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DETERMINATION OF SEASONAL AVERAGE OPTIMAL TILT ANGLE USING SIMPLEX LINEAR PROGRAMMING

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Abstract: This article analyses the optimal choice of the tilt angle for the solar panel in order to collect the maximum solar irradiation in North-central of Nigeria. An isotropic method was used using the data collected at federal Polytechnic Offa, Kwara State, Long. 4.5418^{0}E and lat. 8.4799^{0}N in other to determine the optimum tilt using simplex algorithm. It was discovered that the two seasons in Nigeria; rainy and dry seasons have different optimum tilt angle, one facing the south and one facing the north at the position of the installation PV panel in the northern hemisphere. However, results shows that the range of optimum tilt angle in the dry season is $-30.02 \leq \beta \leq -29.90$ and in rainy season is $27.508 \leq \beta \leq 29.98$ with standard errors $\pm$0.065and $\pm$0.645 respectively. It was also found that the average optimum tilt angle at Offa, Kwara state, north-central part of Nigeria can be written as for the two seasons of the year is $\beta = \pm(\varphi+20)$, and the positive and negative signs represent the orientation of PV panel facing south and north directions respectively.
Keywords: Tilt angle, Simplex Algorithm, PV Panel, Optimum Energy

1. INTRODUCTION

The performance of a Solar cell or Photovotaic (PV) panel depends on many factors which includes the location of the installation of the panel, the environmental factors of the area, the tilt angle and so on, this determine the solar radiation received. The primary factors are the position and angle of tilt of a PV panel in the design of PV system, thus determine the amount of energy captured from the sun. If solar panels are mounted horizontally or vertically, lesser energy is captured than if the panels face due south in the Northern Hemisphere and due north in the Southern Hemisphere and are tilted towards the sun. Hence, the global solar irradiation on tilted surfaces facing in different directions should be considered to estimate solar energy received in architectural planning and the output of a PV panel is highest when the incident ray is perpendicular to the panel plane [Murat et. al, 2004].

However, since energy received by the PV panel depends on the optimum tilt of a location and which also depends on the latitude and the day of the year [D. Ibrahim, 1995]. In Egypt, the optimum tilt is greater (usually latitude +15°) in winter months; whilst in summer months the optimum tilt is lower (usually latitude -15°). In 1991 solar atlas for Egypt was issued indicating that the country enjoy 2900-3200 hours of sunshine annually with annual direct normal energy density 1970-3200 kWh/m2. Nigeria is in advantageous position with solar energy, located in northern hemisphere same position as Egypt. [D. Loy, 2007].

In Addition, The output of a PV panel is highest when the incident ray is perpendicular to the panel plane plane [Murat et. al, 2004]. This collected solar energy depends on local solar irradiation, ground reflection property, the alignment of the PV array and the tilt angle. Applying the active sun tracker is the finest technique to optimize the tilt angle and alignment of a PV panel to receive the maximum solar energy. The solar tracker periodically adjusted to optimum the tilt and the alignment of a solar panel. The sun trackers are either pure mechanical or electromechanical devices but these systems have twofold problems (a) the high investment to install the facility and, (b) the consumption of energy by the tracking devices couple with the variation of tilt angle from one location to another [Khatib, 2015].

2. PREVIOUS WORK DONE

In the last few years, many models that allow calculating global solar radiation on a tilted surface from the available data on a horizontal surface have been presented [Hay, 1979 and Liu & Jordan, 1962]. Some of these models require special measurements [Li & Lam, 2007]; and some apply to only specific cases. There are two ways of approach but both models determine the beam and the ground reflected radiation incident on an inclined surface but the only difference among these approach is the treatment of the sky diffuse radiation. The approach can be either isotropic [Hay, 1979] or anisotropic [Liu & Jordan, 1962] depending on the assumption of the sky diffuse component.

