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Assessment of Finest Tilt Angles and Adjustment Intervals for Maximizing the Utilization of PV Radiation on Solar Panels: A Case Study

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ABSTRACT

The tilt angle of a solar photovoltaic (PV) panel is a key factor that determines the amount of electrical energy output from the panel. Some previous research works recommend approximate number of yearly tilt angles and adjustment intervals for countries located around the tropical latitude but similar recommendation for equatorial regions like Lagos metropolis in Nigeria and other coastal cities is lacking. Thus, this study presents an estimation of the maximum monthly average PV radiation on an adjusted panel and the optimum values of the pane tilt angles, using Lagos as a case study. Both physical measurements and constrained non-linear optimization technique modeled in MATLAB/Simulink are used. The diffused and reflected radiations were included along with the clearness index of the atmosphere for greater accuracy. From the results obtained, a seven-step adjustment interval of tilt angles comprising January to August and September to December (a combination of monthly and seasonal adjustments) is proposed as optimal adjustment intervals for solar panels located in Lagos metropolis. After the optimization process, the maximum radiation energy correlating with the optimum tilt angles were gotten for all the seven adjustment intervals and the average annual energy was estimated at 1555.3 kWh. The effectiveness of the proposed approach was checked and justified by comparing the results with that of daily adjustment of panel tilt angle. These results will be an effective source of information to designers of solar energy in equatorial regions.

Keywords — declination angle; optimum tilt angle; solar angles; solar irradiation; solar photovoltaic module.

1. INTRODUCTION

The industrialization and economic growth of any society in the modern world is anchored on the availability and access to sustainable amount of energy resources. Regrettably, most developing countries like Nigeria are still battling with the problem of inadequate electricity supply despite the abundant natural resources meant for generation of the bulk of electrical energy demand. Electricity generation from conventional source is common and dominate in developing countries. In the world today, replenishable energy sources like wind, solar, biogas, etc. are becoming common sources of energy for electricity generation. Many countries in the world have enacted policies that encourage the use of renewable energy sources instead of fossil fuels for electricity generation because of the environmental pollutions and imminent depletion of the later unlike the former. The PV energy has increased in recognition for energy demand in recent years among the non-conventional energy sources as result of its abundance and environment-friendly characteristics (Awasthi et al., 2020; Bakirci, 2012; Dey & Subudhi, 2020; Kaldellis & Zafirakis, 2012). Solar energy is available globally and free to harvest. Moreover, the cost of solar systems is continuously reducing as studies in this field increases. Incidentally, most developing countries around the globe are located within the tropical axis of the earth (between latitudes 15°N and 35°N) where sunshine is most prevalent (Keyhani, 2016). Therefore, these countries are working hard to maximize the generation of electricity from solar (PV) panels.

Nigeria has great prospect for the exploitation of solar energy by virtue of its location on the globe. Solar energy, by its sustainable nature can go a long way in solving the problem of inadequate electrical energy generation in Nigeria, which is mostly dependent on the use of fossil fuels (Bugaje, 2006; Udoakah & Umoh, 2014). Nigeria is blessed with a solar radiation of 5.535 kWh/m^2/day (Augustine & Nnabuchi, 2009), and studies have confirmed that this is sufficient to satisfy the total electricity requirement of this country if just 0.1% of this energy is converted using a suitable solar technology. However, optimum electrical power can only be harnessed from solar energy if certain parameters of a solar energy system are optimized. Some of those parameters are the global solar radiation, the efficiency of solar system technologies and adjustment intervals (Ramli et al., 2021). These are the concerns being addressed in this research work.

The utilization of photovoltaic (PV) cells for converting solar radiation into electrical energy can be achieved through off-grid or grid-connected configurations. However, the net electrical power generated from PV systems fluctuates with variations in daylight hours and weather conditions. Effective solar radiation falling on a tilted surface refers to the amount of the incident solar radiation that is perpendicular to the surface of the photovoltaic module. This implies that the power received by a PV module is a function of both the power found in the sunlight and the angle between the sun's ray and the PV module. If the absorbing surface of the PV module and sunlight are aligned perpendicularly, the power density on the surface matches that of sunlight, resulting in maximum power density.

