Performance evaluation of bifacial solar pv modules under different climatic regions in Nigeria

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Abstract. Nigeria's annual solar radiation is estimated to be between 1400 and 2500 kWh/m^2. This has made the use of solar energy to generate power in the country feasible. We investigated the performance of a bifacial solar PV system in Nigeria under various climatic regions in this study because bifacial PV modules are known to be location-dependent. The In-Plane solar radiation received by tilted monofacial and bifacial PV modules was calculated and compared using an analytical model. In all climatic regions, the bifacial PV system receives more in-plane solar irradiance. The systems were simulated on PVsyst to determine the energy yield, and the results show that under natural ground (vegetation and sand) of the various regions and optimization of the tilt angle, the bifacial PV system yielded more energy than the monofacial system. The bifacial gain varies depending on location, and system parameters must be optimized to improve the bifacial energy gain.

1 Introduction

Currently, 770 million people live in Africa and Asia without access to electricity. Sub-Saharan Africa alone has 77 % of the world's population without access to electricity [1]. This lack of access to energy has been identified as a major contributor to the region's poor development, both technologically and human development [2]. The downward trend in the cost of solar photovoltaic (PV), climate action, and energy security has resulted in the adoption and deployment of renewable energy technologies (RETs) [3]. Researchers were able to develop a bifacial PV module that has been studied and reported to have the ability to reduce the Levelized cost of energy of solar photovoltaic and increase the energy generation per area it is mounted on [4], [5]. This is because bifacial PV technology absorbs solar radiation by converting light into energy on both the front and back surfaces of the cell/module, boosting the energy potential of the PV modules over the conventional modules [6]. Kreinin et al. [7] reported on the major factors influencing rear irradiance and its contribution to energy generation. These factors are tilt angle, ground clearance height, seasonal sun position, and albedo. Guo et al. [8] compare a vertically mounted bifacial PV module to a monofacial PV module, and the results show that the performance of the bifacial PV module is affected by latitude, albedo, and diffuse fraction. In the literature, the energy gain for a bifacial module over conventional monofacial modules has been reported. When compared to standard modules, bifacial modules can provide up to 25% more energy for an optimal system [9]. Wang et al. [10] reported that in Konstanz, Germany, a bifacial gain of less than 10% is obtainable for an albedo of 0.2 and a bifaciality of 0.6. While bifacial PV module is projected to have a 78 % market share by 2031 [11], worldwide adoption and investment remain slow. This is because investors have not fully understood the technology and the potential benefit of this type of module over monofacial PV modules. Hence,the performance of a bifacial photovoltaic module is discussed in this study using modeling and simulation. We look at system and environmental parameters that can influence energy yield. The following objective were set:

I. Conduct solar resource assessment for the five climatic regions of Nigeria.
II. Determine the In-Plane solar radiation for various modules in each location.
III. Determine the energy yield and bifacial gain by each system in various location.

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2 Methodology

2.1 Irradiance horizontal model

The extraterrestrial radiation, which defines the intensity of solar radiation on a horizontal surface immediately outside the earth's atmosphere, is computed in the first stage using an annually variable term.

$$I_O = 1367.7 \times \left[1 + 0.033 \times \cos\left(\frac{360}{365} \times DOY\right)\right] \quad (1)$$

This extraterrestrial radiation can be used to calculate direct normal radiation, whose definition is the solar radiation incident on a surface oriented normal to the solar radiation. Direct irradiance can be estimated using two types of models: atmospheric transmittance models and models that calculate the global horizontal irradiance decomposition [12]. Because recorded global horizontal irradiance is unavailable, the atmospheric admittance method is used to determine the radiation received by a PV module at a certain location around the world over a year. Ref. [13], [14] proposed a method for calculating the amount of beam and diffuse radiation transmitted through clear atmospheres. It considers zenith angle and altitude for a normal atmosphere as well as four climatic types. The atmospheric transmittance for beam radiation is

$$\tau_b = \frac{I_{DNI}}{I_o} \quad (2)$$

Where I_o is the extraterrestrial radiation and I_{DNI} is the direct normal radiation

$$\tau_b = a_o + a_1 e^{\left(-k/\cos\theta_z\right)} \quad (3)$$

Where z is the zenith angle of the sun the constant a_o, a_1, and k are for standard atmosphere. These constants can be deduced by using the correction factors (see Table 1) and expressed as:

$$a_o^* = 0.4237 - 0.00821(6 - A)^2 \quad (4)$$

$$a_1^* = 0.5055 + 0.00595(6.5 - A)^2 \quad (5)$$

$$k^* = 0.2711 + 0.01858(2.5 - A)^2 \quad (6)$$

Where A is the altitude in kilometers and the correction factor is given as:

$$r_o = \frac{a_o}{a_o^*}, r_1 = \frac{a_1}{a_1^*}, r_k = \frac{k}{k^*}$$

Table 1: Corrector factor for tropical climate [15]