Many papers address the issue of isotropic distribution and the common assumption is in calculating diffuse radiation incident on inclined surface from the horizontal surface and that sky radiation sky diffuse radiation from a horizontal surface into an inclined surface [Liu & Jordan, 1962; Kamali, 2005, Notton, 2006; Duffie & Beckman, 2006; and K. Gopinathan, 1990]. There are several proposal schemes for optimizing the tilt angle of solar PV modules for various latitudes [Kaddoura et. al, 2016 and Hertzog & Swart., 2016]. Mahmoud and Nabhan demonstrated that using of PV mounting structure of adjustable tilt angle can improve the PV by 5.6% [N. M. Mahmoud., 2013]. Yakup and Malik observed that altering the tilt angle every month in a year as altering the tilt angle daily to its optimal value and this acquires a yearly increase in solar irradiation of 5% more than the case of a PV module fixed on a parallel plane [Yakup & Malik, 2011]. Heywood recommended that the optimum tilt angle of yearly used PV module to local latitude angle (φ), $\beta = \varphi$-10° [Heywood, 1971], whereas Chinnery recommended that the optimum tilt angle of PV module applied in South Africa was local $\beta = \varphi$ +10° [C. DNW, 1981]. In the USA, the optimum tilt angle of PV modules applied for space heating should be $\beta = \varphi$+20° [Tang & Wu, 2004].

Furthermore, Qiu and Riffat suggested the tilt angle of the solar collector set within the optimum tilt angle, β = ±10∘ as an acceptable practice [Qiu & Riffat, 2003].Other, computations led to the values of $\beta = \varphi \pm 20°$ [Yellott, 1973], $\beta = \varphi \pm 8°$ [Lewis,1987], $\beta = \varphi \pm 5°$ [Garg, 1987], and $\beta = \varphi \pm 15°$ [Lunde,1980], where φ represents the geographical latitude and the signs + and − refer to winter and summer months, respectively. The disagreement among these values may be due to two main reasons: firstly, the different methods of calculation that were used for the determination of the optimum slope value of a solar panel; secondly, the different empirical models that were considered for the determination of diffuse solar radiance and its link with the amount of global solar radiation. Table 1 and Table 2 give different algorithms proposed for calculating the optimum tilt angle for any location and period.

Table 1: Optimum tilt angle-latitude angle relations [Yadav & Chandel, 2013 and Duffie & Beckman, 2006]

Model	Tilt angle Algorithm
Duffie and Beckman	(ϕ + 15°) ± 15° Negative sign is for summer and positive sign for winter season
Yellot	(ϕ + 20°)
Lof and Tybout	ϕ + (10° → 30°)
Kern and harris	(ϕ + 10°)
Lunde	(ϕ ± 15°)
Garg	ϕ + 15o, ϕ − 15°, 0.9ϕ
Hottel	(ϕ + 20°)
Heywood	(ϕ − 10°)
Elminir et al.	(ϕ + 15°) ± 15°
Chinnery	(ϕ + 10°)

Table 2: Solar PV panel tilt angle [Mariam & Husni, 2006]

Latitude angle	Tilt angle
0-15°	15°
15-25°	Same as latitude angle
25-30°	+ 5° to local latitude angle
30-35°	+ 10° to local latitude angle
35-40°	+ 15° to local latitude angle
40°+	+ 20° to local latitude angle

This article analyses the optimal choice of the tilt angle for the solar panel for the two types of season in Nigeria, Dry season (November to April) and rainy season (May to October) in order to collect the maximum solar irradiation. In this paper, PV panel is located in Offa, Kwara state, North-central of Nigeria (*Long.* 4.5418^{0}E and lat. 8.4799^{0}N). However, accurate mathematical modelling of global and diffuse solar radiation that was used for the simulation in this study is proposed in the next section.

