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Project Planning Analysis of an Off-Grid Photovoltaic Power System Development for the Ikeja Suburb of Metropolitan Lagos, Nigeria

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ABSTRACT

The study examined project-planning parameters for rooftop-based off-grid photovoltaic (PV) energy generation in Ikeja, Metropolitan Lagos using energy planning and analysis methodology. The study determined predominance of small-roof types (97%), with highest orientation from the North between 45 – 90o and rooftop slopes less than 15o (65%). Balance of System analysis showed that inverter capacities (24 – 480 V), required 11.85 – 1848.9 m2 roof areas, 7 – 1154 solar panels, 4 – 52 200AH batteries, 2 – 500 kVA in inverter sizes, and producing 1.11 – 173.5 kVA of power. The PV System's Levelised Costs of Energy (LCOE) and Social Costs of Energy (SCOE) were ₦ 42.42 – 108.12/kWh and 0 N/kWh respectively, much lower than alternative petrol- and diesel-generation systems (LCOE: ₦ 113.40 and ₦ 87.85/kWh respectively; SCOE: ₦ 123 – 282.10 and ₦ 109.73 – 494.38/kWh respectively). The solar supply curves indicate that subsidies would be required the least when carbon costs are the highest. The study showed that the off-grid PV power generation option was techno-economically viable.

KEYWORDS

Off-grid
Project planning
Photovoltaic
Power generation
Energy
Techno-economic
Levelised and social costs

1. INTRODUCTION

Electricity is indispensable to modern life as the infrastructure required to sustain civilized life (transport, healthcare, food, telecoms, entertainment systems, etc) are dependent on electric power supply (Hopf *et al*., 2017; Amelang, 2018; Cilliers and Nyoka, 2018; EIA, 2020). For every modern economy or civilization, adequate power supply is imperative for fulfilled living, and electricity availability is a key indicator of human development (EIA, 2020; Elavarasan *et al*., 2021). Global electricity generation is heavily dependent on non-renewable energy sources; nevertheless, renewables accounted for an estimated 28% of global electricity generation in 2020 (Amelang, 2018; EIA, 2020; Elavarasan *et al*., 2021). Global investment in renewables as an electricity power source is on the rise, with many countries in Europe, Asia and the Americas incorporating off-grid renewable systems (like photovoltaic (PV) infrastructure) for sustainable electricity generation (Mohammed *et al*., 2017; Amelang, 2018; EIA, 2020; Elavarasan *et al*., 2021).

In spite of the large inroads made by renewables in the electricity mix of the developed nations, the same cannot be said for developing nations such as Nigeria (Mohammed *et al*., 2017; Ogundari *et al*., 2017; Ogundari *et al*., 2020). The viability of national infrastructural projects, especially in energy generation, depends not only on technical feasibility but on economic, social and political considerations among others (Mohammed *et al*., 2017; Ogundari *et al*., 2017; Ogundari *et al*., 2020). The ways and manner in which the Federal and State governments in Nigeria address the critical issue of electric power delivery in the country, especially the provisions for renewables in the national energy mix, has been cause of great concern over the years since independence (Sambo, 2008; Akinbami and Momodu, 2012; Adenikinju, 2017; Ogundari *et al*., 2017; Ogundari *et al*., 2020). Nigeria, although energy resource-rich, exhibits a national electric power system with enormous power supply deficits (Adenikinju, 2017; Ogundari *et al*., 2020). The national power infrastructure is dominated by gas-powered thermal plants (7 Thermal and 3 Hydro generation stations) and has estimated total installed, transmission and distribution capacities of 12.5, 5.3, and 7.2 GW respectively (Adenikinju, 2017; Ogundari *et al*., 2020). Actual generated, transmitted and distributed electricity were estimated to be 3.9, 3.6 and 3.1 GW respectively (Adenikinju, 2017; Ogundari *et al*., 2020). With only 40% national grid connectivity in Nigeria, average daily power supply is estimated to be four hours, and power supply is at best erratic (Adenikinju, 2017; Ogundari *et al*., 2017; Ogundari *et al*., 2020). The residential sector accounts for 59.6% of national electricity consumption with the commercial and industrial sectors accounting for 30.4 and 10% respectively (Adenikinju, 2017; Ogundari *et al*., 2017; Ogundari *et al*., 2020). In Nigeria, like many developing countries, renewables share of national electricity generation is very low; specifically, as at 2019, it was only 25% – coming strictly from hydro and marine sources and indicating that solar power contribution was statistically zero (Caleb *et al*., 2018; Ogundari and Otuyemi, 2019; Salu, 2021). In spite of the Nigerian Electricity Regulatory Commission (NERC) commitment to stimulating investment in renewable energy generation in Nigeria, the set target of generating a minimum of 2,000 MW of electricity from national (vast and mostly untapped) potential in renewable energy resources by 2020 has been unattainable (Caleb *et al*., 2018; Ogundari and Otuyemi, 2019; Salu, 2021). Nigeria's power supply limitations are due to organizational failures, inadequate financing, energy infrastructure attacks and theft/fraud, and out-dated equipment/technologies usage worsened by rapid population growth, weakening public infrastructure and institutions, public/private power generation conflicts, and limited power infrastructure planning and development capabilities (Atkins Limited, 2014; Ventures Africa, 2014; Onochie, *et al*., 2015; PwC, 2016; Ugwuanyi, 2018; Arowolo *et al*., 2019; USAID, 2020). Limitations in grid power supply in Nigeria are a factor in the huge domestic shift to off-grid power generation from environmentally-hazardous petrol/diesel generators (Atkins Limited, 2014; Arowolo *et al*., 2019; FGN, 2018; EIA, 2020).

