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Research Article

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Assessment of Solar Radiation as A Power Generation Source in Nigeria

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Abstract

The transition from fossil to renewable energy is becoming pressing and urgent due to the impact of fossil emissions on the environment. With Nigeria's growing population and increasing energy demand, the development of solar energy facilities, solar farms, and photovoltaic application has become crucial. Therefore, it is essential to assess the potential and availability of solar energy across different regions in Nigeria to support this energy transition. This study aims to understand solar radiation's distribution and variation (monthly and seasonal) and investigate regions where solar energy can be efficiently harnessed for energy generation. In this study, locations, divided by Nigeria's geopolitical zones (Northwest, Northeast, Northcentral, Southwest, Southeast, and South-south) where solar energy is abundant and can be efficiently harnessed for energy generation purposes over Nigeria were investigated using surface solar radiation, extraterrestrial radiation, and temperature obtained monthly for 34 years (1990 - 2023) and a model. The investigation focused on the monthly and seasonal variation and distribution of surface solar radiation, clearness index, and the estimated power from a single photovoltaic panel. The result shows that solar energy is abundant in Nigeria and at its peak during December-January-February (DJF) and lesser during June-July-August (JJA). Additionally, the northeast and the northwest receive higher solar radiation throughout the year than the other regions and it can be identified as a good site for solar energy facilities. All regions investigated in this study show a potential as a site for solar energy facilities and photovoltaic applications.

Keywords: Surface Solar Irradiance, Estimated Power, Clearness Index, Photovoltaic

1. Introduction

Our society today depends heavily on energy because it is fundamental to manufacturing and production processes, and this is the case. Energy is a key aspect of wealth creation and in the advancement of our economy [1]. Everyone agrees on its significance for economic growth, and historical evidence shows that there is a significant link between energy supply and economic activity [2,3]. Around 80% of the world's energy production comes from conventional fossil fuels, which also account for the majority of energy consumption [4]. Due to a shortage of fossil resources, the globe will experience energy crises in the future. The entirety of the nations whose economies substantially rely on its use are concerned about this [5]. The majority of developing nations still rely on conventional energy to meet their energy needs. Its rapid depletion and the fact that its discovery, production, and sale have turned into political and environmental issues have made it difficult to distribute energy effectively throughout the world [6]. Without a doubt, a greater reliance on conventional energy has benefited most of the nation overall by creating jobs, advancing infrastructure, creating chances for international alliances, and serving as their main source of income. Conventional energy resources have enabled great industrial and commercial progress, but they have also resulted in significant environmental degradation and climatic change that have a negative impact on people, the environment, and ecosystems such as contributions to ozone depletion, acid rain, and global warming. A change in energy sources is required due to the type of fuel's environmental impact and progressive depletion [7]. As sustainable alternatives to these resources based on fossil fuels, renewable resources, and technologies are therefore being promoted on a worldwide scale. These renewable resources and technologies which are environment-friendly and non-toxic sources for energy production include but are not limited to wind, biomass, hydropower, geothermal, and solar, and have been utilized with proven results.

Furthermore, highlighted that these resources are the perfect replacements for traditional fossil fuel resources because they are limitless [8]. Currently, one main disadvantage of using renewable energy sources is that they are location-dependent and frequently cannot be transported as readily as traditional non-renewable energy sources from the point of abundance to where they are needed.

The sun is the primary source of solar energy, emitting radiation in the wavelengths of 0.3 to 3.0 micrometers [9]. The sun acts as a continuous fusion reactor, releasing nuclear energy that is converted into thermal energy and transported to Earth as electromagnetic radiation. About 1370 MW/m^2 of energy from the sun reaches the top of the Earth's atmosphere, but factors such as the Earth's axis inclination and the atmosphere affect the amount of radiation that ultimately reaches the Earth's surface. Solar energy is the foundation of all other forms of energy on Earth due to its abundance.

Solar energy, in the form of solar radiation, can be harnessed through various systems such as solar thermal, passive heating, and photovoltaic (PV) systems. The amount of solar radiation varies based on factors such as altitude and weather conditions. Solar radiant energy on the Earth's surface is essential not only for studying climate change and environmental pollution but also for applications in agriculture, hydrology, and the food industry, as well as for promoting solar energy development programs. Nigeria receives abundant sunshine year-round, being just above the equator. The average sunshine duration is 6.5 hours daily, with an average flux of 5.55 kWh per square meter per day. The solar energy potential in Nigeria varies from 3.5 - 7.0 kWh/m^2/day [10,11]. Calculated that it would take 150 square miles of photovoltaic (PVS) to equal the output of 1000 megawatts of electricity. These figures indicate that Nigeria has the potential to generate a significant amount of electrical energy from solar energy.

