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Determination of Solar Irradiance Benchmarks for Municipal Off-grid Photovoltaic Power System Development in Lagos State, Nigeria

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Abstract

The chapter examined the solar irradiance benchmarks for off-grid photovoltaic power systems development in Ikeja, Lagos State, Nigeria as a power supply alleviation strategy in the State and strategic model for other sponsors in Lagos State and Nigeria. Solar irradiance analysis, an energy technology foresight analysis method for effective energy planning and evaluation, was used. The solar irradiance analysis determined three solar irradiance measurements – the NiMet pyranometer, the NASA satellite, and the Mechlouch and Brahim (2008) model. The study determined the model graph to be incongruous with the NiMet pyranometer and NASA satellite-derived graph plots while the NIMet and NASA satellite plots essentially overlapped. The study adjudged the model graph as being theoretical and inappropriate while the NiMet and NASA readings gave realistic plots which were deemed acceptable as suitable solar irradiation benchmarks. In conclusion the study established solar irradiance benchmarks of 15 MJ/m2/day (upper (maximin) value) and 20 MJ/m2/day (lower (minimax) value) for the photovoltaic power systems development in Ikeja, Lagos State, Nigeria.

Keywords: *Solar power; Energy planning; Photovoltaics; Off-grid systems*

1.0. Introduction

Energy is a basic infrastructure for national technological and socio-economic development and in its absence, modern life would cease (Ogundari *et al.*, 2017). Electricity is a very significant and exceedingly versatile form of energy, and can be generated from multiple sources – fossil energy and renewables (Momodu *et al.*, 2011). The availability of electricity is critical to industrial and commercial activities in countries; and national electricity access is a clear indicator of a country's wealth and development capabilities. Access to electricity is fundamental to issues such as security, climate change, food production, and strengthening economies while protecting ecosystems (USAID, 2020) and improving electricity supply in any nation would improve socio-economic growth and favourably affect the national quality of life. This may be expressed in increased food production, increased industrial output, adequate shelter, healthcare and other human services, and the provision of adequate and efficient transportation (Bala *et al.*, 2000; Akinpelu, 2011; Ogundari *et al.*, 2017; Ogundari and Otuyemi, 2020).

The provision of a stable electric power sector which operates efficiently and effectively and depends on multiple, reliable sources of electricity has been a major developmental aspiration in Nigeria since the Country's independence in 1960. The reality however, is that Nigeria's electric power sector is anything but effective, efficient nor dependent on multiple, reliable sources of electricity[1]. Limitations to the sector have been attributed to many factors including inadequate institutional management; equipment theft/fraud; limited financing; energy infrastructure attacks, and obsolete facilities and technologies. These limitations are aggravated by huge population growth, failing public infrastructure/institutions, poor power infrastructure manpower, and inappropriate governance and policy development.

In Lagos State, not only is grid power supply grossly inadequate – 1000 MW supply with a 9,000 – 10,000 MW deficit – the national power grid limitations are heightened by the complexities of the Lagos environment (Olurode *et al.*, 2018; Arowolo *et al.*, 2019; Africa Energy, 2019). Lagos State is Nigeria's economic dynamo, generating nearly 65% of the GDP of the national economy. Vibrant and colourful, the State with its 21 million (and counting) people, is estimated to require 16,000 – 27,000 MW of new generation capacity costing $14 – 33 billion by 2030 (MEPB, 2013; Ogunbiyi, N.D.; Atkins Limited, 2014; SPARC, 2014; World Bank, 2015; USAID, 2020). The extant alternative power generation systems in the State – the mini-grid photovoltaic (PV) systems, the grid-connected gas-powered systems, and the off-grid petrol/diesel generators with their adverse environmental, health and climate change implications are inadequate to meet demand (African Renewal, 2017; World Bank Group, N. D.; Ogundari and Otuyemi, 2020).

