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Assessment of Roof Tilt and Building Azimuth for Off-Grid Photovoltaic Power for Buildings in Metropolitan Lagos, Nigeria

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Abstract— The study determined optimum roof tilt and building azimuth for rooftop-based distributed photovoltaic (PV) energy generation in Ikeja, Lagos State, Nigeria, as strategic technological input to alternative power generation and new housing development in Metropolitan Lagos. The energy planning & foresight analysis methodology was used. The data were obtained via literature, Global Positioning System (GPS) systems, energy models, and site visits and comprised manual and satellite imagery, dimensions, roof angles, and coordinates of the building structures in the study area (Rows between 0 – 60^{o}, Columns between 0 – 180^{o}; System sizes: 533 kW, 110 kW, and 0.547 kW). The results showed solar array yield varied from 768,944 kWh per annum for a 500 kVA system to 780 kWh per annum for a 0.5 kVA system. A five-tier rooftop generation template of 245 MWp was consequently developed. The systems ' optimal roof tilt and building azimuth angles were estimated to be 5^{o} and $180^{o,}$ respectively, though combinations of azimuth and tilt angles not exceeding 30^{o} tilt and 90^{o} azimuth gave acceptable yields. The study concluded that the optimum roof tilt and building azimuth for rooftop-based distributed photovoltaic (PV) energy generation in the study area were strategic policy intelligence inputs for the Federal and Lagos State governments' renewable power generation and new housing development programmes.

Keywords— *Off-grid, Strategic Technological Assessment, photovoltaic power generation, Roof tilt, building azimuth, new housing developments, policy intelligence*

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1 Introduction

Energy is a critical infrastructure essential to the minimum operations of a modern society and economy. Electricity is an energy carrier, and civilized life, through the provision of transportation, healthcare, entertainment, food, telecommunications etc., depends on its availability and constant supply. Although non-renewable energy sources accounted for almost 80% of global electricity generation in 2020 [1], with renewables accounting for only 20%, global investment in renewables has increased over the years, especially in off-grid photovoltaic power infrastructure for sustainable electric power supply.

In Nigeria, the investments by the Federal and States governments in electric power supply have yielded limited success, with enormous power supply deficits a regular feature. Gas-powered thermal plants (7 Thermal and 3 Hydro generation stations) dominate Nigeria's electric power infrastructure, with total installed, transmission, and distribution capacities of 12.5, 5.3, and 7.2 GW, respectively while actual generated, transmitted, and distributed electricity was estimated at 3.9, 3.6 and 3.1 GW respectively [2,3]. Power supply in Nigeria is limited by many factors, including organization, government policies, financing, equipment theft, and huge population growth amongst others [4]. Nigeria's residential sector consumes the highest share of the national power supply (59.6%), while the commercial and industrial sectors consume 30.4 and 10%, respectively.

Like many developing countries, Nigeria's share of renewables in national electricity generation is very low; in 2019, it was only 25%, and solar power contribution to this was statistically zero [5, 6,7]. National targets for renewable energy generation have largely been unattainable. Solar power generation from ground-mounted and roof-top photovoltaic (PV) power systems has generated interest in Nigeria in recent years. This roof-top photovoltaic (PV) power system is an off-grid or mini-grid power technology – a self-sufficient energy system that supplies electricity to a localised group of customers and operates in isolation from the national transmission network. It is considered appropriate power technology for the Nigerian market due to the availability and reliability of sunlight, the ease of procurement of the equipment, its cleaner environmental performance relative to petrol/diesel generators, and its substantial opportunities for employment and wealth creation.

The roof-top mounted PV power systems and the high percentage of residential sector consumption of national electricity supply create a fertile ground for energy planning or development planning specialists to examine the country's housing types and supply patterns. Taking into consideration that it may be difficult to reconfigure existing building rooftops for optimum solar power generation, it may be necessary to explore new rooftop designs for new housing developments. It is a known fact that Nigeria has a massive housing deficit; Federal and State Governments' interests in improving electricity generation through rooftop PV systems may therefore stimulate solution provision in addressing the country's housing deficit by establishing the enabling environment for decentralized public and private investment in new housing developments with rooftop PV power generation capabilities. This is in additional to the potential investments in critical electric power infrastructure (including off-grid photovoltaic systems) for regional/national development.