Several studies have inquired about the distribution of solar energy in Nigeria and the need for an urgent transition [12]. Reveals that the so-called urban cities especially in developing countries purportedly connected to the grid network can suffer from severe energy scarcity through a case study of Nigeria. Besides low electricity generating capacity, population increase and rural-urban migration puts pressure on the existing infrastructures thus continuously widening the gap between the demand and supply also suggests the use of decentralized electricity-generating systems via the integration of solar energy technologies [13]. Accurate knowledge of the available solar resources is important for preliminary assessment of solar renewable energy technologies to ensure reliability and foster deployment. According to, about 1.2 billion individuals are still living without access to modern (stable) energy, with about 50% of them residing in sub-Saharan Africa [14-18]. Nigeria, the country with the highest population in the region, has about 100 million citizens living without clean and stable energy [19,20]. According to the rapid growth of Nigeria's population has created a wide gap between the demand and supply of electricity, and the overdependence on fossil fuel has severe adverse socio-economic, environmental, and health effects [21]. Thus, this paper seeks to understand the variation and distribution of solar radiation in Nigeria and investigate regions where solar energy can be efficiently harnessed for energy generation purposes.

2. Data and Methodology

2.1. Study Area

The study focuses on Nigeria, located at latitude 4–14°N and longitude 2–15°E, between the Equator and the Tropic of Cancer, covering a total surface area of 923,768 km2. Nigeria is divided into six geo-political zones; Northeast, Northwest, Northcentral, Southsouth, Southwest, and Southeast as shown in Figure 1 below.

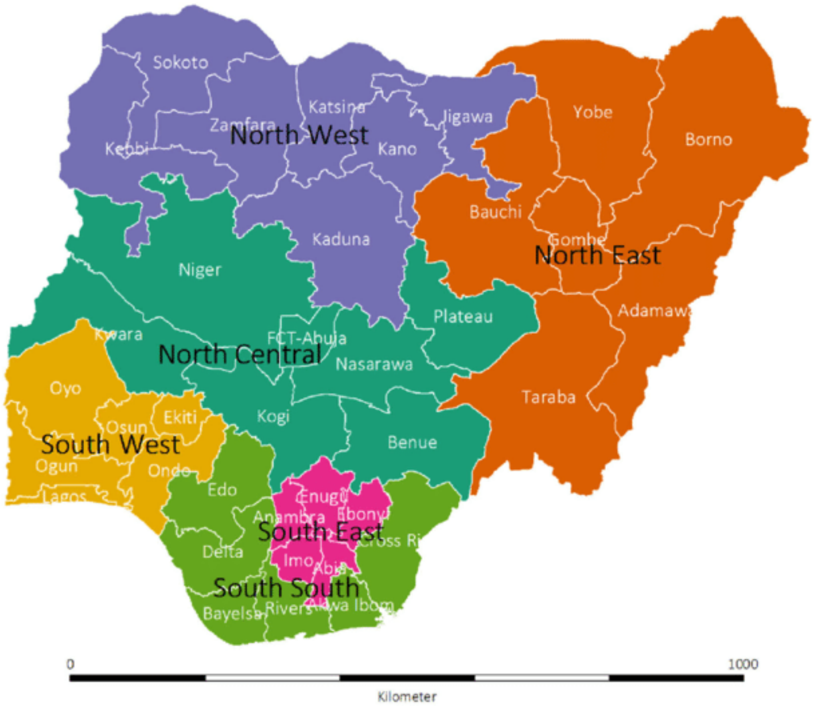


Figure 1: Map of Nigeria Showing Boundaries of Six Geopolitical Zones, 36 States and Federal Capital Territory. Adopted from [22].

2.2. Dataset

34 years (1990 - 2023) data at a spatial resolution of 0.1° × 0.1° (approximately 9 km) and a monthly temporal resolution was used for this study which was sourced from the Era5-Land reanalysis dataset provided by the European Centre for Medium-Range Weather Forecasts (ECMWF), downloaded from the Copernicus climate change service website [23]. Below is the list of variables used for this study:

- Surface net solar radiation (J/m^2): Amount of solar radiation (also known as shortwave radiation) reaching the surface of the Earth (both direct and diffuse) minus the amount reflected by the Earth's surface. The units are joules per square meter (J/m^2). To convert to surface solar irradiance in watts per square meter (W/m^2), the accumulated values was divided by the accumulation period expressed in seconds.
- Surface thermal radiation downwards (J/m^2): Amount of thermal (also known as longwave or terrestrial) radiation emitted by the atmosphere and clouds that reaches the Earth's surface. The units are joules per square meter (J/m^2). To convert to watts per square meter (W/m^2), the accumulated values should be divided by the accumulation period expressed in seconds.
- 2m temperature (K): Temperature of air at 2m above the surface of land, sea or in-land waters. Temperature was measured in kelvin and was converted to degrees Celsius (°C) by subtracting 273.15.

2.3. Methodology

The solar energy, clearness index, and estimated power were studied in the six geo-political zones in Nigeria using surface solar irradiance, extraterrestrial radiation, and temperature. The data were downloaded NetCDF data format over Nigeria where the selected regions were extracted using Python. Conversions of units to standard international (SI) units were done using climate data operators (CDO).