Reforms in Nigeria's public electric sector, the enactment of national and State laws, and the institution of public programmes have enhanced decentralised public and organised private sector participation and funding in critical electric power infrastructure. Lagos State's development aspirations over the next decade depend on strategic domestic electric power development for the delivery of stable and credible power supply (MEPB, 2013; Ogunsanya *et al.*, 2016; Caleb *et al.*, 2018; Ogundari and Otuyemi, 2019). Specifically, the Lagos State Government, through the Lagos State Development Plan (LSDP) (2021-2025), enacted the State Electric Power Sector Reform Law (2018), and instituted the Lagos State Infrastructural Development Initiative and State Embedded Power Programme (EPP) to attain its goals. Furthermore, to meet the electric power requirements of the Lagos megacity, modern electric power infrastructure such as the photovoltaic power system and the natural gas-to-power systems have been added to the regional power mix by the Lagos State Electricity Board under the

[1] The national power infrastructure (made up of 7 Thermal and 3 Hydro generation stations) has estimated total installed, transmission and distribution capacities of 12.5, 5.3, and 7.2 GW respectively. Actual generated, transmitted and distributed electricity were estimated to be 3.9, 3.6 and 3.1 GW respectively. National grid connectivity in Nigeria is around 40% of the population, average daily power supply estimation is four hours, and power supply is at best erratic (Momodu *et al.*, 2011; Ogundari and Otuyemi, 2020).

State Ministry of Energy and Natural Resources to reduce the domestic penchant for the use of fossil fuel generator systems with their consequent environmental concerns

In spite of all these measures to expand power generation and distribution in Lagos State, electric power demand in the State is growing at a rapid rate, and electric power supply is still inadequate and erratic. The limitations in stable power supply and the deployment of new technologies for power delivery could stifle development aspirations in State, and frustrate private sector participation and funding of critical power infrastructure. The adoption of new power supply measures like the photovoltaic power system in the Lagos State energy mix has been limited by planning and implementation inadequacies – although photovoltaic power systems have been installed, many of them have not been operating at maximum efficiency.

Photovoltaic (PV) power system installation technicians/energy planning analysts have been hampered by their limited understanding of the complex technical nature of solar irradiation analysis for photovoltaic power systems delivery[2], and there is a dearth of accurate and specific templates for PV system planning and development. The specific objective of this paper is to develop appropriate technical and economic specifications for the optimal design of a municipal off-grid PV power system for a strategic location, Ikeja, in Lagos State, Nigeria. The study is important as it provides an accurate, cost-effective irradiance benchmark for the development of PV systems that are critical to the implementation of the Lagos state policy goal of diversifying the State's energy mix and serve as a strategic template for sustainable electric power development across Nigeria.

Ikeja, a suburb of Lagos city and capital of Lagos State in Southwestern Nigeria, is located on Latitude 6º35´47.44´´N and Longitude 3º20´31.38´´E. It lies about 17 km North-west of Lagos city and is easily the best place on the Lagos Mainland to situate a business due to its strategic location and market structure. Its centrality and proximity to Lagos city stimulates business and enables it offer middle- and high-end urban living and suitable residential areas. Defining structures in Ikeja include the popular, large computer and computer accessories hub known as the Computer Village and the Murtala Mohammed International Airport. Districts in Ikeja include many economic and industrial hubs such as Oregun, Agidingbi, Magodo, Ogba, Maryland, Opebi, Akiode and Alausa.

1.1. Strategic Overview of Photovoltaic Systems Development Analysis

The sun provides a virtually inexhaustible energy source as a by-product of the nuclear reactions within its core. The energy from the sun, both heat and light, is generated by the fusion of hydrogen nuclei into helium. In its core, the Sun produces 36.96 billion metric tonnes of helium each minute and the resulting energy is radiated out from the sun's core into the solar system. This energy or electromagnetic radiation emitted by the sun is called the solar resource or simply sunlight, and can be captured and converted into useful energy forms like heat and electricity via various technologies. Global interests in renewable and climate-friendly energy options have made solar radiation-based energy – reliable, inexhaustible, and easy-to-use – a huge energy development investment option.