3. METHODOLOGY

Global solar radiation on a tilted

Global solar radiation on a tilted surface (H_T) consists of daily direct solar radiation (H_b), diffuse solar radiation (H_d), and ground reflected radiation (H_r),

$$H_T = H_b + H_d + H_r \quad (1)$$

Daily solar radiation on a tilted surface for a given month can be estimated as follows [Lewis, 1987]:

$$H_T = H_B + H_R + H_D \quad (2)$$

Where, H_T, H_B, H_R and H_D are respectively the monthly average daily total, beam, diffuse, and reflected radiation on a tilted surface in (MJ/m^2/day).

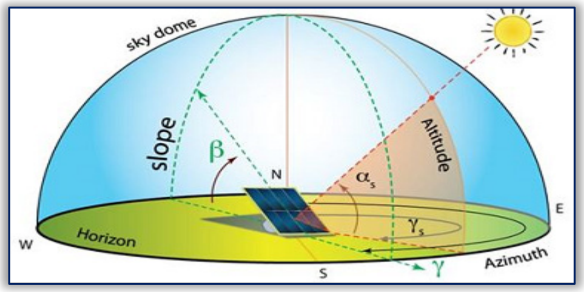

Figure 1: Zenith, azimuthal, and hour angles [opt Tilt angle]

Beam Radiation Incident on a Tilted Surface

$$H_b = H_g - H_d \quad (3)$$

where, H_b, H_g and H_d are respectively the monthly average daily beam, daily global and diffuse radiations on a horizontal surface in (MJ/m²/day),

The monthly average daily beam radiation received on a tilted surface can be expressed as:

$$H_B = \frac{\cos\theta}{\cos\theta_z} = H_b R_b \quad (4)$$

R_b is the ratio of direct (beam) radiation on the tilted surface to that on a horizontal surface

The direct and diffuse components of solar radiation can be estimated using empirical relationships H_d is a function H_g by means of the clearness index KT. Muneer [Muneer, 2004] recommends the model proposed for temperate climates and locations out with the tropics, equation (5) given by [Page,1977] may be used:

$$\frac{H_d}{H_g} = 1.00 - 1.13K_T \quad (5)$$

The daily direct radiation on a tilted surface H_b can be obtained by means of R_b, the ratio of the average monthly direct radiation on a tilted plane to that on a horizontal plane and the parameters to it correlated [Duffie & Beckman, 1991]:

$$R_b = \cos\beta - (\sin\beta(\sin\delta\cos\phi\cos\gamma - \cos\delta\sin\phi\cos\omega\cos\gamma - \cos\delta\sin\gamma\sin\omega) \times (\sin\delta\sin\phi + \cos\delta\cos\phi\cos\omega)^{-1} \quad (6)$$

where, β is the slope of the panel as to the horizontal plane, γ is the azimuth, ω is the solar hour angle, φ is the latitude, and θ and θz are the solar incidence angle on the considered plane and the solar zenith angle, respectively.

Liu and Jordan (1962) have suggested that R_b can be estimated by assuming that there is no atmosphere. In the northern hemisphere the surfaces which are sloped towards the equator, R_b is given as [Ionita & Alexandru, 2012]:

For due south surfaces in the northern hemisphere, sloped towards the equator, the equation for R_b is expressed as:

$$R_b = \frac{\cos(\phi-\beta)\cos\delta\sin\omega_S' \sin(\phi-\beta)\sin\delta}{\cos\phi\cos\delta\sin\omega_S + \frac{\Pi}{180}\omega_S\sin\phi\sin\delta} \quad (7)$$

where ,ωₛ is the hour angle given by:

$$\omega_S' = \min\begin{cases}\cos^{-1}(-\tan\phi\tan\delta) \\ \cos^{-1}(-\tan(\phi-\beta)\tan\delta)\end{cases} \quad (8)$$

where “min” means the smaller of the two values in the bracket. δ and ϕ are the declination angel and latitude angle of a location respectively.