2.3.1. Air Clearness Index

As solar radiation travels through the Earth's atmosphere, it diminishes due to absorption, reflection, and scattering. Various factors, including moisture, dust, clouds, and temperature variations in the atmospheric layers, contribute to this reduction. Among these factors, clouds have the most substantial impact, with seasonal changes in cloud cover affecting the amount of radiation that reaches the Earth's surface. This variability is measured using the clearness index (KT), defined as the ratio of global solar radiation at the Earth's surface to the extraterrestrial radiation at the top of the atmosphere. Essentially, the clearness index indicates the fraction of extraterrestrial solar radiation that reaches the Earth's surface. It can be expressed, according to [24-27] as:

$$KT = \frac{H}{H_o}$$

KT is the monthly average of the clearness Index
H is the monthly average of total surface solar irradiance received
H_o is the monthly average of extraterrestrial radiation received

2.3.2. Estimating Energy Potential Using Power Output Rom Pv

The power output will be estimated using a monocrystalline solar panel. The sample monocrystalline solar panel used in this study as seen in figure 2 is Jinko Solar panel which is a high-efficiency monocrystalline solar panel that is popularly used for private and industrial use in Nigeria because they are affordable, and they perform well even in high temperatures.

Features of the monocrystalline solar panel. Adopted from [28].

Name: Jinko Solar panel

Model of panel: Tiger Neo 66HC

Electricity power: 635Wp

Dimension = 2382 × 1134 × 35 mm

The power output from a single monocrystalline photovoltaic panel was estimated using the expression from [29] given as:

$$P = n_o A G_t \left(1 - 0.0045\left(T_c - 289.15\right)\right) \ldots\ldots\ldots\ldots\ldots (1)$$

n_o = 0.24 (The cell electrical efficiency, calculated as electric power of the solar panel in kilowatt peak (KWp) divided by the area of the solar)

T_c is the air temperature (ºC)

G_t is the surface solar irradiance (w/m^2) flux on the panel

A = 2701188mm^2 = 2.70m^2 (Area of the panel)

Figure 2: Jinko Solar Panel

3. Result and Discussion

3.1. Spatial Distribution of Surface Solar Radiation

The annual, monthly, and seasonal distribution of the monthly average surface global irradiance from 1990 to 2023 in Nigeria is shown in Figure 3 and 4. As shown in Figure 3, the sum of the average annual solar irradiance of each region received in Nigeria is 1291.22 W/m², the northern regions, northeast, northwest, and northcentral are seen to receive more solar radiation with an annual average of 248.87 W/m2, 258.73 W/m^2, 225.97 W/m^2 which are 19.27%, 20.04%, and 17.5% respectively of the total solar irradiance received in the study area. The southern; south-south, southeast, and southwest regions receive an annual average of 177.64 w/m^2, 188.88 w/m^2 and 191.11 w/m^2 which are at a percentage of 13.76%, 14.63% and 14.84% respectively.

Figure 4, shows the monthly spatial distribution of surface solar irradiance in Nigeria shows that the northern regions receive its highest solar radiation in the month of March with an average of 284.53 W/m², especially the northwestern and northeastern regions, the southern region receives its highest solar radiation in February at an average of 222.62W/m² even though it is still lesser compared to the northern regions. The regions receive lower solar radiation during the rainy months. from April, solar radiation intensity begins to reduce through September and the lowest solar radiation in all regions was observed in July and August for as low as 140 W/m2as it can be seen that the southern regions experienced their all-time low in July while the northern regions experienced theirs in August for as low as 150 W/m^2 as seen in figure 4 below. From the seasonal distribution, Nigeria which is characterized by two major seasons, the wet and the dry season. More solar irradiance is received during the December-January-February (DJF) with an annual average of 1416 W/m^2 as seen in figure 3 and this can be characterized by the clear skies and minimal cloud cover observed during this period and it is more intense in the northern regions as the region is more affected by the dry and dusty northeasterly trade wind, harmattan. During September-October-November (SON), the northern region especially the northwestern region is seen to receive the highest radiation during this season and can be seen to reduce towards the south for all seasons. During March-April-May (MAM) and June-July-August (JJA) with an average of 1096.21 W/m2 and 13.74% lesser than September-October-November (SON), it can be seen that lesser solar radiation received in all the regions than the other seasons as the wet season brings a significant reduction in solar radiation received due to an increased cloud cover and frequent rainfall during this period but can still be seen to be substantial in the northern region as the region experiences sporadic rainfall and cloud cover.