The two most common means of generating electricity from sunlight are Solar Cells and Concentrated Solar Plants (CSP). Solar Cells operate on the photo-electric principle. Photo-electric emission occurs (in materials that have this property) when light photons impact a photo-electric material, liberating free electrons in the process and generating a potential difference. Concentrated Solar Power (CSP) systems utilise a set of mirrors or a lens to concentrate incoming sun light to a focal point. This beam concentrates a lot of energy into a very small area thus generating heat. This heat energy is then used to convert water to steam which at high temperature and pressure turns a turbine, generating electricity.

[2] Solar irradiance analysis is an energy technology foresight analysis method used for effective energy planning and evaluation.

The quantity of sunlight which reaches the earth is huge. It is estimated to be, on average, 164 watts per square metre over a 24-hour day period. Sunlight takes approximately 8.3 minutes to reach Earth from the sun's surface (Siemens, 2011). The deserts of the world receive as much energy as the whole of mankind uses annually in under six hours (Siemens, 2011). A means of quantifying this energy is 'Insolation', and it is the amount of solar radiation received by the Earth's surface; or in more technical terms, it is the incident radiant energy emitted by the sun which reaches a unit area over a period of time. Another important term is "Irradiance", and it is the flux of radiant energy, from some source (the Sun), per unit area, normal to the direction of flow through a medium. Insolation can thus be thought of as an integration of the irradiance (a flux) over some time frame.

Insolation data is often collected in situ on earth with the aid of a pyranometer. This is a device which ideally has a cosine response to the angle of incidence of incoming radiation. Thus, the pyranometer has a maximum response when the radiation source is directly overhead and a minimum or zero output when the radiation source is coplanar (horizontal) with the measuring device. Average insolation in Nigeria varies roughly with latitude from about 7.0 kW/m^2/day in the far north to about 3.5 kW/m^2/day in the coastal regions (Ojosu, 1990; Abubakar, 2009).

The facilities required to collect reliable insolation or irradiance data are often not readily available in Nigeria (outside of the Nigerian Meteorological Agency - NiMet) and other developing nations. Consequently, models and satellite derived data are often used. Additionally, the irradiance measurement is a point data source. That is, the reliability of such measurements reduces the further one moves away from the data source. This could be as a result of variations in topography, cloud cover and so on. Irradiance benchmarks are vital in photovoltaic plant design (Durani *et. al.*, 2018), specifically by the dual need to predict balance of system (BOS) requirements and to make appropriate revenue forecasts. While the power system designer needs the peak power measurements to select components for their design, the business analyst requires the yield predictions to determine appropriate pricing and cash flow models. The intrinsic caution of both sets of professionals leads them in opposite directions in yield prediction. While the engineering design aims to adopt the higher power levels for plant design (taking into cognizance reasonable gap above rated power for the BOS requirements), the business risk analyst tends to adopt a conservative or low-yield scenario in order not to arrive at an over-optimistic estimate.

2.0. Methodology

It is generally accepted that *in situ* data such as that derived from pyranometers are more accurate than model-derived and satellite-derived data. This is highlighted by the fact that both model and satellite data are customarily validated via comparison to *in situ* data. The study area was Ikeja, Lagos State, Nigeria, being the location for the municipal off-grid photovoltaic power system initiative.

Three data sources were utilized for the study – Nigeria's NiMet, the United States' National Aeronautics and Space Administration (NASA), and values derived from irradiance models. The model of Mechlouch and Brahim (2008) was used to generate an irradiance dataset used in the analysis. Five years' worth of irradiance data (2013-2018) was collected from the NIMET station at Ikeja, annualized and subsequently grouped on a monthly basis. Similarly, irradiance data from NASA's Goddard Earth Observation Satellite (GEOS) featuring solar irradiance and clearness index were downloaded for the same period. Modelled irradiance data, unlike those derived from actual measurements, are constant for each Julian day in the year.