Ground Reflected Radiation Incident on a Tilted Surface

The monthly average daily ground reflected radiation incident on an inclined surface in (MJ/m²/day) is given by:

$$H_R = \frac{1}{2} H_g \rho (1 - \cos\beta) \quad (9)$$

where, ρ is the solar reflectivity.

The sky diffuse radiation incident on an inclined surface in (MJ/m²/day) is given by:

$$H_D = R_d H_d \quad (10)$$

$$H_D = \frac{1}{2} Hg\rho(1 - \cos\beta) \quad (11)$$

where ρ represents the diffuse reflectance of the ground (also called ground albedo).

The global solar radiation incident on a sloped surface depends on the position of the sun along its daily trajectory (represented by the solar angle ω) and on the orientation of the panel (represented by the slope β and the azimuth γ).

Liu and Jordan model (1962)

$$R_d = \frac{1}{2}(1-\cos\beta) \tag{12}$$

Here Hd is the intensity of diffuse radiation onto a horizontal plane [W/m2].

The monthly mean daily extra-terrestrial radiation on horizontal surface is given by Diffi and Beckman (1991) as follows:

$$H_0 = \frac{24}{\Pi} I_{sc} E_0 \left(\frac{\Pi}{180} \omega_s \sin\phi \sin\delta + \cos\phi \cos\delta \cos\omega_s \right) \tag{13}$$

where, I_{sc} is solar constant= 4.9212MJm^{-2}day^{-1} and E_0 is eccentricity correction factor of the earth's orbit which is inverse relation distance of the sun to the earth given by:

$$E_0 = 1 + 0.033 \cos\left(\frac{360n}{365} \right) \tag{14}$$

The day length N_0 is given by cooper's formula:

$$N_0 = \frac{2}{15} \times \omega_s \tag{15}$$

where n is the day of the year. Recommended average

The declination δ can be computed from the following equation (Duffie and Beckman 1991):

$$\delta = 23.45 \sin\left(360 \times \frac{n+284}{365} \right) \tag{16}$$

Where, n is day number from 1st January to 31st December of the year.

The Proposed Simplex Algorithm for Total Radiation Incident on a Tilted Surface

The total radiation incident on an inclined surface in (MJ/m^2/day) is given by:

$$H_T = H_b R_b + \frac{1}{2} Hg\rho(1-\cos\beta) + H_d R_d \tag{17}$$

The algorithm proposed here is based on the assumption that the daily solar irradiation impinging on a collecting surface is maximized with respect to the angles β, γ, and ω, where β is the slope of the panel as to the horizontal plane, γ is the azimuth, and ω is the solar hour angle, respectively.

Hence, the total solar irradiation falling on tilt surface is calculated by changing the tilt surface between 0o and 90o. Whereas for grass land, ρ is supposed to be 0.3. The optimal tilt angle is held at that solar irradiation on the tilted surface (HT) grows maximum [Lewis, 1987]. For known Rb and Hd / H ratio, monthly average daily irradiation on tilted surface was calculated. For a fixed orientation, the optimum tilt angle can be found by solving the following equation for tilt angle.

This physical condition for the maximization of the solar radiation acquired by a solar panel can be represented by the mathematical expressions [Calabr`o, 2012]:

$$\partial H_T / \partial\beta = \partial H_T / \partial\gamma = \partial H_T / \partial\omega = 0 \tag{18}$$

Their application to the isotropic model of [Liu & Jordan, 1960] provides the following expressions [Calabr`o, 2012]:

$$\partial H_T / \partial\beta = 0 = \sin\beta\left(H_0 + \frac{H_d}{2} - \frac{H_g\rho}{2} \right) - (H_0 \cos\beta(\cos\delta\sin\phi\cos\omega\cos\gamma - \sin\delta\cos\phi\cos\gamma + \cos\delta\sin\gamma\sin\omega) \times (\sin\delta\sin\phi + \cos\delta\cos\phi\cos\omega)^{-1} \tag{19}$$

$$\partial H_T / \partial\gamma = 0 = \sin\gamma(\cos\delta\sin\phi\cos\omega - \sin\delta\cos\phi) - \cos\gamma\cos\delta\sin\omega \tag{20}$$

$$\partial H_T / \partial\omega = 0 = \sin\omega\sin\delta\cos\gamma - \cos\delta\cos\phi\sin\gamma - \cos\omega\sin\delta\sin\phi\sin\gamma \tag{21}$$