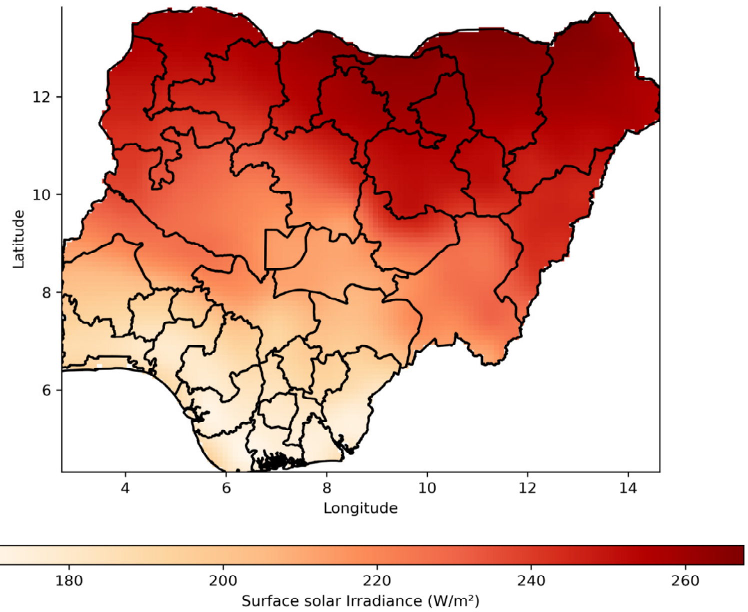
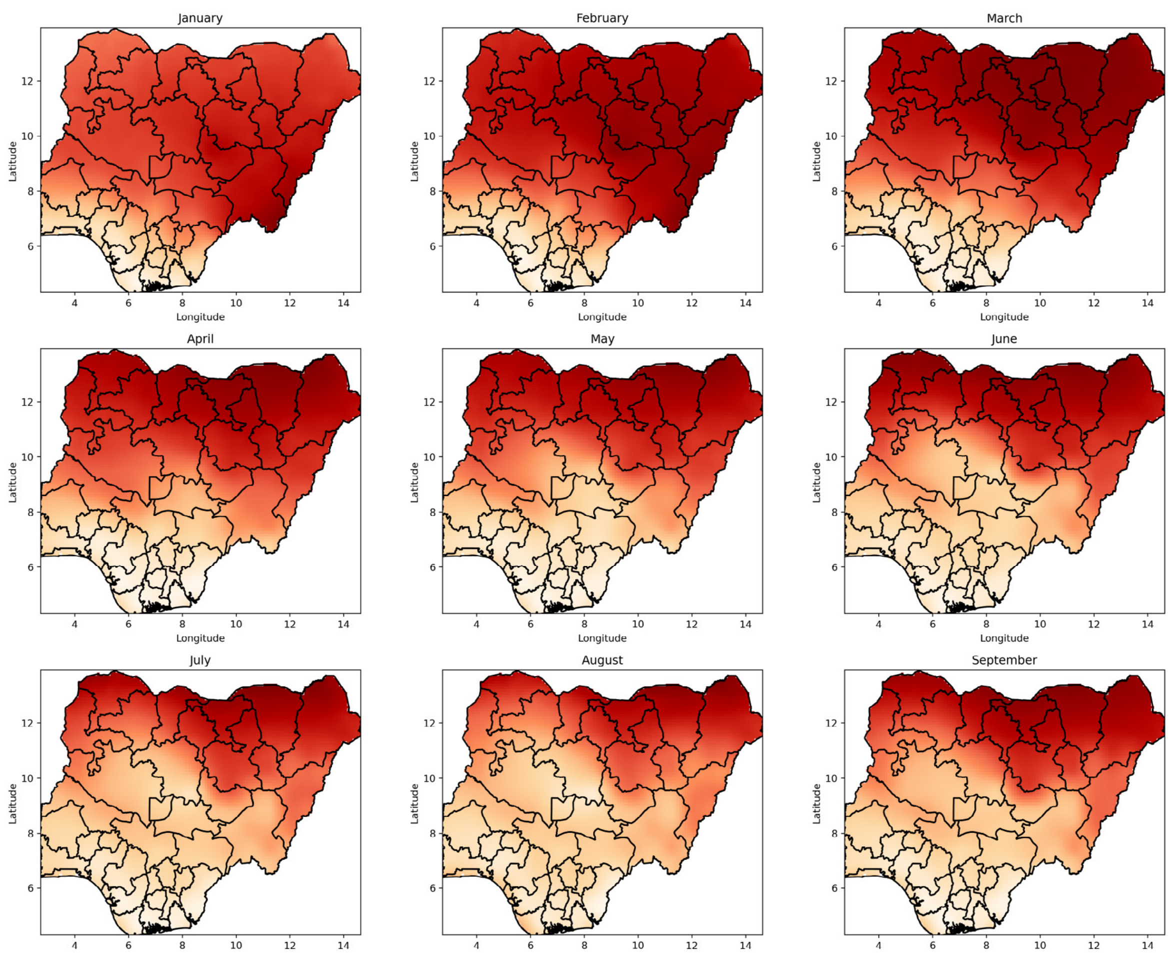