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The Lagos State scenario is a reflection of Nigeria (Ventures Africa, 2014; USAID, 2020; Ehingbeti, 2021)]. In spite of being Nigeria's economic livewire (30% of national total GDP, 90% of Nigeria's foreign trade and 70% of all industrial investments) with a Gross Domestic Product (GDP) of $136.6 billion, 40% of residents are off the national grid and 80% of them depend on petrol/diesel generators (MEPB, 2013; MEPB, 2015; Lagos State Government, 2018). Although State electricity demand is almost 10,000 MW, grid supply is only 1,000 MW (MEPB, 2013; MEPB, 2015; Lagos State Government, 2018).

National and State electric sector reforms, including the Electric Sector Reform Act (2005) and the Lagos State Electric Power Sector Reform Law (2018) establishing the Lagos State Infrastructural Development Initiative and the State Embedded Power Programme (EPP) have empowered decentralised public and private investment in critical electric power infrastructure (including off-grid photovoltaic systems) for regional/national development (MEPB, 2015; Caleb *et al.*, 2018; FGN, 2018; Ugwuanyi, 2018; Arowolo *et al.*, 2019; Ogundari *et al.*, 2020; USAID, 2020; Ehingbeti, 2021; Salu, 2021).

The Lagos State Development Plan (LSDP) (2021-2025) advocates sustainable economic and industrial growth dependent on critical power infrastructure delivery (e.g. integrated power projects, off-grid alternative energy systems and mini-grid photovoltaic (PV) power plants) with an immediate strategic target of 3,000 MW-domestic electricity generation by 2023 and upper-limit of 27,000 MW of new electric generation capacity by 2030 entailing almost $33 billion in energy generation investment (Caleb *et al.*, 2018; Ogundari *et al.*, 2020; USAID, 2020; Salu, 2021). The mini-grid PV power system – a self-sufficient energy system that supplies electricity to a localised group of customers and operates in isolation from the national transmission network – is considered appropriate intervention technology due to the abundance and supply reliability of sunlight in Lagos State, the relatively affordability of the equipment, its cleaner environmental performance relative to petrol/diesel generators, and its significant potential for employment and wealth creation (Caleb *et al.*, 2018; Salu, 2021). The establishment of PV power plants in Lagos suburbs face the challenges of availability and cost of land in a highly urbanised and densely populated place (Caleb *et al.*, 2018; Salu, 2021). Rooftop installations thus represent a means of avoiding the cost and availability challenge of land-based installations (Caleb *et al.*, 2018; Salu, 2021).

The adoption of this mini-grid PV alternative power system in the residential areas of Metropolitan Lagos has been impeded by the ineffectual project planning and implementation of the alternative power infrastructure by State and private sector actors. Thus, this study provides a strategic project planning/implementation assessment of the mini-grid PV alternative power infrastructure in Metropolitan Lagos using the Ikeja suburb as a case study. Specifically, the study would determine the technical and economic specifications for rooftop-based distributed photovoltaic (PV) energy generation in the study area as strategic policy intelligence for the Embedded Power Programme of the Lagos State government in particular and the Federal Government in general.

1.1. Overview of Ikeja, Lagos State

According to the Lagos State Government, 2018 and the Lagos State Ministry of Economic Planning and Budget (MEPB, 2015), Ikeja is a suburb of Lagos City (located about 17 km northwest of the City) and the capital of Lagos State. Ikeja's central location in the State and proximity to Lagos City (the business capital of Nigeria) grants it strategic positioning to stimulate business and enables it offer middle- and high-end urban living and suitable residential areas. With defining structures like the popular, large computer and computer accessories hub known as computer village and the Muritala Mohammed International Airport, technology-based business opportunities incorporate the Information and Communication Technology (ICT), Aviation, Energy, Finance & Marketing sectors amongst others. Business districts include Oregun, Agidingbi, Magodo, Ogba, Maryland, Opebi, Akiode and Alausa. The city, like the rest of Nigeria has a large electricity deficit, resulting in widespread use of diesel and petrol generators to meet industrial and residential needs, and thus a stimulating market for PV power technologies.