The model and satellite derived data were both compared to the pyranometer data from NIMET. The data sets obtained were analysed using appropriate inferential statistics to determine correlation and skewness, and essentially determine the appropriate solar irradiance benchmarks for the study area from the obtained data sets. The inferential statistics tools included:

Correlation

$$Correl(X,Y) = \frac{\sum (x-\bar{x})(y-\bar{y})}{\sqrt{\sum (x-\bar{x})^2 \sum (y-\bar{y})^2}}$$ ______ Eqn. 1

Skewness Testing

A skewness test which is used to determine the degree of asymmetry of a distribution around its mean was also carried out. For a normal distribution, the skew would be zero indicating a perfectly symmetrical distribution. These two near-zero negative numbers indicate that both distributions have slightly longer tails on the left hand side.

$$skew = \frac{n}{(n-1)(n-2)} * \sum \left(\frac{x_i - \bar{a}}{s}\right)^3$$ ______ Eqn. 2

Where:

n is the sample size
ā is the mean
x_i is the *i*th value, and
s is the standard deviation

The non-parametric Kolmogorov Smirnov (K-S) test which does not require normality was carried out. The critical value of the K-S statistic is described by Eqn. 3

$$K - S_{critical} = 1.224 * \sqrt{\frac{m+n}{m*n}}$$ ______ Eqn. 3

Where:

1.224 is a constant for a specific confidence level (0.05 in this case), and
m and *n* are the sample sizes.

The Mechlouch and Brahim (2008) model, which is a convenient method of determining the global hourly horizontal radiation, is determined in this method by the following algorithm:

$$G_H = A_k * A_N * A_T$$

The A terms are functions described as:

$$A_k = 1.1296k - 23.04\, for\ k < 0.5$$
$$A_k = 297672k - 37.853\, for\ 0.5 < k \leq 1$$
$$A_N = 0.01407 \sin\left[\frac{360}{365}(284 + N)\right] - 0.0357$$
$$A_t = t^4 - 47.958t^3 + 795.68t^2 - 5291t + 12158$$

Where:

G_H= Hourly Global Solar Radiation
N= Julian day
t= hour of the day
K= degree of cloudiness

The total daily global solar radiation (GD) is obtained by summing up the hourly solar radiation (G_H) over the total number of daylight hours (t_1 to t_2):

$$G_D = \sum_{t_1}^{t_2} G_H$$

In situations (or complex scenarios) where the probability of each of many possible outcomes is uncertain, the decision-maker can utilise mathematical and statistical models to guide the decision-making process. The concept of the minimax, minimin, maximin and maximax criteria is widely used in decision and game theories.

In solar PV project planning, the PV system's engineer requires maximum irradiance/power yield measurements for the BOS design; whereas the business risk analyst requires a conservative, low-yield irradiance measurement for project financial estimates for successful PV plant deployment. In order to accommodate these two opposing but equally important constraints, the maximin and minimax criteria of quantitative techniques for decision making were utilized. In order to have a low (and thus conservative) estimate for the irradiance which will not be overly pessimistic as to be impracticable; the highest point in the minimum irradiance region was selected. This is the maximin criterion. The minimax criterion on the other hand, is used to select the lowest point in the maximum region of the irradiance curve. This is the minimax criterion.

3.0. Results

Results of the simulation for one year using the Mechlouch and Brahim (2008) model are shown in Figures 1 and 2 for both diurnal and annual windows. The smoothness of these two curves indicates noiseless data. This is not unexpected considering that the model is an idealization of processes which rely on fairly regular variations such as hour angle, declineation etc. The diurnal variation of Figure 1 shows an incremental rise in irradiance from zero at sun rise (06:00 hours) to a maximum of 1200 W/m^2 at noon and a gradual decrease to zero at sunset (18:00 hours). Figure 2 on the other hand shows a gradual decrease from a maximum of 28 MJ/m^2 in January to a minimum of about 14 MJ/m^2 around midyear and then a gradual rise to a maximum of about 28 MJ/m^2 at year's end.