Figure 3: Annual Average of Surface Solar Irradiance



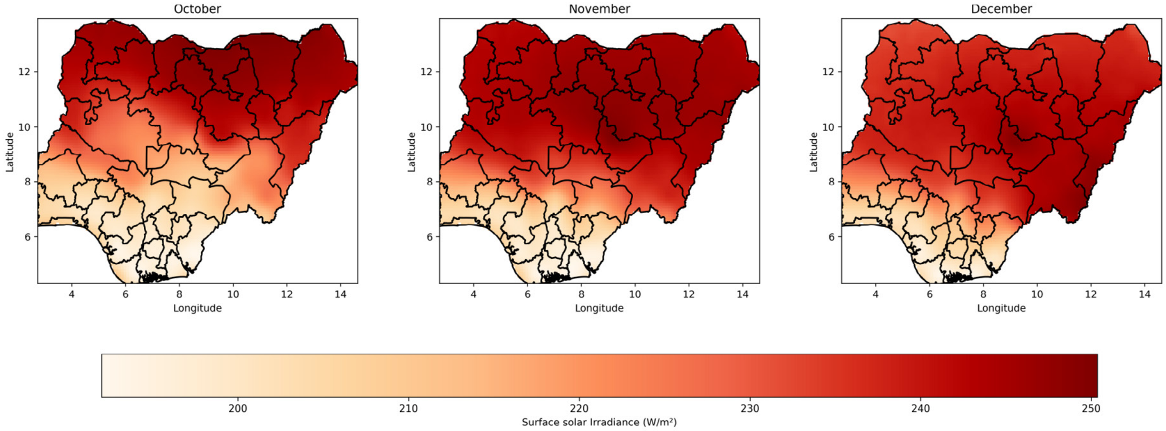


Figure 4: Monthly Average of Surface Global Irradiance

3.2. Monthly Variation of Surface Solar Irradiance

Figure 5 shows the monthly average variation of surface solar irradiance, The highest solar radiation occurred in the month of March in the northern region, with the northwest experiencing the highest. The southeastern and southwestern regions experience their highest solar radiation in February and January respectively. The northern region experiences the least solar radiation in August, while in the southwest it occurs in June, and in the southeast and south-south in July.

It is noticeable that there is a reduction in solar intensity between the months of June and August across the regions. This decrease in solar intensity can be attributed to the rainy season, during which the regions experience a high amount of cloud cover and rainfall. Cloud cover can scatter and absorb sunlight, thereby reducing the amount of solar radiation that reaches the Earth's surface.

Between the months of November and March, the highest solar radiation levels are seen to occur, unlike in the northern region, where a downward trend is observed towards the end of the year but an upward trend in the south.

Figure 6 shows the distribution of monthly surface solar irradiance received in Nigeria for each region. It is evident that the northcentral and all the southern regions have a wider spread, indicating more variability compared to the northeast and northwest regions. The northwestern region receives the most intense solar radiation, followed by the northeastern, northcentral, southeastern, southwestern, and south-south regions, which receive the least solar radiation. The mean surface solar irradiance observed in northcentral, northeast, southeast, south-south, southwest and northwest is 225.99 W/m², 248.87 W/m², 188.88 W/m², 177.64 W/m², 191.11 W/m², and 258.73 W/m², respectively. Northern Nigeria receives an abundance of solar radiation compared to southern Nigeria, which can be associated with geographical, climatic, and atmospheric factors of the region such as elevation level, cloud cover, and inclination angle.