Climate Factor	Type	Correction	Tropical
r_o			0.95
r_1			0.98
r_k			1.02

For each zenith angle and altitude up to 2.5 km, the transmittance of this standard atmosphere for beam radiation can be computed. The clear-sky direct normal radiation is

$$I_{DNI} = I_O \tau_b^m \quad (7)$$

Horizontal direct radiation (I_{HDIR}), which refers to direct radiation incidents on a horizontal surface, can be estimated directly from DNI as [8]:

$$I_{HDIR} = DNI \times \cos(\theta_Z) \quad (8)$$

To calculate the total radiation, the clear-sky diffuse radiation on a horizontal surface must also be estimated. For clear days, Liu and Jordan discovered an empirical relationship between the transmission coefficients for beam and diffuse radiation, this was modified by [16];

$$I_{DHI} = 0.3(1 - \tau_b^m) I_o \cos(\theta_z) \quad (9)$$

Where m is the air mass given as $m = \frac{P_a}{101.3\ \cos(\theta_Z)}$, $P_a = 101.3 e^{-\left(\frac{a}{8200}\right)}$ and a is the altitude in meters[16], [17]. The global horizontal radiation becomes;

$$I_{GHI} = DNI\ \cos(\theta_Z) + I_{DHI} \quad (10)$$

$$I_{GHI} = I_O \tau_b^m \cos(\theta_Z) + 0.3(1 - \tau_b^m) I_o \cos(\theta_z) \quad (10a)$$

$$I_{GHI} = I_O \cos(\theta_Z)[\tau_b^m + 0.3(1 - \tau_b^m)] \quad (10b)$$

2.2 Optical model on Plane of module

The in-plane irradiance on the module is determined using the transposition model [18];

$$I_t = I_{bt} + I_{dt} + I_{gt} \quad (11)$$

Where I_{bt} is the sum of the direct normal irradiance on the plane of array, I_{dt} is the sum of the diffuse irradiance and I_{gt} is the sum of the ground reflected irradiance on the plane of array. The bifacial gain is given as [19]:

$$Bifacial\ Gain\ (\%) = \left(\frac{Y_b}{Y_m} - 1\right) \times 100 \quad (12)$$

2.3 Input Parameters Considered

we consider the environmental and system parameters to estimate the in-plane solar radiation received on monofacial and bifacial modules considered in selected locations on the 21st of April and the 21st of August. The month of April and August were chosen as they represent the wet and dry season variation in the country [20]. To determine the performance of the system under different climatic conditions, a 90 kW_p system will be design and simulated with the PVsyst software 7.2.5. The same size and type of module (JKM400M-72-72H-BDVP & JKM400M-72H-V) for bifacial and monofacial panel will be selected within the software for the simulaton of the

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system. Table 2 and 3 consist of other parameters to be considered for the simulation.

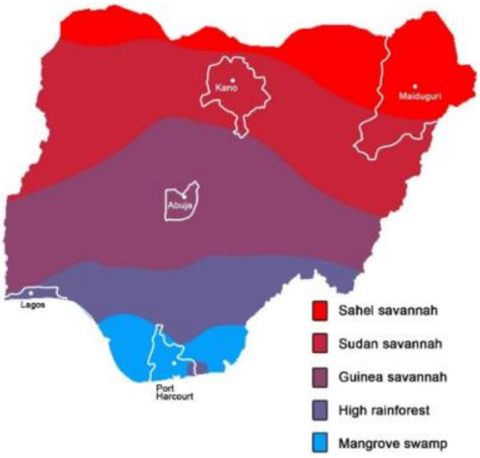

Figure 1 Climatic regions in Nigeria [21]

Table 2 Climatic regional locations

Location	Latitude	Altitude (m)	Tilt Angle	Albedo
Port Harcourt	4.8472° N, 6.9746° E	20	10^0	0.20
Kano, Nigeria	12.0022° N, 8.5920° E	488	15^0	0.25
Borno	11.8846° N, 13.1520° E	314	15°	0.25
Nassarawa	8.5475° N, 7.7118° E	199	10°	0.25
Lagos	6.5244° N, 3.3792° E	41	10°	0.20

Table 3 Electrical Specification and Quantity

Characteristics	Monofacial	Bifacial	Inverter
P_{mpp} (W_p)	400	400	30000
V_{mpp} (V)	41.0	40.9	300 – 600
I_{mpp} (A)	9.80	9.76	
V_{oc} (V)	49.8	48.8	
I_{sc} (A)	10.36	10.24	
Quantity	225	225	3

3 Result and Discussion

Figure 2 shows the global horizontal irradiance available in the selected locations for the month of April and August. The considerable differences in values between

April and August seasons are ascribed to aerosol particle attenuation in the dry season and increased cloudiness and humidity in the wet season [7].