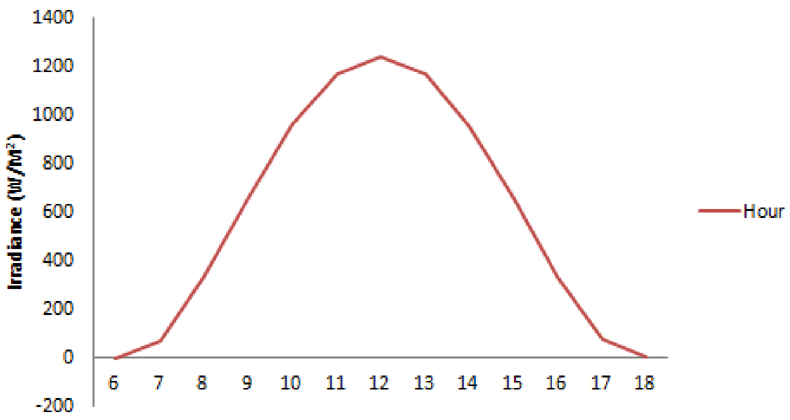

Fig. 1: Diurnal Trend of Solar Irradiance for Ikeja (Derived from the model of Mechlouch & Brahmin for Julian day 12)

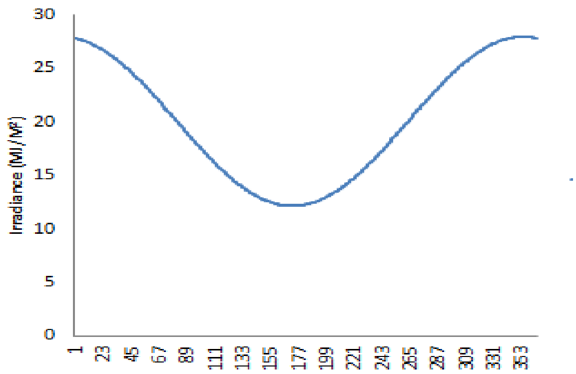

Fig 2: Annual Model Predictions

The plot of the five years' worth of pyranometer-derived irradiance data time series is presented in Figure 3. This five-year average daily solar irradiation plot has maximum readings at the start and end of about 22 and 25 MJ/m^2 respectively, and a minimum reading of about 14 MJ/m^2 in the mid-year period. The graph appears noisy thus reflecting the daily fluctuations as a result of cloudiness, rain, fog pollution etc which cannot be easily predicted. As accurate as the pyranometer is, it is a point data source which might have variations from other portions of the study area.