2. METHODOLOGY

Melius *et al.* (2013) identified three generally accepted methods of determining solar PV rooftop potential from the literature. These methods are:

i. Constant-value: A value pre-determined from the literature or empirically is assumed as the percentage of rooftop area suitable for solar installations. A variety of sources have arrived at the suitability values of 22% to 27% for residential structures (Chaudhari *et al.*, 2004; Denholm and Margolis, 2008) and 60% to 65% for commercial structures (Frantzis *et al.*, 2007; Paidipati *et al.*, 2008). This method adopts a one size fits all to each of the two identified building types (residential and commercial). Whilst relatively quick and easy to use, this method involves generalizations which ignore the specifics of individual structures.
ii. Manual selection: This method involves the use of aerial photographs or Google Earth images of individual structures to determine rooftop suitability area. It is very accurate and gives building specific estimates incorporating virtually all variables such as building orientation, rooftop tilt and shading area. It is however only suitable for individual buildings and not easily amenable to rapid, large-scale deployments.
iii. LIDAR/GIS-based methodology: This method involves the use of LIDAR (Light Detection and Ranging) technology derived data in a GIS (Geographic Information System) environment. This method is more detailed than the constant value method whilst being capable of handling much larger number of buildings than the manual method.

In this study, the constant value and manual selection methods were used. This study entailed using an energy planning and project foresight analysis framework consisting of three sections (Brown *et al.*, 2015; Gagnon *et al.*, 2016):

i. Section 1 – the determination of the rooftop-based PV potential;
ii. Section 2 – the determination of the PV system design based on Section 1; and
iii. Section 3 – the determination of the economic viability of the PV system design

2.1. The Determination of the Rooftop-based PV Potential

Five years' worth of daily solar irradiance data were obtained from a Nigerian Meteorological Agency (NiMet) station in Ikeja. The available rooftop area for solar panel deployment was obtained from a 0.8m-resolution satellite image of Ikeja downloaded using the Universal Map Downloader (UMD) software. This satellite image was first geo-referenced and digitised. The surface area and GPS coordinate of each identified roof was then exported from the ARCGIS database into the Microsoft excel spreadsheet environment. For the determination of the effective rooftop area, a combination of the constant value and manual method was utilized. The assumptions of the constant value method are presented in Table 1, while the equation for the manual method is presented as Eqn. 1. Ground-truth analysis process was used to determine the suitable sample size from the identified rooftop population.

$$\text{Effective Rooftop Area} = 0.5 \times 0.8 \times 0.4 \times \text{Actual Rooftop Area} \tag{1}$$

Table 1: Assumptions of the Constant Value Method

Metric	Assigned Value	Rationale
Roof Morphology	0.5	Most common roof form factor
Panel Shading Factor	0.8	Industry standard
Roof Structural Integrity Allowance and shading from trees and adjacent structures	0.4	Conservative estimate

Ground-truth analysis process: Typical satellite images are captured when the satellite is directly overhead, resulting in a plan view image that is essentially flat. To correct for this underestimation of actual roof area, a ground-truth analysis was carried out on several randomly selected buildings determined using the Yamani formula (Eqn. 2) for determining a suitable sample size from a known population.

$$n = \frac{N}{1+N(e^2)} \tag{2}$$

where n is the sample size, N is the known population size, e is the confidence level (usually 5%).

Field data collected included GPS coordinates and pictures of the buildings. Image analysis was carried out with the ImageJ image processing software. The satellite image shows the rooftops as planar, which give erroneous estimates for total roof area critical for PV installation. From the sampled buildings, a mapping of actual roof area was performed which when correlated with the corresponding planar satellite data resulted in the correctional regression equation (Eqn 3):

$$y = 1.1485x - 0.1768 \tag{3}$$

where x = satellite planar roof area, and y = corrected roof area.

2.2. The Determination of The PV System Design

Based on actual roof area per structure identified, the roof area photovoltaic (PV) generation capacity was determined. This entailed determination of total PV modules and charge controller demand per rooftop based on PV system design analysis (IFC, 2015). The determination of maximum value allowance for thermal and voltage limits of the module strings are shown in Eqns 4&5:

$$mVR = V_{oc(STC)} * 1.15 \tag{4}$$

$$CR = I_{sc(STC)} * 1.25 \tag{5}$$

where: mVR = minimum Voltage Rating, V_{oc} = open circuit voltage at Standard Test Conditions (STC), m_{CR} = minimum Current Rating, I_{sc} = short circuit current at STC.

The determination of maximum power transfer from the PV modules to the inverter entails (IFC, 2015):

$$V_{MPP\,(module)} * n_{min} > V_{MPP(inverter)} \tag{6}$$

where V_{MPP} (module) = Maximum Power point Voltage of PV modules, n_{min} = Minimum number modules in a string, VMPP (inverter) = Maximum Power point Voltage of inverter.

Sizing the PV system requires several parameters, namely, daylight hours, individual battery voltage (12 V), and system voltage. The total generation capacity within the hours of effective sunshine can be deduced by Eqn. 7:

$$Energy_{array} = w * h \tag{7}$$

where w = watts, and h = hours.

PV module energy generation, taking into consideration system efficiency:

$$E_g = \frac{P_{pv} * \eta R * \eta I * PSH}{sf} \tag{8}$$

where PPV = PV system Power, E_g = daily Electricity generation, PSH = Peak sun duration, sf = the safety factor (compensates for panel inefficiencies), nR = the charge controller efficiency, nI = the Inverter Efficiency.