This set of equations can be solved with respect to the angles β, γ, and ω [Calabr`o, 2012]:

$$\beta=\tan^{-1}\left[\begin{matrix}H_0(\cos\delta\sin\phi\cos\omega\cos\gamma\\ -\left\{\begin{matrix}\sin\delta\cos\phi\cos\gamma+\cos\delta\sin\gamma\sin\omega)\\ \times\left(H_0+\frac{H_d}{2}-\frac{H_g\rho}{2}\right)\end{matrix}\right\}\times(\sin\delta\sin\phi+\cos\delta\cos\phi\cos\omega)^{-1}\end{matrix}\right] \quad (22)$$

$$\gamma=\tan^{-1}\left[\frac{\cos\delta\sin\omega}{\cos\delta\sin\phi\cos\omega-\sin\delta\cos\phi}\right] \quad (23)$$

$$\omega=\sin^{-1}\left[\left(\begin{matrix}\langle\sin\delta\cos\delta\sin\gamma\cos\gamma\cos\phi\rangle\\ \pm\sqrt{\left\langle\begin{matrix}\sin^4\delta\times\left\{\begin{matrix}\sin^2\phi\cos^2\gamma\cos^2\gamma\\ +\sin^4\phi\sin^4\gamma\end{matrix}\right\}\\ -\sin^2\delta\cos^2\delta\\ \times\sin^2\phi\cos^2\phi\sin^4\gamma)\end{matrix}\right\rangle}\times\left(\begin{matrix}\sin^2\delta\cos^2\gamma\\ +\sin^2\delta\sin^2\phi\sin^2\gamma\end{matrix}\right)^{-1}\end{matrix}\right)\right] \quad (24)$$

The transcendent equations (13), (14), and (15) can be solved by iterative methods with respect to the angles β, γ, and ω, which provide, respectively, the optimum tilt and orientation of the solar panel and the angular position of the sun in the sky where the maximization of the solar radiation on the panel occurs

$$\frac{\partial H_T}{\partial\beta}=0 \quad (25)$$

Now, since diffuse and ground reflected parts are negligible, the above equation turns into

$$\frac{\partial R_b}{\partial\beta}=0=\frac{\sin(\phi-\beta)\cos\delta\sin\omega_S\cos(\phi-\beta)\sin\delta}{\cos\phi\cos\delta\sin\omega_S+\left(\frac{\pi}{180}\right)\omega_S\sin\phi\sin\delta} \quad (26)$$

$$\beta=\phi-\tan^{-1}\left(\frac{\pi/180\,\omega_S\sin\delta}{\cos\delta\cos\omega_S}\right) \quad (27)$$

For fixed values of φ, ωs and δ for a particular month at a specific location, the optimal tilt angle of the solar PV module is easily determined. $\cos\delta\cos\omega_S$

Estimation of Hourly Solar Radiation on a Horizontal Surface from Daily Data When hour-by-hour performance estimations for a solar system are needed, it is necessary to start with daily data and then to estimate hourly values from daily data. The ratio of hourly total radiation I to daily total radiation H on a horizontal surface is expressed as a function of day length. The ratio I/H is represented by the following equation of (Collares-Pereira, Rabl 1979):

$$\frac{I}{H}=\pi/24\frac{(c_1+c_2\cos\omega)(\cos\omega-\cos\omega_S)}{\left(\sin\omega_S-\frac{\pi\omega_S}{180}\cos\omega_S\right)} \quad (28)$$

$$c_1=0.409+0.501\sin(\omega_S-60) \quad (29a)$$

$$c_2=0.6609-0.4767\sin(\omega_S-60) \quad (29b)$$

The ratio of hourly diffuse radiation (Id) to the daily diffuse radiation (Hd) on a horizontal surface is a function of time and day length. Liu and Jordan (1962) reported that Id/Hd is the same as I0/H0, and is estimated from the following equation.