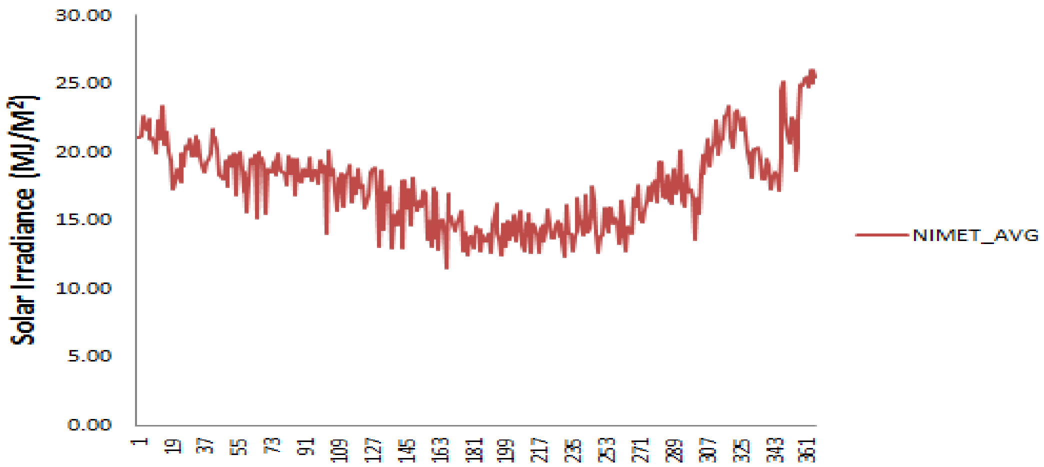

Fig. 3: Annualised Trend of 5-Year NIMET Irradiance Data

Five-year data from the GEOS satellite was also obtained and plotted (Figure 4). Like the NiMet graph, this time-series plot also appears noisy. This is also reflective of clouds and other factors which influence the sensor readings on board the satellite. The plot shows the same characteristic peaks and lows at the start, end and middle of the year. A plot of the two data sources (pyranometer and satellite) on the same axes is presented in Figure 4.

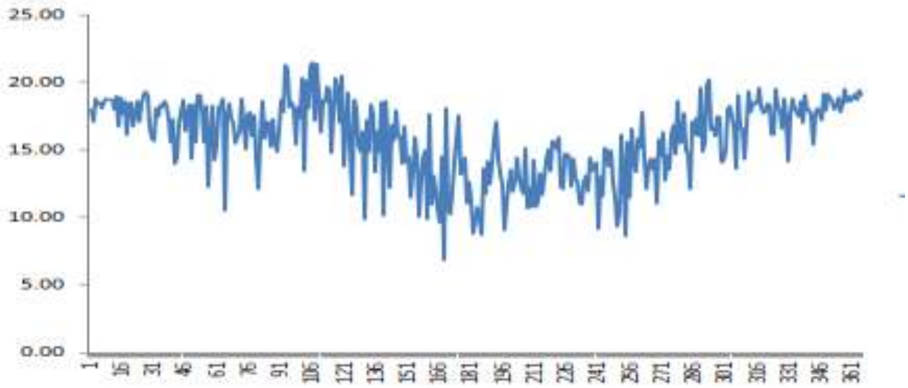

Fig. 4: GEOS Irradiance Data (Annualised)

Superimposing Figures 3 and 4 gives Figure 5. The two curves exhibit significant overlap which could be interpreted as a close relationship. Figure 5 shows that at both the start and end of the graph, the satellite data appears to underestimate the irradiance.

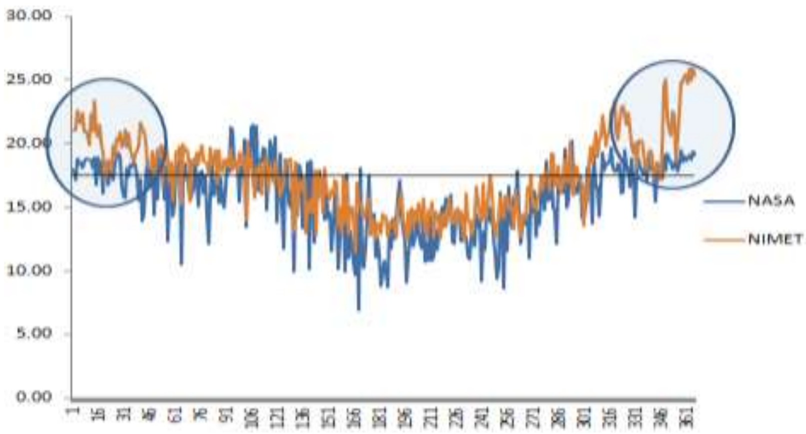

Fig. 5: Comparison of NIMET and GEOS Irradiance Datasets (Annualised)