The adoption of the off-grid, rooftop PV power system in new housing developments in suburbs in Nigeria in general and Metropolitan Lagos in particular has been impeded by ineffectual alternative power infrastructure planning and implementation by decentralized public and private sector actor's consequent to limited information on the angle and orientation of rooftops in building construction. While previous research centred on optimizing roof tilt, there is limited research on improvements obtainable via optimizing roof tilt and building azimuth. Therefore, This study develops a strategic technological analysis of this alternative power infrastructure using buildings in the Ikeja suburb of Metropolitan Lagos as a case study.

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Ikeja is the capital of Lagos State and a suburb of Lagos City, which is essentially Nigeria's business capital [8]. Having a central location in the State and being only about 17 km northwest of the city, grants Ikeja vantage for business development and middle- and high-end urban living. Defining areas include the Computer Village and the Murtala Mohammed Airport, while Business Districts include Oregun, Agidingbi, Magodo, Ogba, Maryland, Opebi, Akiode, and Alausa. Wealth creation and business opportunities are in ICT, Aviation, Energy, Finance, Advertising, Entertainment, and Hospitality. This study specifically determined the optimum roof tilt and building azimuth for rooftop-based distributed photovoltaic (PV) energy generation in the study area as strategic policy intelligence for power programmes of the Federal and Lagos State Governments.

The following sections include a literature review and identification of the key parameters for solar array yield optimisation. The methodology presented outlined the use of GIS imagery for enumerating individual buildings and determining their corresponding roof surface areas, the use of ImageJ software to determine actual roof area a representative sample, and the design considerations for solar photovoltaic arrays were also presented. Finally, the simulations carried out with the PV Watts model were presented. The results of simulations for the various system sizes were also presented. The conclusion and recommendations section presented the summary of results obtained and their utility for players in industry or government.

2 Literature Review

Mounting solar panels on rooftops necessitates maximizing solar panel yield while not disturbing the original purpose of the roof. Various researchers have explored various schemes to maximize or characterize solar panel yield.

2.1 Theoretical Review

Roof shape and slope are important parameters for a structure's safety, especially when exposed to wind loads (Singh and Roy, 2019). In addition to the roof slope and shape, the building orientation plays a key role in solar panel electricity yield.

2.1.1 Roof shape, slope and effect on suction

According to Bernoulli's Principle a decrease in surface pressure is accompanied by an increase in the velocity of a fluid (air in the case of wind design) over an object (Fig. 1). This fundamental idea is applicable in a wide variety of fields, including piping systems, aviation design, roof designs and building enclosures [9]. The Bernoulli equation is reduced to the following equation when used to determine pressure differences between the roof system and the wind flow above it. Here, ρ is the fluid's density (in this case, air) and v is the fluid's velocity (speed).

$$\Delta P = \frac{1}{2}\rho v^2 \quad (1)$$

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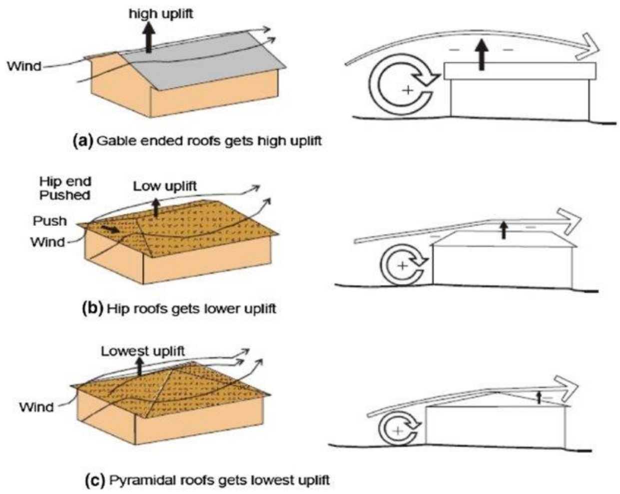

Fig. 1: Flow patterns over different roof shapes - gable, hip, and pyramidal Source: Ashok (2015)

Wind load on a building is also highly affected by its surroundings, which may be the shape of nearby buildings, the height of buildings, or the distance of surrounding structures from the principal building. Wind load has two main components when affecting a building - drag force and lift force, which may be positive or negative wind pressures. A study of tension leg platform superstructure showed that there is a surge increase in the drag force and heave reactions; however, the influence of the current drag is determined by the extent of the wave energy spectrum [10].