Calculating for Inverters: In the inverter selection process, apart from matching voltages and power between the PV array and the inverter, the 'ac' part of the inverter must also be considered. The rule of thumb is to use an inverter-array power ratio less than unity. This sub-one power ratio helps to provide an additional buffer in case of PV output spikes. The IFC utilizes a range of 0.8-1.2 for the ratio of inverter to array power. Therefore, if 0.8 < powerratio < 1.2,

$$Power\ ratio = \frac{P_{inverter(input)}}{P_{pv}} \tag{9}$$

$$\eta_{100\%} = \frac{P_{inverter\,(output)}}{P_{inverter\,(input)}} \tag{10}$$

Calculating for Charge controllers: Charge controllers regulate the voltage and current from the PV panels. They protect the battery from overcharging/overheating thus prolonging battery life. Charge controllers often implement the Maximum PowerPoint Tracking scheme to regulate charging current. The most important selection criterion for the charge controller is that it must be able to handle the maximum current possible from the PV modules plus an additional buffer of about 30%. This can be expressed as:

$$charge\ controller\ rating = Array\ Current_{short\ circuit} * 1.3 \tag{11}$$

Calculating for Battery Size: In sizing batteries, effort must be made to prevent too deep a discharge of the battery array. It is not advisable to discharge a deep cycle battery beyond 50%. If this 50% threshold is selected for example, the implication for battery size is that the pv array should be able to fully recharge the battery bank within the specified number of daylight hours. Additionally, the system could be in use during the recharge period. Considering these, the battery will require 50% of pv capacity to recharge and the other 50% for day time load. If the battery is thus constrained to be discharged to half capacity, roughly the same load can be consistently powered throughout every 24-hour period.

Considering losses and a 40% depth of discharge:

$$\boldsymbol{C_{Ah} = \frac{Daysofautonomy * E_g}{V_B * DOD * \eta B * \eta I}} \tag{12}$$

where Days of autonomy refers to number of days of operation without sunlight (fraction of a day in the tropics), Eg = daily electricity consumption; CAh = the capacity of the battery bank (Ah); DOD = the depth of discharge of batteries; VB = the voltage of the battery bank; nB = the battery efficiency; nI = the Inverter Efficiency.

2.3. The Determination of the Economic Viability of the PV System Design

The economic analysis entailed using the following methods:

Life Cycle Cost Analysis (LCCA): an economic method of project evaluation in which all costs arising from owning, operating, maintaining and ultimately disposing of a project during its lifecycle are considered to be potentially important to that decision (Fuller and Petersen, 1995).

$$LCC = \sum_{t=0}^{N} \frac{C_t}{(1+r)^t} \tag{13}$$

$$C_t = Capital\ cost + Recurring\ costs + Salvage\ cost \quad (14)$$

where N = Project Life span, R= interest rate.

Levelised Cost of Electricity (LCOE): the ratio of lifetime costs to lifetime electricity generation, both discounted to a common year using a discount rate that captures the cost of finance (in our case, the Weighted Average Cost of Capital or WACC). This means the LCOE is the minimum price at which electricity generated must be sold to break even (NREL, 2018).

$$LCOE = \frac{\sum_{t=0}^{N} \frac{C_t}{(1+r)^t}}{\sum_{t=1}^{N} \frac{E_t}{(1+r)^t}} \quad (15)$$

where r = the WACC (in the case of this study this is 11% as defined by NERC), and N = the investment life.

Society Cost Electricity (SCOE): used to obtain a more realistic estimate of which electricity generation technologies would most benefit Nigerian society. SCOE is based on all costs and benefits to society as a whole including environmental and social externalities

Externalities refer to situations when the effect of production or consumption of goods and services imposes costs or benefits on others which are not reflected in the prices charged for the goods or services being produced (Medina-Mijangos *et al.*, 2021). Pollution is an example of a negative externality (also termed external diseconomy), while a dam, constructed for the purpose of generating electricity might be useful for irrigation purposes or freeing up up-stream land for agriculture, may be considered an example of a positive externality (or external economy). As a result of negative externalities, the manufacturer's break-even costs are often lower than the product's social costs. (Gönenç, *et al.* 2001).

Unlike the LCOE, SCOE is not a well-defined metric; SCOE builds on LCOE, adding quantitative estimates of the costs of the externalities. SCOE calculations improve with more data provided.

SCOE values for Nigeria were calculated as follows:

$$\text{SCOE} = \text{LCOE} + \text{cost of climate change damage} + \text{cost of air pollution damage} + \text{system integration costs} \quad (16)$$

For PV systems, costs of climate change and environmental pollution are zero as there are no greenhouse gas (GHG) emissions. Furthermore, as the PV design is essential off-grid, there are no integration costs, and Eqn. 16 simplifies to:

$$SCOE = LCOE \quad (17)$$

For grid, petrol and diesel power generation, which produce GHG emissions and by implication have climate and air pollution damage costs, Eqn. 16 becomes Eqn. 18 (since there are no system integration costs).

$$\text{SCOE} = \text{LCOE} + \text{cost of climate change damage} + \text{cost of air pollution damage} \quad (18)$$

Estimates of the cost of carbon and other pollutants vary widely in the literature. Three levels were selected from the literature with L1 having representative values of the lower bound of pollution cost estimates. Similarly, L2 and L3 have representative values of the medium and highest bounds of carbon and pollution costs. Table 2 shows these levels and their representative values.