Figure 6 shows the comparisons between the three variations of the solar irradiance – the pyranometer, satellite and model-generated graphs. The Figure shows close relationships between the data sets, and illustrates that the satellite data underestimates the estimate the irradiance at the start and end of the graph. The plot of the model prediction differs greatly from that of both the NIMET pyranometer data and the satellite derived data. In fact both the NIMET and satellite data essentially overlap for the most part. The NIMET data set was found to be almost perfectly aligned to a normal distribution whilst the NASA satellite data set was slightly skewed from normal. Incidentally, the start and end of the year in Nigeria coincides with the height of the harmattan season. The harmattan is a dry, dusty north easterly wind which brings cold dry and hazy conditions to West Africa every year from around November to February and March.

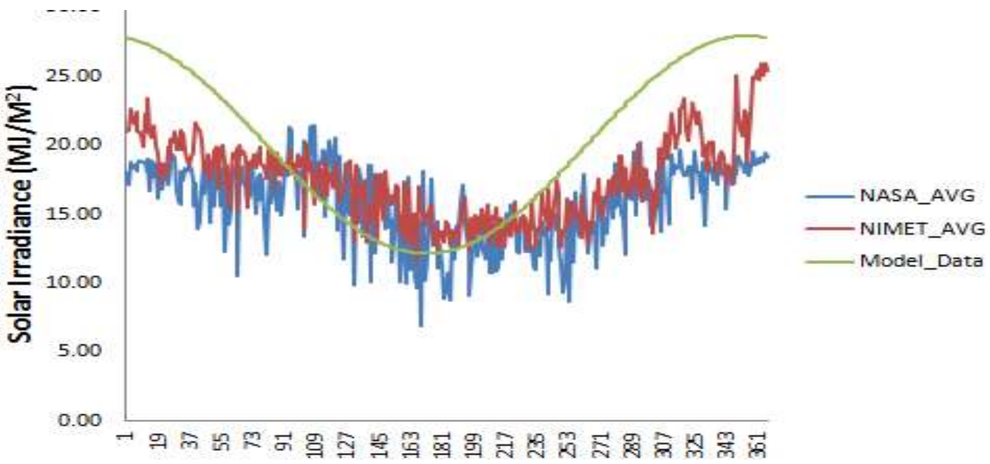

Fig 6: Annual Solar Irradiance Plots for the 3 Data Sources

The possibility is very strong that this dust haze maybe responsible for the differences in both pyranometer and satellite readings relative to the model plot. The model plot gives the textbook, theoretical curve while the NiMet and NASA readings give the practical reality on ground. Taking these into consideration, it is reasonable to consider the model plot as off-the-mark, and postulate the NiMet pyranometer and NASA satellite overlapping plots as the more suitable benchmarks for solar irradiation in the study area.
In assessing this postulation, Table 1 shows the Root Mean Square (RMS) error of both data sets with the pyranometer data. The much lower value of the RMS error of the satellite data compared with the model predicted values' RMS error ultimately informed the decision to favour further investigation of the satellite data with respect to the pyranometer data. The skewness test confirmed a certain level of skew which is considered insignificant because the skew values for both distributions were close to zero (-0.8646 and -0.8538) (Salu, 2021).

Table 1: RMS Error of Satellite and Model Datasets with respect to Pyranometer Dataset

	RMS Error
NASA – NiMet ($kW/m^2/day$)	2.810
MODEL – NiMet ($kW/m^2/day$)	4.621

As a consequence of the slight deviations from the normal, the non-parametric Kolmogorov Smirnov (K-S) test which does not require normality was carried out. Since the critical K-S statistic (0.090543) was found greater than the maximum difference (0.002732), it was concluded that no significant difference exists between the two data sets (Salu, 2021). After ascertaining that the means of the two datasets do not differ significantly and that they both are very close to normally distributed and have almost the same variance, it can be concluded that the satellite and NIMET datasets are sufficiently statistically close such that either one can be used for forecast at that point. It is thus a reasonable assumption to generalize that if the satellite-based irradiance data closely follows the accurate pyranometer data at a particular point, the satellite data can be assumed to present a reasonably accurate estimate of irradiance at other points within the study area where no pyranometer measurements exists. Thus, for specific buildings or areas, the requisite data can be downloaded and used to make a specific estimate whilst for a large area study such as this work entails either of the two data sets could be used. Using the NiMet data plot, the solar irradiation benchmarks were selected (Figure 7) to cater for the options of system design and yield prediction. The upper and lower levels were selected using the minimax and maximin criteria respectively (See Figure 7) and presented in Table 2.