2.1.2 Roof shape and effects on runoff and building orientation

Roof orientation, also known as azimuth, is a roof's position relative to the sun. Roof orientation is important and is a primary component used to design a solar power system (Figure 2). For solar panels to produce maximum output, they need to access as much sunlight as possible. So, roofs that face north are ideally suited for solar power for those in the southern hemisphere. However, for someone living in the northern hemisphere, south-facing roofs are preferable.

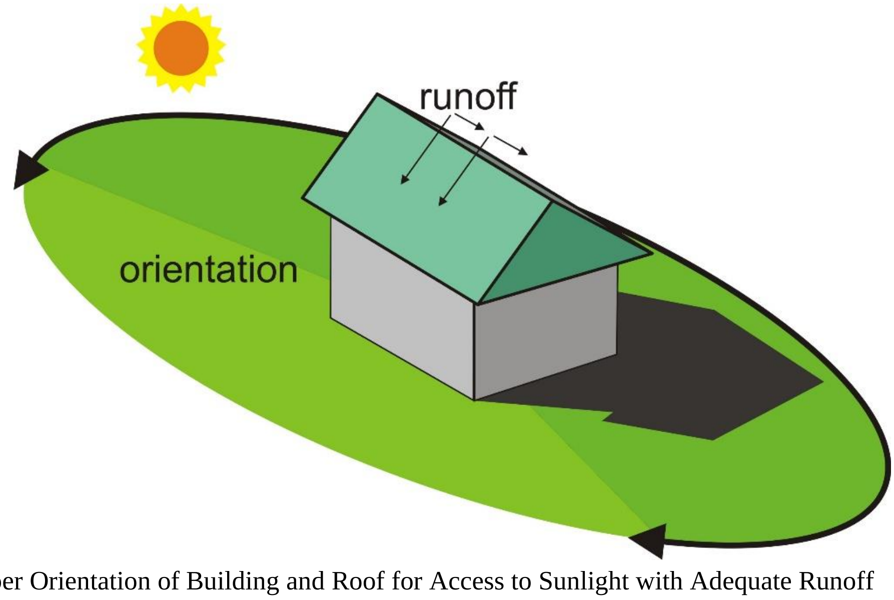

Fig. 2: Proper Orientation of Building and Roof for Access to Sunlight with Adequate Runoff

Also, of importance following building orientation is the roof angle, or pitch. Solar panels on the roof produce more power when they directly face the sunlight. Thus, the best roof angle depends entirely on the solar power

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objectives while considering what time of the year the best results can be obtained with regard to solar orientation, weather, and even wind loads. Roof shape also affects the runoff rate during precipitation – as steep roofs produce more runoffs than less steep ones – and wind loads. Wind loads must be considered for the roof's structural integrity during design as high wind-induced suctions can cause major damage that could lead to rain intrusion and loss of interior substances [11]. Proper tradeoffs and optimization should be carried out to ensure the roof meets adequate runoff requirements while ensuring suitable azimuth given a geographical location.

2.1.3 Building Feature Factor Determinants

Several technical and aesthetic factors and critical cost considerations come into play when choosing the roof slope and building orientation [12]. When deciding on roof slope and building orientation, balancing technical, aesthetic, and cost-related considerations ensures a well-designed, efficient, and economically viable structure [13]. A holistic approach considers all these factors to create a sustainable and aesthetically pleasing building that aligns with its surroundings while optimizing cost performance and minimizing long-term expenses. These building features and attendant factors are highlighted below in Table 1.