Scientific concepts pertaining to the models for describing solar radiation and techniques for determining the optimum tilt angle have been examined in various papers. The values of the optimum tilt angle have been estimated for various tropical locations like Jordan, Libya, Syria, turkey, etc. (Agha & Sbita, 2000; Skeiker, 2009). Factors affecting PV tilt angle such as latitude, weather condition, temperature variation, panel adjustment frequency and relevant recommendations were also reported (Al-Tajer et al., 2024; Karafil et al., 2015). Numerous technical and academic works have been published on the optimization of tilt angles, with case studies conducted in various countries worldwide. Considering the importance of global solar radiation and its influence on Earth's surface, including its effects on agriculture and climate changes, it is essential to develop methods that can assess global solar radiation even when only limited data is available. Since the direct measurements of solar radiation is unavailable in many areas, empirical models have emerged as effective alternatives for predicting global solar radiation. Studies have recommended adjusting the tilt angles of PV panels on a monthly, seasonal, or yearly basis to maximize energy production. (Jamil et al., 2016; Moghadam et al., 2011; Muslim, 2019). Due to the variation in solar radiation across different geographical locations, local researchers in Nigeria have recently undertaken efforts to estimate the average monthly global solar radiation and clearness index for specific regions within the country during different times of the year. (Adejumo et al., 2017; Adeniji et al., 2019; Tasie et al., 2022)

Limited efforts have been made to explore the maximization of energy generated from the sun via optimization of panel tilt angles. A specific researcher utilized existing solar radiation models to determine the monthly values of the ideal tilt angle and maximum solar isolation for photovoltaic (PV) systems in Enugu state, Nigeria.(Augustine & Nnabuchi, 2009) The findings in the work indicated that the optimal irradiation occurs during the rainy season when the tilt angle is 0 degrees, while during the dry season, the optimal irradiation is achieved with tilt angles ranging from 20 to 60 degrees.

Optimization of a fixed tilt angle for solar panels is a more suitable approach for meeting domestic energy demands. Various research works proposed different numbers of yearly intervals to achieve maximum utilization of solar radiation. In a study outlined in (Ramli et al., 2021), a method was developed using two different models. The first model divides the year into fixed periods consisting of a set number of days, while the second model allows flexibility in allocating the number of days to each period, enabling the capture of maximum solar radiation at specific tilt angles. Implementing such complex models in local environments requires advanced mathematical tools and may not be suitable for domestic loads or regions with low per capita income. Another challenge is the presence of aerosol mass loading during the harmattan season, which significantly reduces the intensity of solar radiation. Factors like sky clearness can influence the results, making it essential to consider fluctuating weather conditions when determining the optimal number of intervals in this study (Augustine & Nnabuchi, 2009).

It has become necessary to determine a more practicable number of periods or intervals per year for tilt adjustment in Lagos metropolis where the utilization of stand-alone solar PV modules is on the rise. Recommendations on the different number of yearly adjustment intervals of tilt angle were applied mainly to countries located around the tropical latitudes, but their application to equatorial regions like Lagos metropolis and other coastal cities is lacking. Such places witness heavy downpour which reduces the clearness of the sky.

Thus, the purpose of this study is to determine the optimum tilt angles and adjustment intervals that can maximize the generation of electrical energy from solar PV Panels located in Lagos Nigeria. The study shall investigate the variation of average monthly solar irradiation with the PV panel tilt angle in Lagos environment so as to determine the peak values and the corresponding optimum tilt angles. The study shall also determine the minimum adjustment frequency to obtain an improved annual electricity generation over that generated with the daily adjustment of the tilt angle.

This research proposed a computational model for estimating the average monthly PV radiation on a tilted panel located in Lagos which also served as the objective function in the optimization process. The variation of monthly averages of the total solar radiation at different tilt angles (varying from $0^{\circ} - 90^{\circ}$) using this model were determined for the twelve months of the year. The effects and contributions of direct beam, diffuse and albedo radiations were highlighted.

The remaining part of this paper is organized as follows: section II presents the mathematical models used in this paper. Section III presents and discussed briefly the data used for the study. Results obtained from the study are presented in section IV while section V presents the concluding remarks and recommendations.

2. MATERIALS AND METHODS

2.1. Mathematical Formulations

This section presents the theoretical framework and mathematical modelling of the approach used in this paper.