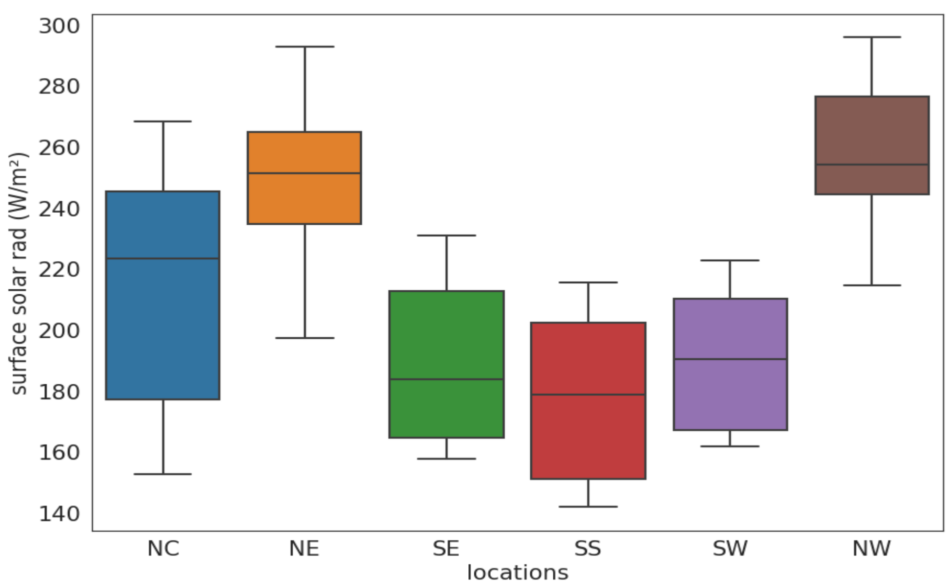


Figure 5: Monthly Variation of Surface Solar Irradiance

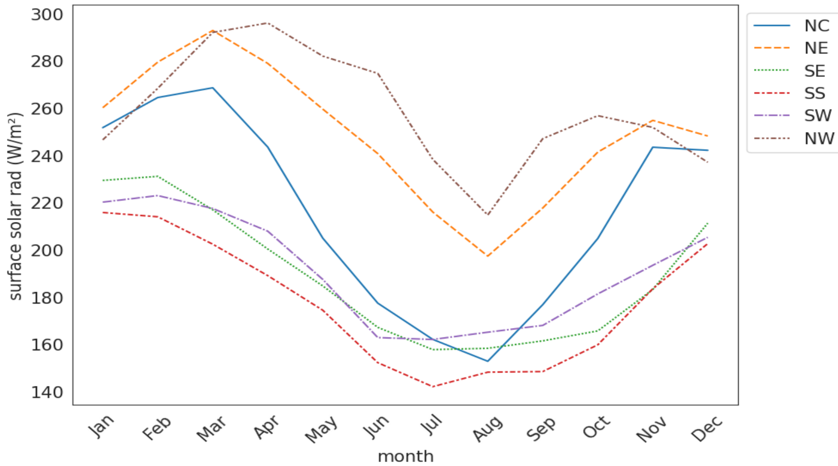


Figure 6: Monthly Distribution of Surface Solar Irradiance

3.3. Monthly Variation of Clearness Index

In Figure 7, the monthly clearness index across all locations ranges from 0.3 to 0.8. According to Li and Lam (2001) and Li and Lam (2004), a clearness index of 0-0.15 is described as overcast, >0.15-0.7 is described as cloudy, and >0.7 is described as a clear sky. This describes the average condition of each location. The northcentral region was observed to have a clearness index between 0.4-0.7, indicating that on average, a cloudy condition is experienced in this region. The interquartile range (IQR) shows that there is a variation in the condition. The northeastern region ranges from 0.5-0.8. The IQR describes a variation between cloudy and clear sky conditions in this region. The southeastern region is seen to experience lesser clearness as it ranges from 0.4-0.6, indicating a cloudy condition. From the IQR, it is left-skewed, meaning a cloudy condition is dominant in this region. The Southsouth region can be seen to have poor clearness compared to other regions, as it has the lowest value of clearness index ranging from 0.3-0.6, indicating a cloudy condition. It can be seen to have a smaller IQR and it's right-skewed, showing that a cloudy condition is dominant in the Southsouth region. Southwest experiences a clearness index between 0.4-0.6, having the same maximum as the southwestern region. Sitting beside each other, it is expected and a cloudy condition is dominant in this region. The northwestern region has the highest value of the clearness index ranging from 0.5-0.8, indicating a cloudy to clear sky. From Figure 7, it can be seen that it is slightly right-skewed, indicating a dominance of clear sky throughout the year.

It can be seen that over the southern region of Nigeria, a cloudy condition is dominant, and large quantities of diffused and reflected radiation are expected in the region, unlike the northern regions, which experience less cloudy conditions and clearer skies.

Figure 8 shows the monthly distribution of the clearness index for each location. It can be observed that all the lines are moving in the same pattern, with all the lowest points in the month of August for all regions, similar to the results obtained by [30] except the South-south region experiencing its lowest point in the month of July. This is expected as July and August fall in the rainy season in Nigeria, and it is expected to be cloudier. From October to December and January to March are seen to have clearer skies compared to the other months, especially in the northern region. The northwestern and northeastern regions experience their clearest sky in the month of March, the northcentral in February, and the southern regions in January.