Table 1: Building features and factors

Building Feature	**Factors**
***Roof Slope*:**	i. Climate and Weather Conditions: The local climate determines the ideal roof slope to efficiently handle rainfall and snow load. In tropical areas such as Nigeria, roofs tend to be less steep. ii. Roofing Material: Different materials have specific slope requirements, impacting the type of slope chosen. iii. Building Design and Style: Architectural style influences the roof slope to ensure it complements the overall design. iv. Structural Considerations: Considering structural integrity and cost, the slope must align with the building's design and load-bearing capacity. v. Energy Efficiency: The roof slope affects energy consumption and can influence heating and cooling costs based on climate and solar orientation. vi. Local Building Codes: Roof slopes should adhere to local regulations, ensuring safety and stability. vii. Longevity and Durability: Proper roof slope prevents water accumulation and improves roofing material lifespan. viii. Cost and Construction Complexity: Steeper slopes require more materials and labor, which may impact the budget and complexity of construction.
Choice of Building Orientation	i. Solar Orientation: The building's orientation impacts its exposure to sunlight and influences passive solar heating and cooling. ii. Climate and Ventilation: Proper orientation enhances natural ventilation, impacting cooling needs and energy efficiency. iii. Views and Surroundings: Orientation can optimize views of landscapes and surroundings for aesthetic appeal. iv. Privacy and Noise: Building orientation can mitigate noise exposure and enhance privacy. v. Passive Solar Design: Optimized orientation can reduce energy consumption through passive solar heating and lighting. vi. Urban Planning and Site Constraints: Orientation may be influenced by site limitations and urban planning requirements.

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	vii. Energy Efficiency: Building orientation affects energy usage and overall operational costs. viii. Cultural and Aesthetic Considerations: Aesthetic preferences and cultural norms may influence the orientation choice.
Cost of Building	i. Material Costs: Steeper roofs require more materials, increasing roofing expenses. ii. Labor Costs: Installing steeper roofs demands more labor and can result in higher labor costs. iii. Structural Support: Additional support may be required for steeper roofs, adding to the construction expenses. iv. Maintenance Costs: Steeper roofs are costlier due to the complexity and safety risks involved. v. Building Shape and Complexity: Orientation may impact building design and construction complexity, influencing costs. vi. Glazing and Insulation: Optimized orientation may require additional investments in glazing and insulation. vii. Shading and External Features: Implementing shading elements for energy efficiency can add to the construction budget. viii. Energy Efficiency Upgrades: While beneficial in the long run, energy-efficient technologies can increase initial costs.

2.2 Empirical Review

The ideal PV panel orientation would be perfectly horizontal at the earth's equator, where the sun is directly overhead. The earth's tilt on its North-South axis and the resultant variation in this N-S line due to the movement around the sun produces a seasonal variation. Several authors have suggested varying tilt adjustment schemes. [14] suggested

$$\boldsymbol{\theta}_{\textbf{orientation}} = \begin{cases} \emptyset + 25^{o} & \textbf{November, December and January} \\ \emptyset + 15^{o} & \textbf{February, September and October} \\ \emptyset - 15^{o} & \textbf{August} \\ \emptyset - 25^{o} & \textbf{May, June and July} \\ \emptyset & \textbf{March and April} \end{cases}$$

where θ and ϕ are the panel orientation and latitude of site respectively.

While this result was based on primary research in Nigeria and uniquely suited for the Nigerian environment, it would be impractical to adjust the tilt of rooftop panels five times annually.

[15] suggested:

$$\boldsymbol{\theta}_{\textbf{orientation}} = \begin{cases} \emptyset + 15^{o} & \textbf{Optimum power production} \\ \emptyset - 15^{o} & \textbf{Maximum power production} \\ \emptyset & \textbf{Uniform power production} \end{cases}$$

The majority of research publications, however, favor a double adjustment scheme, with adjustments once in winter and once in summer (dry and wet seasons, respectively, in the near-equatorial regions) ([16]**;** [17]). This is probably for convenience:

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$$\boldsymbol{\theta}_{\mathbf{orientation}} = \begin{cases} \emptyset + 5^{\mathbf{o}} & \textbf{Dry Season} \\ \emptyset - 5^{\mathbf{o}} & \textbf{Rainy Season} \end{cases}$$

Okundamiya et al. (2011) [18], using the HDKR model, determined that annual solar panel yield in Nigeria can be improved by as much as 10% if the panel tilt is in the optimal setting. However, this work only focuses on tilt without considering improvements obtainable by optimizing roof tilt and building azimuth.

3 Methodology

The study area is the Ikeja suburb of Metropolitan Lagos, Nigeria. The primary data comprised of manual imagery, dimensions and roof angles of the building structures in the study area, and the coordinates of each structure. The secondary data comprised satellite imagery. A 0.8m-resolution satellite image of Ikeja was downloaded using the Universal Maps Downloader (UMD) tool. The satellite image was initially geo-referenced and subsequently digitised. The surface area, building GPS coordinates, and orientations (Azimuths) were then extracted from the ARCGIS database into a Microsoft Excel spreadsheet. The satellite image showed the rooftops as planar, which gave erroneous estimates for the total roof area critical for PV installation. The effective rooftop area was determined from the actual rooftop area using the Constant Value method [19, 20] presented in Table 1 and the manual method in Eqn. 1.