2.1.1. Solar Radiation Model

In relation to our specific location of interest, a model developed by the authors of (Ramli et al., 2021) is explored. The process of determining the energy received by a tilted solar PV module at an angle from the horizontal involves intricate calculations. According to the Isotropic model, the total solar radiation received by the tilted module, H_t is the combination of direct beam radiation, H_B, diffuse radiation reaching the tilted surface, H_D, and reflected or albedo radiation, H_R (Keyhani, 2016; Mamun et al., 2022).

$$H_t = H_B + H_D + H_R \qquad (1)$$

- *Direct Beam Radiation*

The beam radiation on a tilted surface is regarded as that part of the beam radiation that falls on a horizontal surface during an average day of a particular month. Calculating the direct beam radiation on a tilted surface, denoted as H_B, is relatively simple when provided with the measured components H_g and H_d, the sun's position, and the orientation of the surface (Mamun et al., 2016). Disregarding any reflection factors, the equation for the hourly global solar radiation on a tilted surface under clear sky conditions is stated as follows:

$$H_B = (H_g - H_d)R_b \qquad (2)$$

where H_g represents the global irradiation, which refers to the measured total solar radiation falling on a horizontal surface. H_d represents the measured diffused irradiation. Global irradiation can be obtained from either weather station data or calculated based on sunshine hours. R_b refers to the conversion factor for beam radiation; it is the ratio of direct normal irradiance on the tilted surface to that on the horizontal ground surface, as shown in Fig. 1.

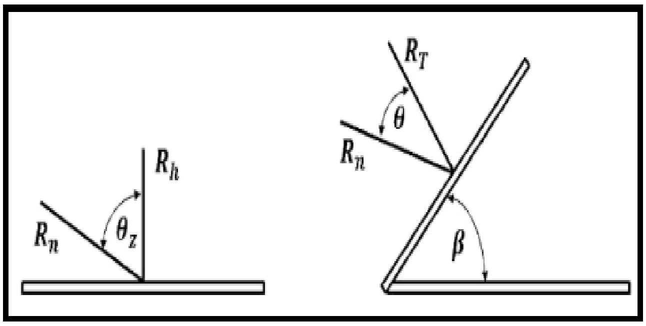


Figure 1: The PV radiation on a tilted and horizontal surfaces (Jamil et al., 2016)

From fig. 1, according to the Liu & Jordan model quoted in (Augustine & Nnabuchi, 2009)

$$R_b = \frac{R_T}{R_h} = \frac{R_n cos\theta}{R_n cos\theta_z} = \frac{cos\theta}{cos\theta_z} \qquad (3)$$

where

$$cos\theta = \cos(\emptyset - \beta)\, cos\delta sin\omega_s + \left(\frac{\pi}{180}\right) \omega_s \sin(\emptyset - \beta) sin\delta \qquad (4)$$

$$cos\theta_z = cos\emptyset cos\delta sin\omega_s + \left(\frac{\pi}{180}\right) \omega_s sin\emptyset sin\delta \qquad (5)$$

R_n - PV insolation on a horizontal surface

Θ is the incident angle on a tilted surface

θ_z is the incident angle on a horizontal surface (equivalent to zenith angle).

R_h is the solar insolation on a plane that is normal to the direction of propagation.

Ø (in degree)- latitude of the location
δ (in degree) -declination angle
ω_s(in degree) - sunset hour

$$\omega_s = \cos^{-1}(-\tan\emptyset\tan\delta) \qquad (6)$$

Diffuse irradiation H_d refers to the monthly mean daily value for the diffused irradiation incident on a horizontal surface.

$$H_d = H_g(1.0 - 1.13K_T) \qquad (7)$$

where H_d is the diffuse solar irradiation (MJ/m^2/day), H_g is the global solar irradiation (MJ/m^2/day) and K_T is the clearness index calculated as (Bakirci, 2012)

$$K_T = \frac{H_g}{H_o} \qquad (8)$$

where H_o is the extraterrestrial solar irradiation on a horizontal surface (MJ/m^2/day). It is given by:

$$H_o = \frac{24I_{sc}E_o}{\pi}\cos\theta_z \qquad (9)$$

where I_{sc} is the solar constant, whose value is 1367W/m^2

E_o is the eccentricity correction factor given as

$$E_o = 1 + 0.033\cos\left(\frac{360n}{365}\right) \qquad (10)$$

The declination angle, δ, the tilt angle, β and latitude, Ø are related as follows:

$$\beta = |\emptyset - \delta| \qquad (11)$$

where

$$\delta = 23.45\sin\left[360 \times \frac{(284+n)}{365}\right] \qquad (12)$$

n – day of the year (which begins with 1st January)