$$\frac{I_d}{H_d}=\pi/24\frac{(\cos\omega-\cos\omega_S)}{\left(\sin\omega_S-\frac{\pi\omega_S}{180}\cos\omega_S\right)} \quad (30)$$

4. RESULTS AND DISCUSSION

Computer program in Microsoft Excel were developed using the above formulate to calculate the optimum tilt angle for monthly average daily total radiation for both the rainy and dry season. The month July and August represent the middle rainy season while November represents the late to early dry season (shown Figure 2, Figure 3 and Figure 4). Similarly, the month of January and February represent the mid dry season and April represents late dry to early rain season (shown Figure 5, Figure 6 and Figure 7).

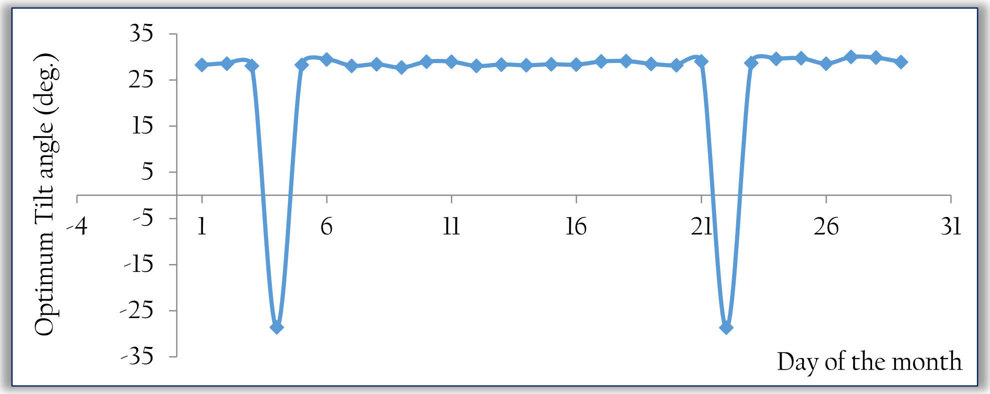

Figure 2: Graph of Daily optimum tilt angle for the month of August

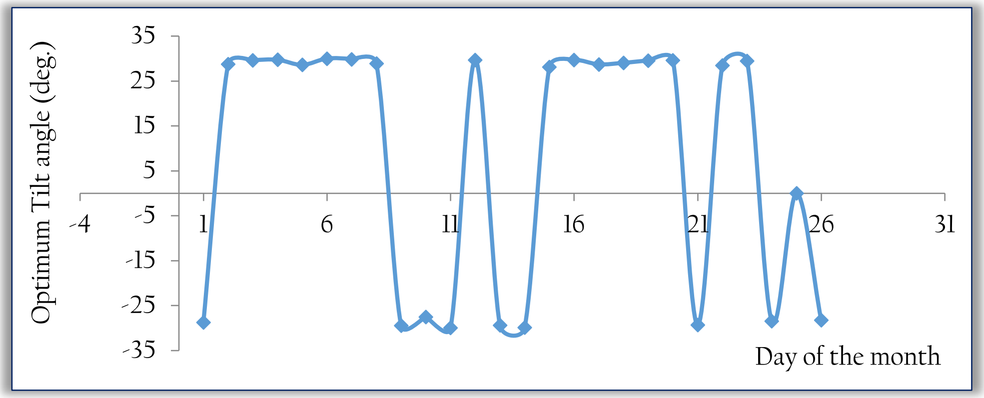

Figure 3: Graph of Daily optimum tilt angle for the month of July

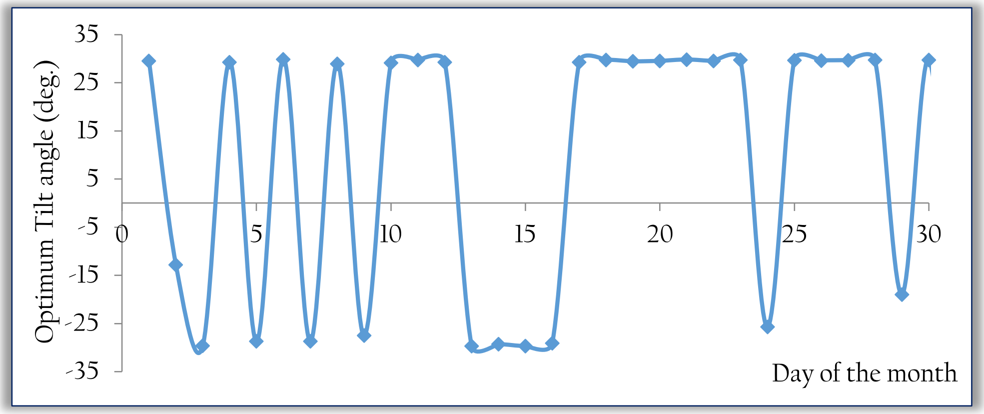

Figure 4: Graph of Daily optimum tilt angle for the month of November