Table 2: 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

$$Effective\ Rooftop\ Area = 0.5 \times 0.8 \times 0.4 \times Actual\ Rooftop\ Area \qquad (2)$$

NOTE: To correct for the planar rooftop satellite imagery and the underestimation of actual roof area, a ground-truth analysis was executed on several randomly selected buildings determined using the Yamani formula (Eqn. 2) for suitable sample size determination from a known population.

$$n = \frac{N}{1+N(e^2)} \qquad (3)$$

Where

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

From the sampled buildings, the corrected roof area was determined using the correctional regression equation (Eqn 3):

$$\mathbf{y} = 1.1485\text{x} - 0.1768 \qquad (4)$$

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Where
x = satellite planar roof area, and
y = corrected roof area
The PV system design was determined based on the building roof area analysis using the International Finance Corporation, IFC's recommended standards [21]:

$$\boldsymbol{mVR} = V_{oc(STC)} * 1.15 \quad (5)$$

$$\boldsymbol{mCR} = I_{sc(STC)} * 1.25 \quad (6)$$

Where:
${}_mVR$= minimum Voltage Rating
V_{oc}= open circuit voltage at STC
${}_mCR$= minimum Current Rating
I_{sc}=short circuit current at STC

The PV module maximum power transfer to the inverter:

$$V_{MPP\ (module)} * n_{min} > V_{MPP(inverter)} \quad (7)$$

Where:
$V_{MPP\ (module)}$ = Maximum Power point Voltage of PV modules
n_{min}= Minimum number of modules in a string
$V_{MPP\ (inverter)}$ = Maximum Power point Voltage of inverter

The PV system sizing depends on daylight hours, individual battery voltage (12 V), and system voltage. PV system generation capacity within the hours of effective sunshine:

$$Energy_{array} = w * h \quad (8)$$

Where:
w = watts, and h = hours

PV module energy generation, taking into consideration system efficiency:

$$\boldsymbol{E_g} = \frac{\boldsymbol{P_{pv} * {}_nR * {}_nI * PSH}}{\boldsymbol{sf}} \quad (9)$$

Where:
E_g = daily Electricity generation
P_{PV} = PV System Power
PSH= Peak sun duration
sf = the safety factor (compensates for panel inefficiencies)
${}_nR$ = the charge controller efficiency
${}_nI$ = the Inverter Efficiency

a. **Calculating for Inverters**: The IFC utilizes a range of 0.8-1.2 for the inverter to array power ratio. Therefore,

If $0.8 < powerratio < 1.2$

$$\textbf{Power ratio} = \frac{P_{inverter(input)}}{P_{pv}} \quad 10$$

$$\eta_{100\%} = \frac{P_{inverter\,(output)}}{P_{inverter\,(input)}} \quad 11$$

b. **Calculating for Charge Controllers**: Charge controllers regulate the voltage and current from the PV panels, thus prolonging battery life. 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:

$$\textbf{Charge controller rating} = Array\ Current_{short\ circuit} * 1.3 \quad 12$$

Calculating for Battery sizing: Discharging a deep cycle battery beyond 50% is not advisable. Considering losses and a 40% depth of discharge:

$$C_{Ah} = \frac{DaysOfAutonomy * E_g}{V_B * DOD * {}_nB * {}_nI} \quad 13$$

Where:

Days of Autonomy refers to the number of days of operation without sunlight (a fraction of a day in the tropics)

E_g =daily electricity consumption

C_{Ah} = the capacity of the battery bank (Ah)

DOD= the depth of discharge of batteries

V_B = the voltage of the battery bank

${}_nB$ = the battery efficiency

${}_nI$ = the Inverter Efficiency

3.1 NREL PV Watts Model (version 5) Simulations

The data on building latitude and longitude, roof slope angle range determined from the *ImageJ* analysis, building azimuth angles obtained from the digitized satellite imagery, and the PV system design analysis were fed into the NREL Watts Model simulation to determine yield optimization.