Project Cost Template: Components were selected from recognized lists of suppliers and products registered for large scale utility projects. An estimate of the required initial investment was thus deduced for use in subsequent calculations of LCC, LCOE and SCOE based on various levels of carbon costs (Table 2).

Table 2: Carbon Costing Template

Level	Carbon Cost (\$/tnC)	Prognosis	Sources
L1	40	Optimistic	Frantzis *et al.*, 2007; Paidipati *et al.*, 2008
L2	104	Moderate	Brown *et al.*, 2015; Gagnon *et al.*, 2016
L3	446	Pessimistic	Paidipati *et al.*, 2008; Brown *et al.*, 2015

3. RESULTS

This section presents the results of the study.

3.1. Satellite Image of Ikeja obtained from Universal Map Downloader (UMD) Software

Plate 1 shows a portion of the satellite image of Ikeja as obtained from the Universal Map Downloader (UMD) software, while Plate 2 shows the digitized image of Plate 1. A total of 31,564 individual roof areas were identified and digitized in these Plates, giving total area of 9.68 Sq. Km.

Plate 1: Screenshot of a portion of the satellite image of Ikeja

Plate 2: Screenshot of a portion of the digitized image of Ikeja

The effective rooftop area was determined as follow

$$Effective\ Rooftop\ Area = 0.5 \times 0.8 \times 0.4 \times Actual\ Rooftop\ Area$$

$$Effective\ Rooftop\ Area = 0.5 \times 0.8 \times 0.4 \times 9.68\ Sq.Km = 1.54\ \text{Sq. Km}$$

The ground-truth analysis to determine suitable sample size from the known population of 31,564 individual roof areas for the determination of the correctional regression equation showed:

$$n = \frac{N}{1+N(e^2)}$$

where n is the sample size, N is the known population size, e is the confidence level (usually 5%).

$$n = \frac{31{,}564}{1+[31{,}564(0.05^2)]} = \frac{31{,}564}{79.91} = 395 \text{ buildings}$$

Thus 395 buildings were determined as the suitable sample size.

3.2. Characteristics of Sampled Building Rooftops in the Ikeja Area

From Table 3, it can be seen that most of the rooftops in the Ikeja Zone of Lagos Metropolitan Area may be considered Small (effective rooftop area of less than 1000 m^2) (97%). This infers that most buildings are situated within one plot of land, and may be considered to be residential or small commercial buildings. As Ikeja is in the northern hemisphere, for maximum PV energy generation, solar panels should face true South [Ventures Africa, 2014; USAID, 2020]. The orientation of the buildings as shown in Table 3 shows that none of the buildings meet this criterion. This infers those residential buildings in the area were not built with the plan to generate PV energy in mind. This might require PV panels' installation to be executed at different angles and positions to maximize PV energy generation. Interestingly, the roof slope data show that 65% of the buildings have roof slope less than 15°, and a further 20% have roof slope between 15° and 25°. This shows that a huge percentage (85%) of the buildings in Ikeja Area have roof slope angles less than 25°. This would indicate that the roofs were close to being horizontal, and should ideally create a potential to maximize roof area for PV energy development. The reality is that this predominant rooftop slope was implemented, not for PV energy development, but consequent to homeowners trying to reduce the cost of roof construction as much as possible.

Table 3: Analyses of Rooftops of Sampled Buildings in the Ikeja Area

Parameter	Percentage
Effective Area	%
Large > (5000 m2)	0.41%
Medium (1000 – 5000 m2)	2.3%
Small < (1000 m2)	97%
ORIENTATION (from North)	
orientation < 45o	6,785 (21.5%)
45o < orientation < 90o	9,224 (29.22%)
90o < orientation < 135o	6,985 (22.13%)
135o < orientation < 180o	8,571 (27.15%)
ROOF SLOPE	
slope < 15o	(65%)
15o < slope < 25o	(20%)
slope > 25o	(15%)

3.2.1. *Estimated PV Power Systems Capacities for the 5 Roof Area Groupings*

Utilising the calculated system sizes grouped into five readily available inverter capacities in the Nigerian market (24, 72, 120, 240 and 480 V), the average values of Balance of System (BOS) components (comprising average roof area, average number of solar panels, average number of 200AH batteries, average power and average inverter sizes) were determined (Table 4).

As depicted in Table 4, the 480V battery system size would be predicated on rooftops with average areas of 1848.9 m^2, requiring an average of 1154 solar panels and 52 200-AH batteries, and generating an estimated average power rating of 173.5 kVA which could be met by the acquisition of inverters with average size of 500 kVA. This procedure was repeated for the different PV system sizes across the BOS specifications.