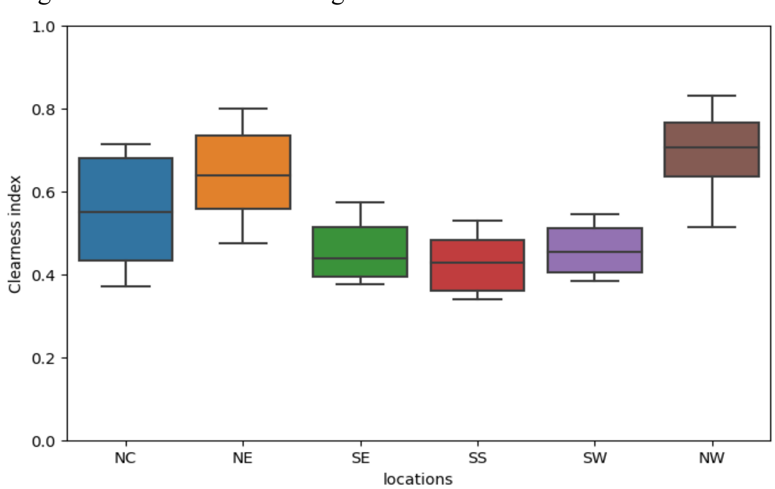


Figure 7: Monthly Variation of Clearness Index

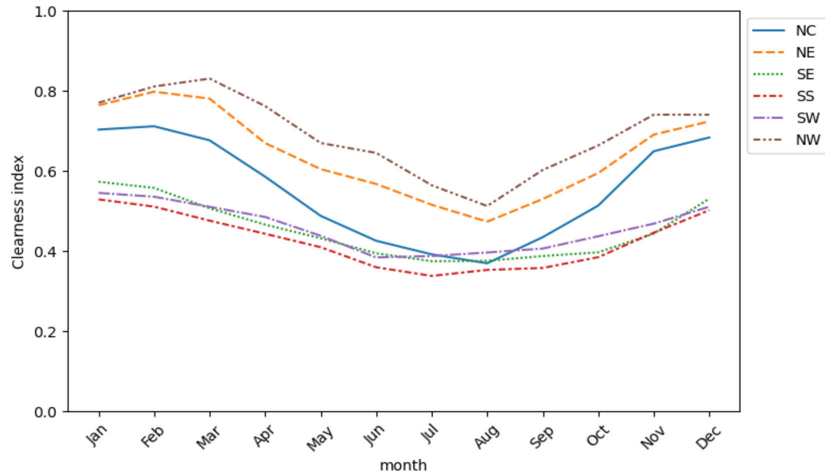


Figure 8: Monthly Distribution of Clearness Index

3.4. Estimated Energy Output

The estimated energy output from a single photovoltaic panel for each region was calculated using temperature and solar radiation data as seen in figure 9 and figure 10 below. From Figure 9, the northwestern region had the highest estimated output, ranging from 303.27 watts to 404.05 watts, with an average of 357.58 watts with low variability indicated by the left-skewed interquartile range (IQR). The northcentral region had an estimated output between 217.37 watts and 377.03 watts, with an average of 316.04 watts and high variability shown by the right-skewed IQR. The northeastern region also had a high estimated output, ranging from 278.86 watts to 408.95 watts with an average of 353.81 watts. The southern region had lower estimated solar energy compared to the northern region, with the southeastern, south-south, and southwest regions showing estimated outputs ranging from 223.66 watts to 324.78 watts with an average of 259.86 watts, 201.62 watts to 304.47 watts with an average of 253.18 watts, and 229.69 watts to 314.32 watts with an average of 268.89 watts, respectively, and all showing less variability in the estimated solar output.

The monthly variation of estimated solar energy output is shown in Figure 10. The highest estimated solar energy output was observed in March for the northwest with an estimate of 357.58 watts, northeast, and northcentral regions, in February for the southeastern and southwestern regions, and in January for the south-south region. These months had the highest clearness index, as shown in Figure 4. The lowest estimated solar energy was observed in August for all the northern regions as stated above, in July for the southeast and south-south regions, and in June for the southwest region. The mean estimated solar energy for the northcentral, northeast, southeast, south-south, southwest, and northwest regions were 316.04 watts, 353.81 watts, 259.86 watts, 253.18 watts, 268.89 watts, and 357.58 watts, respectively.