Hence, the angle of tilt for a solar panel can be determined as follows,

$$\beta = \emptyset - 23.45\sin\left[360 \times \frac{(284+n)}{365}\right] \qquad (13)$$

- *Diffuse Radiation*

Modeling the diffuse radiation incident on a tilted surface is challenging due to its time-dependent and unknown spatial distribution. However, the isotropic model, introduced by [20], offers a simple approach for tilted surface models. It is assumed in the model that the entire diffused radiation is distributed uniformly across the entire sky dome. Diffuse radiation on a unit area of a tilted surface is the product of the diffuse sky radiation measured on a horizontal plane and the view factor from the surface to the sky, taking into account the tilt angle (β). According to (Nfaoui & El-Hami, 2018),

$$H_D = H_d R_d = \frac{1+\cos\beta}{2} \qquad (14)$$

R_d - diffuse conversion factor

- *Albedo or Reflected Radiation*

Albedo radiation is regarded as the solar radiation that got reflected from the horizontal ground surface and get to the tilted solar panel. To determine the ground reflected radiation that is incidented on a tilted surface in various orientations, a widely adopted approach assumes that the area within the collector's field of view acts as a diffuse reflector, and there are no obstacles on the horizon. As a result, the ground reflected radiation is considered to be diffuse and can be calculated using the methodology proposed by [3].

$$H_R = H_g R_r = H_g \rho_g \left(\frac{1-\cos\beta}{2}\right) \qquad (15)$$

$\rho_g = 0.25$ (reflectivity or ground albedo)

Where H_g is the measured total solar radiation on a horizontal surface; ρ_g is the ground reflectivity or albedo. Typically, a value of 0.2 is assigned to ρ_g as it is a widely accepted and commonly used reference mean value proposed by (Udoakah & Okpura, 2015). This value is often utilized in applications where specific albedo measurements are not available.

- *Overall Daily Solar Radiation*

The overall daily PV irradiation on a tilted panel (H_t) is given as the total of the direct beam irradiation, the albedo radiation, and the diffused radiation. This is mathematically presented in (16).

$$H_t = (H_g - H_d)R_b + H_g\rho_g\left(\frac{1-cos\beta}{2}\right) + H_d\left(\frac{1+cos\beta}{2}\right) \quad (16)$$

- *Clearness Index*

Clearness index (K_T) is defined as the ratio of the average daily values of the horizontal radiation received at a specific location and the total extraterrestrial solar radiation for that location. It could be calculated from measurement recorded in the weather station as follows,

$$K_T = \frac{H_g}{H_0} = a + b\frac{S}{S_0} \quad (17)$$

Where,

S is the recorded sunshine hours

S_o is the day length

a,b are empirical constants

H_g is the solar radiation data of that area.

- *Estimation of Average Monthly Distribution*

One of the key objectives of this work is to estimate the average monthly solar radiation falling on a tilted panel and its variation with changes in tilt angle for each month in a year. The monthly average of solar irradiation on a tilted paned is calculated in this work as the mean value of the daily total irradiation over a month period.

- Average monthly radiation,

$$\overline{H}_k = \sum_{i=1}^{N} \frac{H_{ti}(\beta_k)}{N} \quad (18)$$

In this study, a MATLAB script named 'Solaradiation.m' was developed to calculate the monthly averages of beam radiation, the diffused radiation, the albedo radiation, and the global radiation at different tilt angles for Lagos. The code was developed following a simplified approach proposed in (Bakirci, 2012; Udoakah & Okpura, 2015). Relevant meteorological parameters were used in the determination of the global solar radiation.

Using methods outlined in this study and the meteorological parameters provided, the monthly averages of total irradiation were computed for various tilt angles, that ranges from 0° to 90° in steps of 2°. The analysis focused on the contributions and effects of each component (that is, beam, diffuse, and albedo) in both general cases and at their respective optimum angles.