Table 5 shows the different levelised and social costs of electricity generation for the different power systems available for Ikeja. The table shows that the grid system had the lowest LCOE for the various electricity systems at ₦29.05/kWh. The lowest LCOE for the photovoltaic system was ₦43.42/kWh for a 480V, 500kVA system. The Social costs of electricity at different levels showed that grid electricity generation had the lowest costs across the three levels (for conservative estimates (L1) it was ₦36.00/kWh, for medium estimates (L2) it was ₦47.80/kWh, and for pessimistic estimates (L3) it was ₦109.00/kWh).

Table 4. Estimated PV Power Systems Capacities for the 5 Roof Area Groupings

Average Roof Area (m^2)	Average Number of Solar Panels	Average Number of 200 AH Batteries	System Size (Volts)	Average Power (kVA)	Average Inverter Sizes (kVA)
1846.9	1154	52	480	173.5	500
237.72	148	15	240	23.29	100
69.78	44	7	120	6.54	10
36.04	22	6	72	3.38	5
11.85	7	4	24	1.11	2

The predicted balance of systems (BOS) costs for the Ikeja photovoltaic energy generation model (IPEGM) were plotted against a model from the National Renewable Energy Laboratory (NREL) of the US Department of Energy's Office of Energy Efficiency and Renewable Energy (Figure 7), and both plots can be seen to be closely aligned, suggesting the high accuracy of the BOS predictions. Several jumps (level changes) are however observed in the IPEGM curve which are being attributed to the boundaries of each group design in the roof area continuum.

Figure 8 shows the variation of the LCOE calculated for the IPEGM against their roof areas. The values are in log units to accommodate the large variations (from the very large to the very small) in values of both cost and roof area. The trend is downwards over time, showing that as the plant size and power (analogous to the roof area) reduces, the Levelised Cost of Electricity increases. This implies that smaller plants are less cost efficient when compared to larger plants, and a 2-kW plant would be expected to be more expensive, on a per kWh-basis, compared to a 20-kW plant.

The LCOE for the photovoltaic system was compared to the LCOEs of off-grid petrol and diesel generation technologies in the Nigerian market for the same household rooftops (Figure 9). The area "1" under the curve and bounded by the diesel price point on the right represents the region in which roof top solar is more profitable than operating a diesel power plant.

Table 5: Comparison Levelized and Social Costs of Electricity for Different Power Systems

	Photovoltaic					Grid	Petrol	Diesel
System Size	480V, 500 kVA	240V, 100 kVA	120V, 10 kVA	72V, 5kVA	24V, 2 kVA	Conservative Estimate @ $40/tonne Carbon		
	₦/kWh	₦/kWh	₦/kWh	₦/kWh	₦/kWh	₦/kWh	₦/kWh	₦/kWh
LCOE	43.42	65.48	77.30	69.30	108.12	29.05	113.40	87.85
SCOE: L1						36.00	123.33	109.73
						Medium Estimate @ $104/ tonne Carbon		
SCOE: L2						47.80	160.33	205.44
						Pessimistic Estimate @ $446/ tonne Carbon		
SCOE: L3						109.00	282.10	494.38

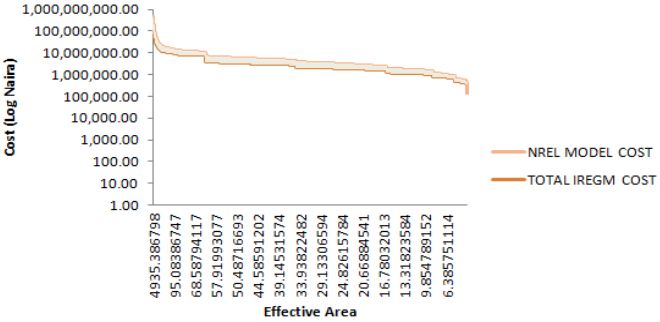

Figure 7: Cost trends of NREL and IPEG models

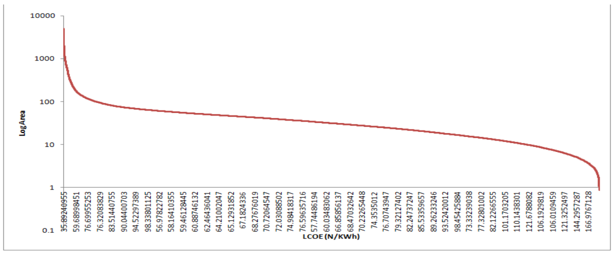

Figure 8: Variations of the LCOE of the IPEGM against their roof areas (Log)

The area "1"+"2" represents the region of rooftop solar profitability over and above operating a petrol generator. The region "2" on its own represents the difference in profitability between running diesel and petrol generators (diesel is more efficient in LCOE terms). In this region ("2"), diesel is more efficient than rooftop solar. Region "3" represents the region in which the rooftop solar is not profitable in comparison to both petrol and diesel.