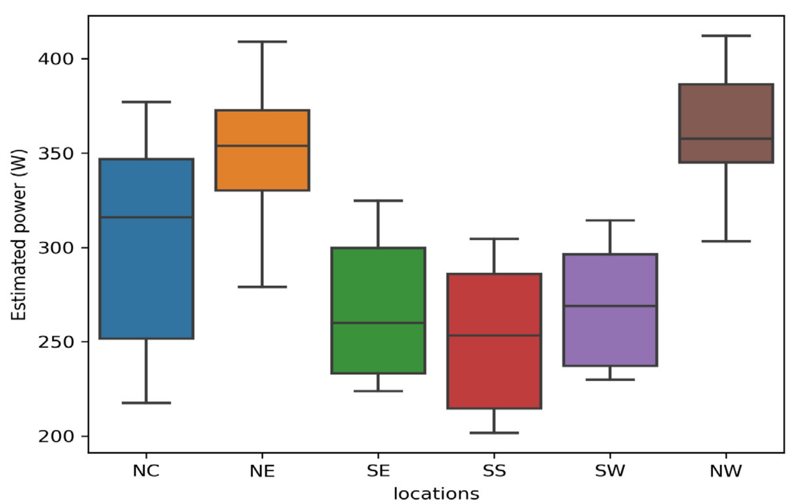


Figure 9: Monthly Variation of Estimated Power

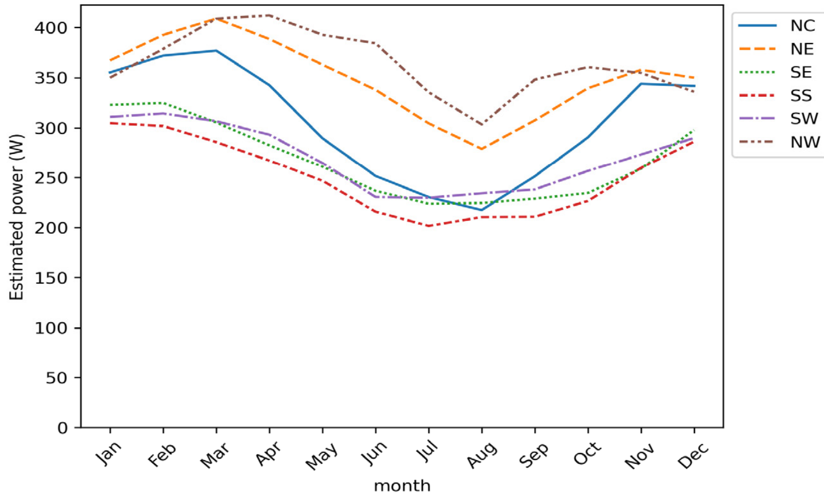


Figure 10: Monthly Distribution of Estimated Power

3.5. Discussion

This study investigates the distribution of solar radiation, clearness index and solar energy potential over Nigeria as a way of generating renewable and clean energy.

The outcome of the analysis and result demonstrated in this study shows that Nigeria as a whole is a potential site for solar energy generation due to the abundance of solar irradiance but varies by regions. It was obvious that the Northern region receives abundance of solar radiation, especially the northwestern regions which receives at an average of 284.53 W/m2. According to the spatial distribution, it can be seen that the intensity of solar radiation increases northward from the south and this can be associated with the difference in geographical and elevation levels, lesser cloudiness in the northern region, and its close proximity to the earth's equator. The monthly spatial distribution reveals that there is abundance of solar potential in Nigeria during December-January-February (DJF) but it's more intense in the northwestern and northeastern region during the September-October-November (SON) but June-July-August (JJA) is seen to receive lesser solar radiation and this is as a result of more cloud cover occurrences during this period. The reduction in the solar intensity during the wet season has an effect on the amount received, this reduction can significantly decrease solar power output because photovoltaic (PV) systems rely on direct sunlight to generate electricity efficiently.

The monthly spatial and variation plot also showed the month of February and match for Southern and Northern regions respectively experience the highest solar radiation, and in July, august for the south and north respectively experienced the lowest, the same can be seen to occur with the clearness index which describe the characteristic of cloud cover which have impact on the solar radiation reaching the surface, it was seen to be higher in the southern region which is obvious due to the closeness of the region to the ocean and experience higher relative humidity compared to the northern region. The estimated power from a single photovoltaic panel from equation 1, estimated using solar radiation and temperature reveals more power can be harnessed in the north, especially northwest and northwest compared to the south and it's estimated to be the highest in the months that falls in the pre-dry and dry season.

4. Conclusion

Nigeria has the potentials for cleaner energy development—namely wind, solar, hydro etc. It is estimated that Nigeria receives 3.5 - 7.0 kWh/m2/day of solar insolation [10]. Despite this immense potential, the country has only made little effort in harnessing this clean energy resource. Countries like Germany and Japan, which have relatively lower solar radiation levels, have become global leaders in solar energy generation through effective policies, investments in technology, and large-scale adoption. For instance, the solar insolation across Nigeria is greater than that across Germany as Germany receives an average solar radiation of approximately 2.9 to 3.6 kWh/m²/day, yet it has installed over 66.7 GW of solar capacity, [31]., similarly, Japan receives an average radiation of about 3.6 to 4.6 kWh/m²/day but achieved substantial growth in renewable energy generation.

In this study, we conducted an in-depth investigation into the potential sites for harnessing solar energy efficiently in Nigeria. We gathered and analyzed 30 years' worth of monthly data on surface solar radiation, extraterrestrial solar radiation, and temperature for various regions in Nigeria. The data were carefully averaged for each region to evaluate the clearness index and estimate the energy developed from a model.

Our analysis revealed that northwestern Nigeria receives the highest amount of solar radiation. Overall, all regions experience high levels of solar energy, particularly in the month of March. The average estimated energy for the regions is as follows: 316.04 watts for northcentral, 353.81 watts for northeast, 259.86 watts for southeast, 253.18 watts for southsouth, 268.89 watts for southwest, and 357.58 watts for northwest. Additionally, the mean solar radiation observed in each region is as follows: 225.99 W/m² for northcentral, 248.87 W/m² for northeast, 188.88 W/

m² for southeast, 177.64 W/m² for southsouth, 191.11 W/m² for southwest, and 258.73 W/m² for northwest.

Furthermore, our analysis of the monthly variation of surface solar radiation indicated that the northern regions, particularly the northwestern region, receive an abundance of solar radiation. The clearness index also pointed to a clearer sky in these regions, further highlighting their potential for solar energy harnessing. Moreover, the estimated power from Jinko photovoltaic panel suggested that the northern region has greater potential than the southern region, making it a more viable site for solar energy facilities. While the northern regions were identified as better sites for solar energy facilities, our findings also indicated that the southern regions receive a significant amount of solar radiation, making them potential locations for setting up solar energy facilities as well. This comprehensive research provides valuable insights that can aid the country in recognizing the potential for photovoltaic applications and transitioning from fossil fuel-based energy generation to renewable energy sources. By utilizing this information, Nigeria can work towards reducing emissions from fossil sources and embracing sustainable energy practices.

Acknowledgements

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