3.2 Image J Analysis

Image J is a Java-based digital image processing software initially developed for biological research. Over the years the user community has continuously improved the programme with various plug ins. Image J was used to extract angles from images of roof structures, making it fairly easy to determine actual roof areas in combination with the corresponding satellite image.

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4 Results

The calculations and results from the study are presented in this section.

4.1 Variation of Solar Array Yield with Roof Elevation and Azimuth

The simulation experiments used to obtain yield results for varying combinations of roof elevation and building azimuth are presented as an array in which each cell defines a particular yield as a function of row (elevation) and column (azimuth elements). The rows were sampled at 0º, 5º, 10º, 30º, 45º, 60º, while the columns were sampled in 45º steps from 0º through 180º. Results for these simulation experiments are presented for several system sizes (533 kW, 110 kW, and 0.547 kW) in Tables 1, 2 & 3, and Figures 1, 2 & 3.

4.2 533 kW System

Large variations were observed in the system's yield from a high of 768, 944 kWh/annum to a low of 457, 504 kWh/annum. These figures correspond to a significant difference of 40%. The combination of azimuth and tilt with the highest yield is 180º and 5º, respectively while the lowest yield is given by the 0º, 60º combination. (See Table 3 and Figure 3).

Table 3: Annual Yield Prediction (in kWh) for a 533-kW system

		Building Azimuth (degrees)				
		0	***45***	***90***	***135***	***180***
Roof Tilt (degrees)	***0***	765830	765830	765830	765830	765830
	5	760689	760949	763466	766788	768944
	10	751348	751880	756963	763540	767838
	30	672950	677524	695285	711425	721776
	45	574844	590433	621077	636891	645394
	60	457504	489996	533743	541654	538592

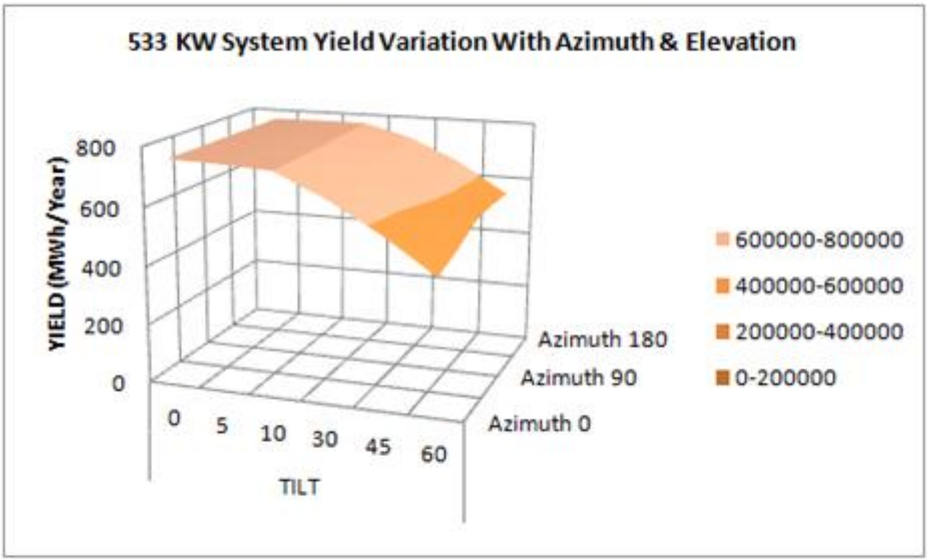

Fig. 3: 533 kW Yield Optimization Curve

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4.3 110 kW System

A similar trend was observed in the variation of the system yield. The yield was maximum at the 5 º tilt and 180 º azimuth point whilst the minimum occurred at the 60º, 0 º point (See Table 4 and Figure 4)

Table 4: Annual Yield Prediction (in kWh) for a 110-kW system

		Building Azimuth (degrees)				
		0	***45***	***90***	***135***	***180***
Roof Tilt (degrees)	***0***	158051	158051	158051	158051	158051
	5	156990	157044	157563	158249	158694
	10	155062	155172	156221	157579	158466
	30	138883	139827	143492	146823	148959
	45	118636	121853	128177	131441	133196
	60	94419	101125	110153	111786	111154