Once the price of global warming and environmental pollution (Table 1) is factored into the LCOE to produce the SCOE, there is an immediate effect. The price points of the various technology options (grid, petrol and diesel) shift rightwards, indicating an increase in competitiveness of the solar option. Figure 10 shows the SCOE at $40/tn of Carbon. The grid price point is shifted such that the largest roof sizes within the study area become competitive. The petrol and diesel price points on the other hand are so much shifted to the right as to be virtually uncompetitive (with respect to roof top solar) along the larger part of the study area.

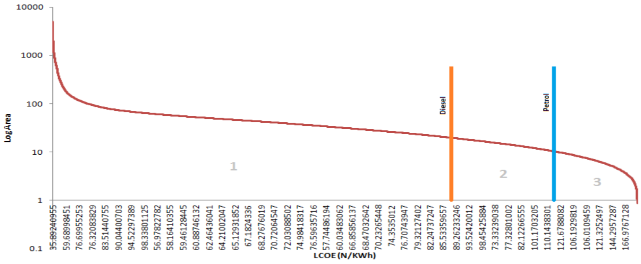

Figure 9: Comparison LCOEs for the PV system against the petrol and diesel systems

A more pessimistic view of the deleterious effect of carbon on the environment and humans is the L2 level for which a representative value of $104/tnC was adopted. At this level virtually all roof tops are more cost effective than both diesel and petrol power plants (Figure 11). Considering the same Figure, although the grid price point has shifted slightly rightwards; the grid option is still more cost effective than the vast majority of roof tops in the study area.

Thus, it is only when the most pessimistic view of the effect of carbon dioxide and other pollutants is considered that the roof top PV option becomes more viable than the grid. This conclusion is at odds with the literature which shows quite clearly that PV is more cost effective on the long run than grid electricity.

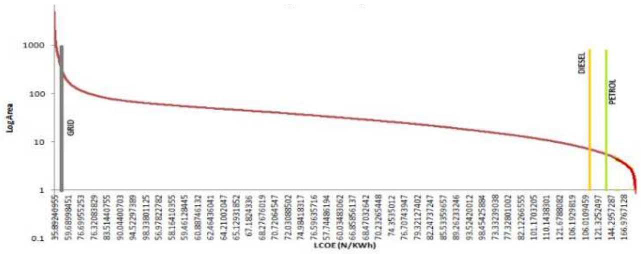

Figure 10: Plot of SCOE against roof area at $40/tn Carbon

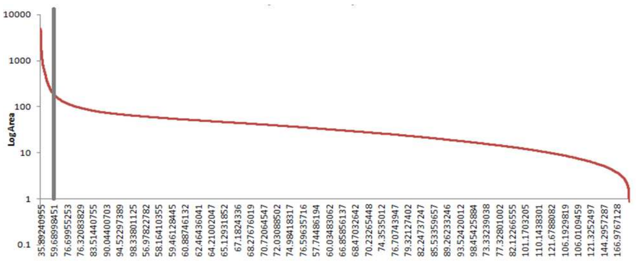

Figure 11: Plot of SCOE against roof area at $104/tn Carbon

It is only when the top echelon (L3) of environmental costs is applied that a significant shift is observed in the grid price point. At this level, the roof top solar is observed to be more cost effective than grid electricity (Figure 12).

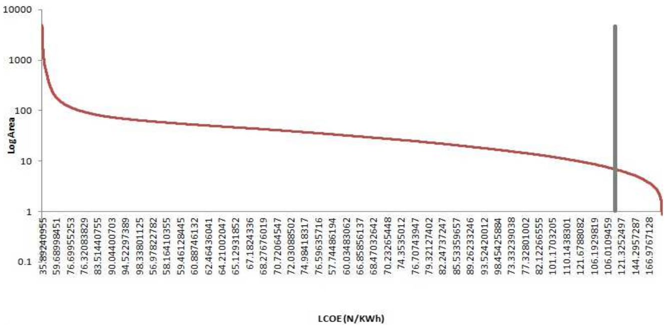

Figure 12: Plot of SCOE against roof area at $446/tn Carbon

Figures 13, 14, and 15 depict the solar supply curves or energy supplied at the specific LCOEs of $40, $104, and $446 per tonne of Carbon respectively. These correspond to Low (L1), Medium (L2) and High (L3) carbon and other pollutants' costs. Predictably, more energy can be supplied as LCOE increases. The curve is however asymptotic to the line OC. The fact that the supply curve is asymptotic to the line OC is a reflection of the fact that the number of structures is finite and so the power that can be generated is similarly finite. As the supply curve approaches the line OC therefore the energy generated cannot surpass the asymptote; as a result, the LCOE can only increase. The intersection of the Solar Supply Curve and the grid tariff or levelized cost of electricity of running a diesel or petrol generator represents the price point at which the solar becomes competitive with respect to the competing energy source. The results tally with previous results in that it is only at the L3 level of carbon and pollution cost that solar PV becomes competitive in comparison to the grid whilst at L1 level, the roof top PV is already comparable to diesel and petrol.