Table 2: Solar Irradiance Benchmarks

Irradiance Value	Criterion	Purpose
15 $MJ/m^2/day$	Maximin	Yield Prediction
20 $MJ/m^2/day$	Minimax	Engineering Design

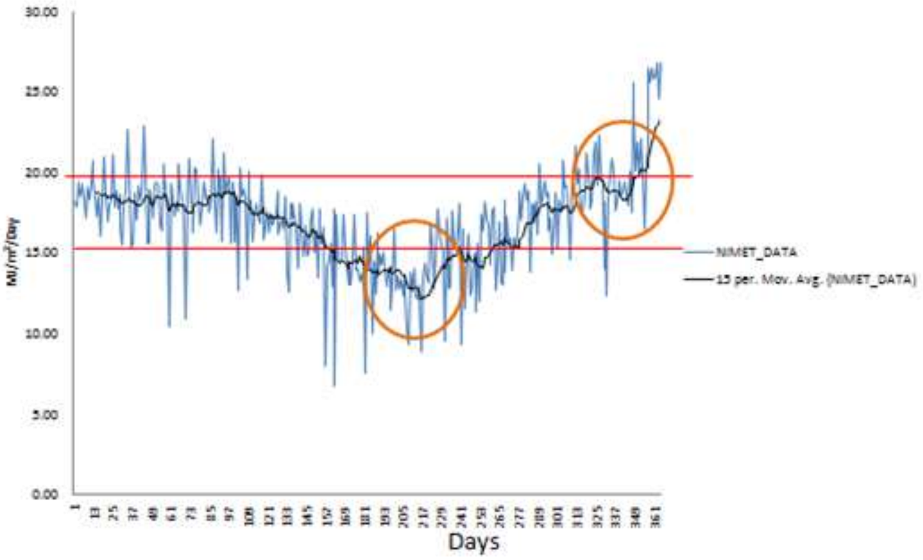

Fig 7: Upper- and Lower-Level Solar Irradiance Benchmarks

5.0 Summary and Conclusion

This study focused on the determination of solar irradiance benchmarks for off-grid photovoltaic power systems development in Ikeja, Lagos State, Nigeria as a power supply alleviation strategy in the State and strategic model for other sponsors in Lagos State and Nigeria. Solar irradiance analysis, an energy technology foresight analysis method for effective energy planning and evaluation was used.

The solar irradiance analysis determined that there were three platforms for solar irradiance determination – the NiMet pyranometer measurement, the NASA satellite measurement, and the Mechlouch and Brahim (2008) model measurement. The study ascertained that the model graph was inconsistent with the graph plots for both the NIMET pyranometer data set and the NASA satellite derived data set while the NIMet and NASA satellite data essentially overlap for the most part. The study adjudged the model plot as giving a textbook, theoretical curve while the NiMet and NASA readings gave the practical reality on ground. Taking these into consideration, it was presumed reasonable to consider the model plot as inappropriate for the solar irradiance benchmark, while accepting the NiMet pyranometer and NASA satellite overlapping plots as the more suitable benchmarks for solar irradiation in the study area.

In conclusion the study established the solar irradiance benchmarks for the photovoltaic power systems development in Ikeja, Lagos State, Nigeria to have the upper (maximin) value of 15 $MJ/m^2/day$ and lower (minimax) value of 20 $MJ/m^2/day$.

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