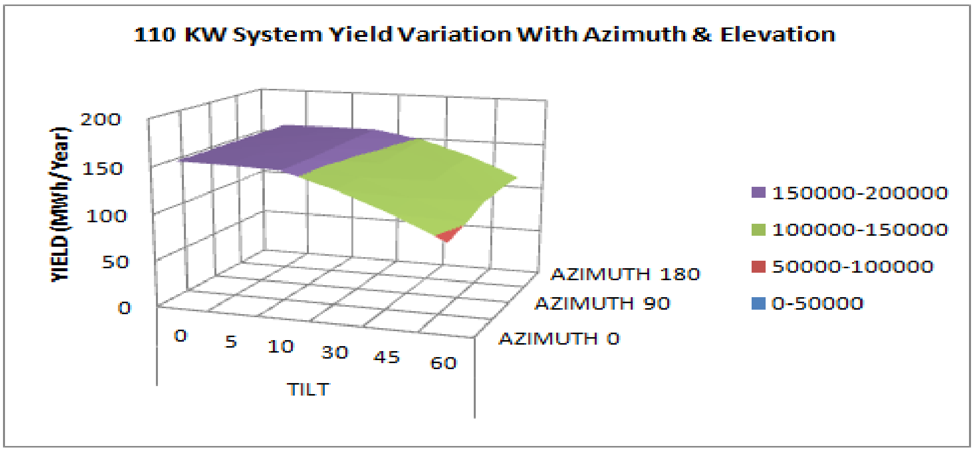

Fig. 4: 110 kW Yield Optimization Curve

4.4 540W System

Virtually the same trend was observed in the variation of the system yield at 540 watts as with the other system capacities. The yield was maximum at the 5º tilt and 180º azimuth point whilst the minimum occurred at the 60º,0º point. (See Table 5 and Figure 5).

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Table 5: Annual Yield Prediction (in kWh) for a 540 W system

		Building Azimuth (degrees)				
		0	***45***	***90***	***135***	***180***
Roof Tilt (degrees)	***0***	777	777	777	777	777
	5	772	772	774	778	780
	10	762	763	768	775	779
	30	683	687	705	722	732
	45	583	599	630	646	655
	60	464	497	541	549	546

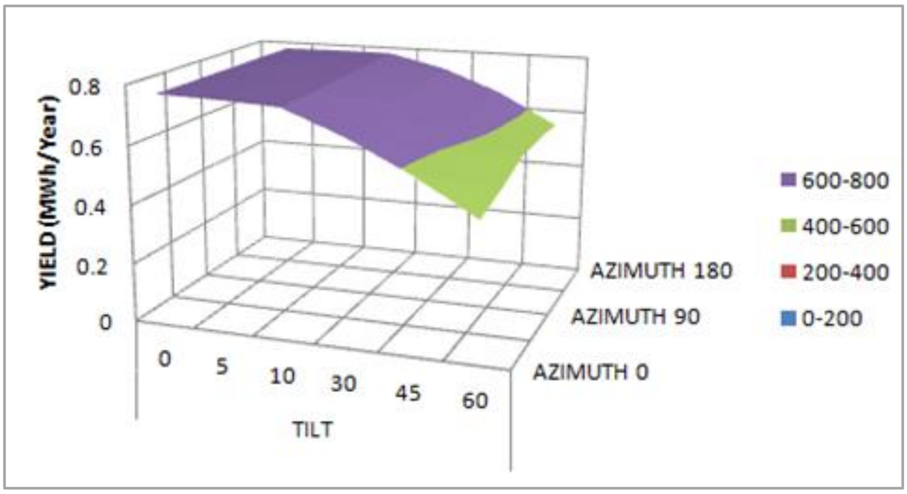

Fig 5: 540 W Yield Optimization Curve

5 Conclusion and Recommendations

This work has generated the optimal combinations of roof tilt and building azimuth for buildings in the study area. The optimal roof tilt and building azimuth angles for the study area were found to be 5° and 180 °, respectively, which agrees with literature). However, combinations of azimuth and tilt angles not exceeding 30 ° tilt and not lower than 90 ° azimuth still give reasonable power yields (assuming two-thirds of the maximum solar yield threshold of acceptability). Regulators, building designers, and potential homeowners are encouraged to use the calculated tilt and azimuth limits in building design to achieve maximum solar yield. The Lagos State Government and other stakeholders are encouraged to utilize the PV systems template for alternative electricity development in new housing schemes in the study area.

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