The figures show that as the price of carbon increases, the competitiveness of the rooftop solar supply rises relative to the grid and the petrol/diesel generation options. At the $ 104

/tonne of carbon level of subsidy, the petrol/diesel generation become more expensive than the solar supply option, while the grid is still cheaper than all these options. It is only at the $ 446/tonne level of carbon that grid price becomes comparable to about 40% of the roof generation, while being cheaper than both the petrol and diesel generation options.

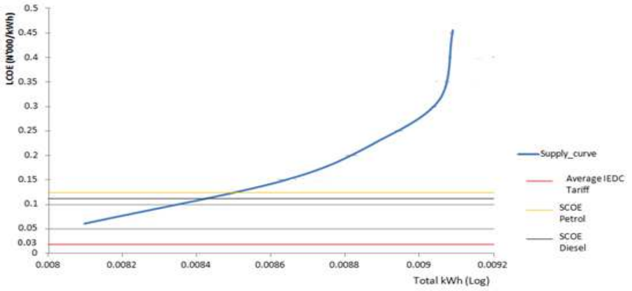

Figure 13: Solar supply curve at Low Carbon Cost of $40/tonne

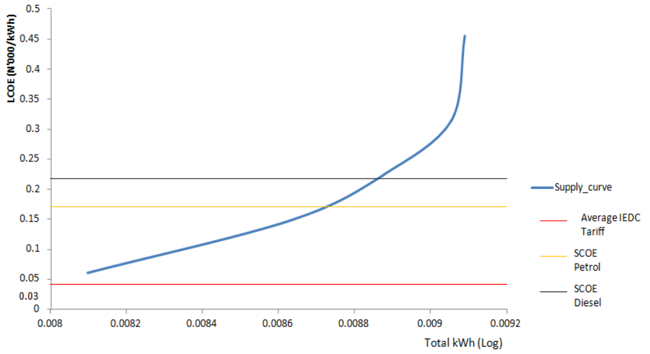

Figure 14: Solar supply curve at Medium Carbon Cost of $104/tonne

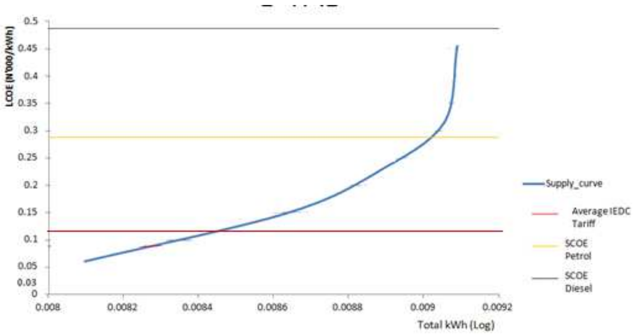

Figure 15: Solar supply curve at High Carbon Costs of $446/tonne

It is important to note that the provisions of subsidy by the Nigerian government on some energy forms distort the electricity market in several ways. Firstly, the subsidy on petroleum products in effect results in a government subsidisation of generator use. This unintended subsidy of petrol generator use makes petrol more competitive than it actually is with respect to solar PV. Apart from this, the Nigerian government subsidises grid electricity through the instrumentality of the MYTO. Socioeconomic and political factors inform the choice of government to expend trillions of naira on petroleum product prices and electric utility tariffs. Literature has shown that these subsidies are not sustainable [12]. Top-down policies such as taxation and punitive laws are difficult to apply on individual property owners if the intent is to encourage adoption of renewable energy resources. Thus, a removal of petroleum subsidies which unintentionally encourage the use of generators might lead to social unrest and an unintended knock-on effect on other key sectors of the economy which are dependent on these products; such as manufacturing and transportation.

4. SUMMARY AND CONCLUSION

The study examined the techno-economic specifications for rooftop-based off-grid photovoltaic (PV) energy generation in the Ikeja Area of Metropolitan Lagos. An energy planning and analysis methodology was used. The study determined predominance of small roof types (97%), with highest orientation from the North between 45 – 90° and rooftop slopes less than 15° (65%). The study further determined the average values of Balance of System (BOS) components (comprising average roof area, average number of solar panels, average number of 200AH batteries, average power and average inverter sizes) for the 5 roof area groupings based on the five readily available inverter capacities in the Nigerian market. This assessment revealed the range of inverter capacities (24 – 480 V), would require average roof areas of 11.85 – 1848.9 m^2, on average 7 – 1154 solar panels, requiring, on average 4 – 52 200AH batteries, producing averagely 1.11 – 173.5 kVA of power, demanding average inverter sizes of 2 – 500 kVA. The Levelised and Social Costs of Energy (LCOE and SCOE) for the PV system were 42.42 – 108.12 and 0 ₦/kWh respectively, much lower than alternative petrol- and diesel generation systems (LCOE: ₦ 113.40 and ₦ 87.85/kWh respectively; SCOE: ₦ 123 – 282.10 and ₦ 109.73 – 494.38/kWh respectively). The solar supply curves indicate that subsidies would be required the least when carbon costs are the highest. The study concluded that rooftop-based off-grid photovoltaic (PV) energy generation in Ikeja suburb of Metropolitan Lagos was technically and economically viable and appropriate for the Embedded Power Programme in Lagos State.

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