Out of Mind 2012: An Updated Study on the Undergrounding of Overhead Power Lines." Washington, DC: Hall Energy Consulting. Prepared for the Edison Electric Institute.

Humphreys, Colin J. 2008. "Solid-State Lighting." *MRS Bulletin* 33 (4): 459–470.

IIEC (International Institute for Energy Conservation). 2015. "Energy Efficiency Guidelines for Street Lighting in the Pacific- Promoting Energy Efficiency in the Pacific (Phase 2)." Bangkok.

Jeremy, Lagorse, Damien Paire, and Abdellatif Miraoui. 2009. "Sizing Optimization of a Stand-Alone Street Lighting System Powered by a Hybrid System Using Fuel Cell, PV and Battery." *Renewable Energy* 34 (3): 683–691.

Leena, Tähkämö, Anne Ylinen, Marjukka Puolakka, and Liisa Halonen. 2012. "Life Cycle Cost Analysis of Three Renewed Street Lighting Installations in Finland." *The International Journal of Life Cycle Assessment* 17 (2): 154–164.

Masoud, Mahmoud I. 2015. "Street Lighting Using Solar Powered LED Light Technology: Sultan Qaboos University Case Study." In *IEEE 8th GCC Conference and Exhibition (GCCCE)*. Muscat, Oman.

Mills, Evan, and Mary Ann Piette. 1993. "Advanced Energy-Efficient Lighting Systems: Progress and Potential." *Energy* 18 (2): 75–97.

Monroy, Carlos Rodriguez, and Antonio San Segundo Hernández. 2008. "Strengthening Financial Innovation in Energy Supply Projects for Rural Exploitations in Developing Countries." *Renewable and Sustainable Energy Reviews* 12 (7): 1928–1943.

Murray, I. J., S. Plainis, K. Chauhan, and W. N. Charman. 1998. "Road Traffic Accidents: The Impact of Lighting." *Lighting Journal* 63 (3): 42–43.

New York City Global Partners. 2009. "Best Practice: LED Street Lighting Energy and Efficiency Program." Los Angeles.

Nunoo, S., Attachie, J. C. and Abraham, C. K. 2010, September. "Using Solar Power as an Alternative Source of Electrical Energy for Street Lighting in Ghana." In *2010 IEEE Conference on Innovative Technologies for an Efficient and Reliable Electricity Supply*, 467–471. Tarkwa Ghana: IEEE.

Ohunakin, Olayinka S., Muyiwa S. Adaramola, Olanrewaju M. Oyewola, and Richard O. Fagbenle. 2014. "Solar Energy Applications and Development in Nigeria: Drivers and Barriers." *Renewable and Sustainable Energy Reviews* 32: 294–301.

Olatomiwa, Lanre, Saad Mekhilef, A. S. N. Huda, and Olayinka S. Ohunakin. 2015. "Economic Evaluation of Hybrid Energy Systems for Rural Electri Fi Cation in Six Geo-Political Zones of Nigeria." *Renewable Energy* 83: 435–446. doi:10.1016/j.renene.2015.04.057.

Owens, D. Alfred, Joanne M. Wood, and Ustin M. Owens. 2007. "Effects of Age and Illumination on Night Driving: A Road Test." *Human Factors: The Journal of the Human Factors and Ergonomics Society* 49 (6): 1115–1131.

Pogue, Michael. 2004. "Investment Appraisal: A New Approach." *Managerial Auditing Journal* 19 (4): 565–569.

Premium Times. 2016. "Abuja Residents Lament Poor State of Traffic Street Lights." https://www.premiumtimesng.com/news/top-news/212320-abuja-residents-lament-poor-state-traffic-street-lights.html.

Road Lighting Part 2: Performance Requirements. 2003. United Kingdom.

Rosenfeld, Arthur, Celina Atkinson, Jonathan Koomey, Alan Meier, Robert J. Mowris, and Lynn Price. 1993. "Conserved Energy Supply Curves for US Buildings." *Contemporary Economic Policy* 11 (1): 45–68.

Schreuder, D. A. 1988. "Relationship between the Level of Public Lighting and Traffic Safety: A Supplementary

Review of the Literature." National Technical Information Service Report number R-88-10. Washington DC: The National Academies of Sciences, Engineering, and Medicine. https://trid.trb.org/view.aspx?id=310437.

Stefano, J. D. 2000. "Energy Efficiency and the Environment: The Potential for Energy Efficient Lighting to Save Energy and Reduce Carbon Dioxide Emissions at Melbourne University, Australia." *Energy* 25: 823–839.

Ward, H., N. Shepherd, S. Robertson, and M. Thomas. 2005. "Night-Time Accidents: A Scoping Study. Report to the AA Motoring Trust and Rees Jeffreys Road Fund." London: Centre for Transport Studies, UCL (University College London).

Willis, K., N. Powe, and G. Garrod. 2003. "The Value of Improved Street Lighting in Rural Areas." Newcastle.

Wu, M. S., H. H. Huang, B. J. Huang, C. W. Tang, and C. W. Cheng. 2009. "Economic Feasibility of Solar-Powered Led Roadway Lighting." *Renewable Energy* 34 (8): 1934–1938. doi:10.1016/j.renene.2008.12.026.

Appendix A

Conversion factors (Babatunde et al. 2018; British Petroleum 2017)

1 kW = 1000 W

12,000 kWh = 1 tonne of oil equivalent

1 l = 2.68×10^{-3} tonnes of CO_2

1 kWh = 1.25×10^{-3} tonnes of CO_2