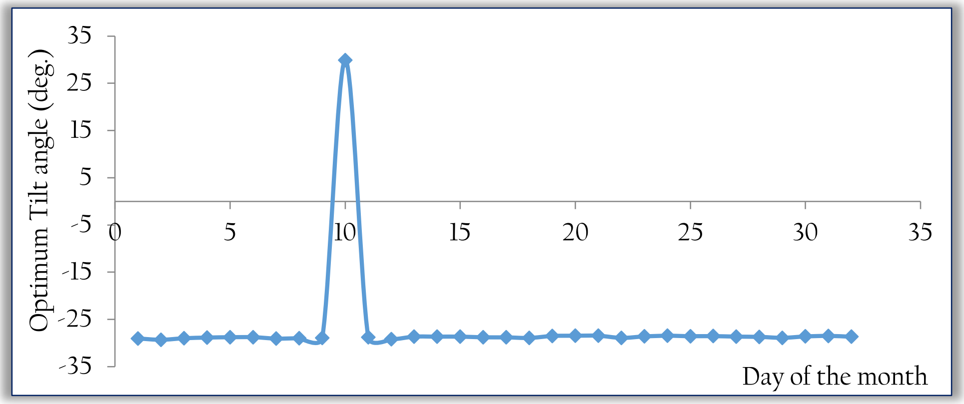

Figure 5: Graph of Daily optimum tilt angle for the month of January

From Figure 2 and Figure 3, it is seen that the most of the curve is around positive axis showing the optimum daily tilt angle is around +28° to +29° except some few cases where -28° to -27°.
However, The optimum angle of tilt of a flat-plate collector in November in Figure 4 is switching between the two axis because there is change in the season condition and is between -27° to -28° and +28° to +29°. Yet setting the tilt angle to positive will gives more maximum energy received due to more positive tilt angle than negative angles.
Figure 5, Figure 6 and Figure 7 show the optimum daily tilt angle for maximum energy receive in the month of January, February and April respectively for the dry season. Figure 5 and Figure 6 show the optimum tilt angles for each month of the dry season of year for maximum energy received range between -27° to -29°.