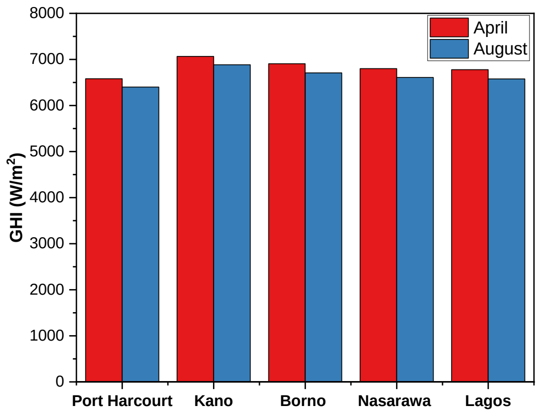

Figure 2 Global Horizontal irradiance in each of the location

3.1 Daily In-plane Irradiance received by a bifacial and a mono-facial module

The monofacial and bifacial PV modules are tilted at an angle greater than the latitude and oriented toward the equator. Figures 3 and 4 depict the amount of in-plane irradiance incidents on the modules. The bifacial PV module tilted towards the equator receives the most radiation in all the climatic regions of Nigeria. It has been reported by [22] that the amount of irradiance striking the modules affects their performance and energy yield. Therefore, Bifacial PV modules are expected to yield more energy.

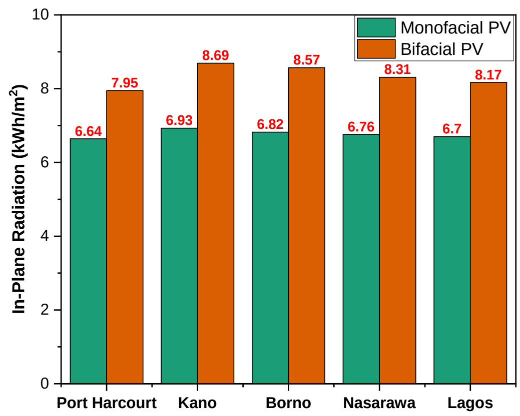

Figure 3 Single Day In-Plane radiation on Monofacial and Bifacial PV modules in the various climatic regions for April

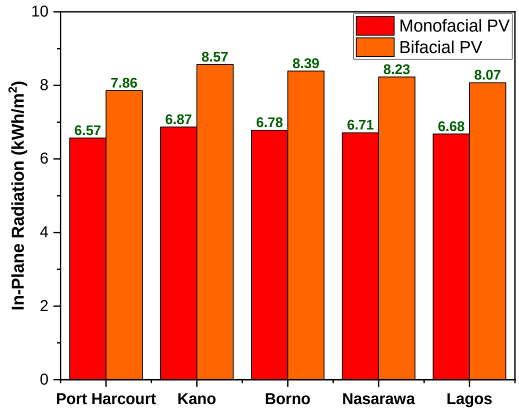

Figure 4 Single Day In-Plane radiation on Monofacial and Bifacial PV modules in the various climatic region for August

3.2 System Energy Production

The result from the simulation of a 90kWp is shown in figure 5. The 90kWp system was simulated with a fixed mounting structure for both bifacial and monofacial systems. The tilt angle and albedo were varied with respect to each of the locations to represent real-life scenarios. This resulted in an annual energy yield of 129.4MWh/year for bifacial PV systems and 124.7MWh/year for monofacial PV systems in Port Harcourt, 164.8MWh/year for a bifacial PV system, and 158.1 for monofacial PV system in Kano, 160.7MWh/year for a bifacial PV system and 154.0MWh/year for Borno, 154.2MWh/year for a bifacial PV system and 147.7MWh/year for a monofacial PV system in Nasarawa and 141.2MWh/year for a bifacial PV system and 135.1MWh/year for monofacial PV system in Lagos. The bifacial gain, defined as the extra energy yield by a bifacial module of the same system size installed under the same conditions as the monofacial system, was calculated and represented in figure 5. Sun et al. [19] reported a similar result, and in the authors' global analysis of bifacial PV modules, latitude below 30° with an albedo of 0.25 will have less than 10% bifacial gain.

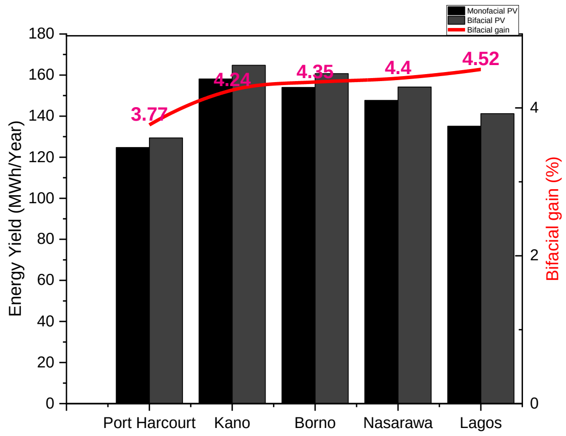

Figure 5 Energy yield and bifacial gain

4 Conclusion

In summary, this study used an analytical method to determine and compare the radiation received by an inclined monofacial and bifacial module under two different climatic conditions. The bifacial PV module was discovered to receive more in-plane irradiance under the different climatic regions. The solar radiation at the chosen location varies with latitude. We simulated the energy yield of the two systems using PVsyst, and the analysis revealed that with an albedo of 0.20 and 0.25 for natural ground [23], the bifacial PV system will have a bifacial energy gain over the monofacial system depending on the climatic region the system will be installed. System parameters such as albedo, tilt angle, and module elevation above ground should be optimized to increase the energy yield from bifacial PV modules.

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