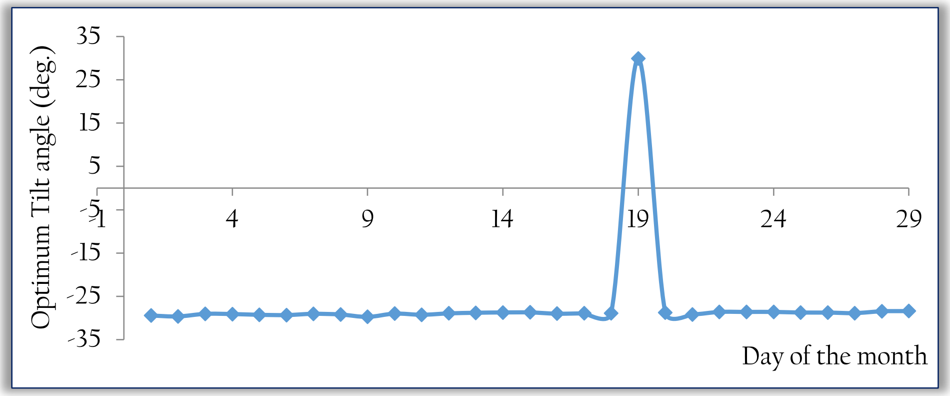

Figure 6: Graph of Daily optimum tilt angle for the month of February

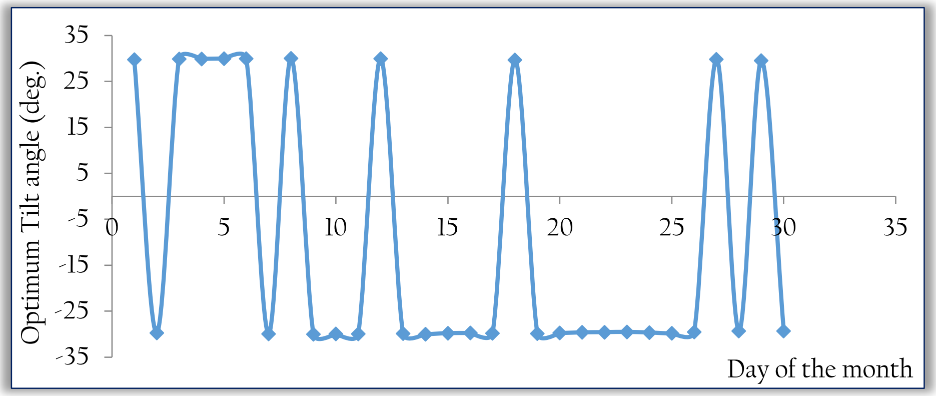

Figure 7: Graph of Daily optimum tilt angle for the month of April

Figure 7 shows the optimum tilt angle alternating between from positive to negative tilt angle with the positive tilt angle between 28° to 29°, and the negative optimum tilt angle between -27° to -29°. the positive and negative signs means that for the positive in northern hemisphere which represents the rainy season the orientation of PV panel is south faced and negative sign which represents the dry season the orientation of PV panel is north faced.

5. CONCLUSIONS

The optimum tilt is different for each months of the year. The collected solar energy will be greater if we choose the optimum panel tilt for each month. The statistical results shows that the range of optimum tilt angle in the dry season to the nearest 2.d.p, $-30.02 \leq \beta \leq -29.90$ and for the rainy season, the optimum tilt angle is $27.508 \leq \beta \leq -29.98$.the standard deviation for the rainy and dry seasons are 0.652 and 0.426 respectively. The skew values are 9.44 and 5.99 and the mean and median values are β= -29.32 and β= 28.71, and - β= 28.57 and β= 28.85 respectively. The standard error $\pm$0.065and $\pm$0.645 respectively. The PV panel should face South during rainy season and North during the dry season. The results show that the average optimum tilt angle at Offa, Kwara state, north-central part of Nigeria can be written as for the two season months is $\beta=\pm(\varphi+20+a)$, where a ranges from 1 to 2, and the positive and negative signs means that for the positive in northern hemisphere which represents the rainy season the orientation of PV panel is south faced and negative sign which represents the dry season the orientation of PV panel is north faced.

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