- *Formulation of the Optimization Problem for the Mean Monthly Solar Radiation for Lagos Metropolis*

A typical optimization problem is generally formulated as follows:

$$Minimize\ p(y) \quad (19)$$

$Subject\ to$

$$s(x) = 0\ and\ r(y) \leq 0 \quad (20)$$

Where $p(y)$ is the objective function; y is the vector of design variables; $s(y)$is the set of equality constraints; $r(y)$ is the set of inequality constraints.

The aim of this optimization process is to maximize the average monthly radiation. Therefore, the objective function in this case is defined as in (21) below:

$$\max[\bar{H}_k(\beta_k)] \qquad (21)$$

The above statement can be translated to minimization problem as presented in (22).

$$\min[-\bar{H}_k(\beta_k)] \qquad (22)$$

Where $\bar{H}_k(\beta_k)$ is the objective function and are positive integers; $\beta_k = (0,1,2,3,\dots)$

The constraints imposed on the problem are inequality constraints:

$$\beta_k \geq 0 \ \ and \ \beta_k < 0 \qquad (23)$$

The optimization was carried out separately for each month of the year using the constrained non-linear optimization technique in the *Matlab Optimization Toolbox*. This decision was based on the outcome of the calculation of solar energy received at fixed optimum tilt angle. It is noted that the curves representing the variation of average monthly radiation are continuous over the tilt angle interval and characterized by single local maximum. This implies that global optimization techniques and heuristic search algorithms are not appropriate for this kind of optimization problem, but a simple gradient method is sufficient which guarantees fast convergence. That is the reason for the choice of constrained non-linear optimization technique in this study.

- *Steps in using the Matlab Optimization Toolbox*

In this paper, *Matlab Optimization Toolbox* was used to estimate the optimum tilt angles and the equivalent maximum values of monthly average of total radiation on the tilted solar panel. The proposed algorithm is described below. This is a summary of the steps to set up the optimization problem, run the optimization and view results in the Optimization Toolbox or alternatively at the command line.

1.) The problem was initially delineated in MATLAB Toolbox syntax, wherein the objective function was utilized to generate a function file through the subsequent method:

The days encompassed within each month, spanning from January to December as per the Julian calendar, were discerned.

The declination angles and sunset hour angles and the total radiation on a tilted solar panel for each Julian day of the current month were calculated using equations (16) and (18). The implementation requires the conversion of the days involved in each month to their corresponding values in the Julian calendar.

Finally, the objective function is the negative of the formula for average total radiation while β stands as the function argument.

$$f(\beta) = -\sum_{n=1}^{N} \frac{H_{tn}(\beta)}{N} \qquad (24)$$

The function file used for the objective function for each month of the year was saved with the name '*operadi.m*'.

2.) The constraints functions were also defined as a separate file or anonymous function.

Generally, the constraint functions have the form $\mathrm{C_{inq}}(y) \leq 0$ for inequality constraints and $\mathrm{C_{eq}}(y) = 0$ for equality constraints. However, the constraints encountered in this study are no functions but mere boundaries. The constraints imposed on the problem are inequality constraints:

$$\beta_k \geq 0 \quad \text{and} \quad \beta_k < 90$$

These constitute the lower and upper boundaries in the domain of optimization. Hence, no function file is required for these constraints. The non-linear constraint function box is left empty. The rest of the procedure continued inside the optimization *App* or in the *matlab editor*.

3.) The matlab optimization is run in two ways namely:

i. Using the Optimization app
ii. Using command-line functions

The configurations required in the App before running the optimization are shown under the *'Problem Setup and Results'* pane (see Fig. 2). The command line functions are written and executed as a script in a *Live Editor*.

4.) The default Solver, *fmincon* - Constrained nonlinear minimization was selected which is appropriate for a nonlinear function with constraint. This choice was based on the mode of the variation of mean total radiation $\overline{H}_k$ with tilt angle β, meaning that a simple search technique is sufficient. The shape of the curves displayed in Fig. 4 and 5 are characterized by single local maximum. Hence, global optimization techniques are not required in this case. The default Algorithm, Interior point was also selected.

5.) In the *Objective function box*, is the objective function handle *@operadi*. In the *Start point box*, [0] specifies the initial point where solver begins its search for a local minimum. In the bounds constraint function box, the lower and upper limits were set at 0° and 90° respectively before running the solver.

6.) The $MATLAB$ statements for the running of optimization using command line does take the following form:

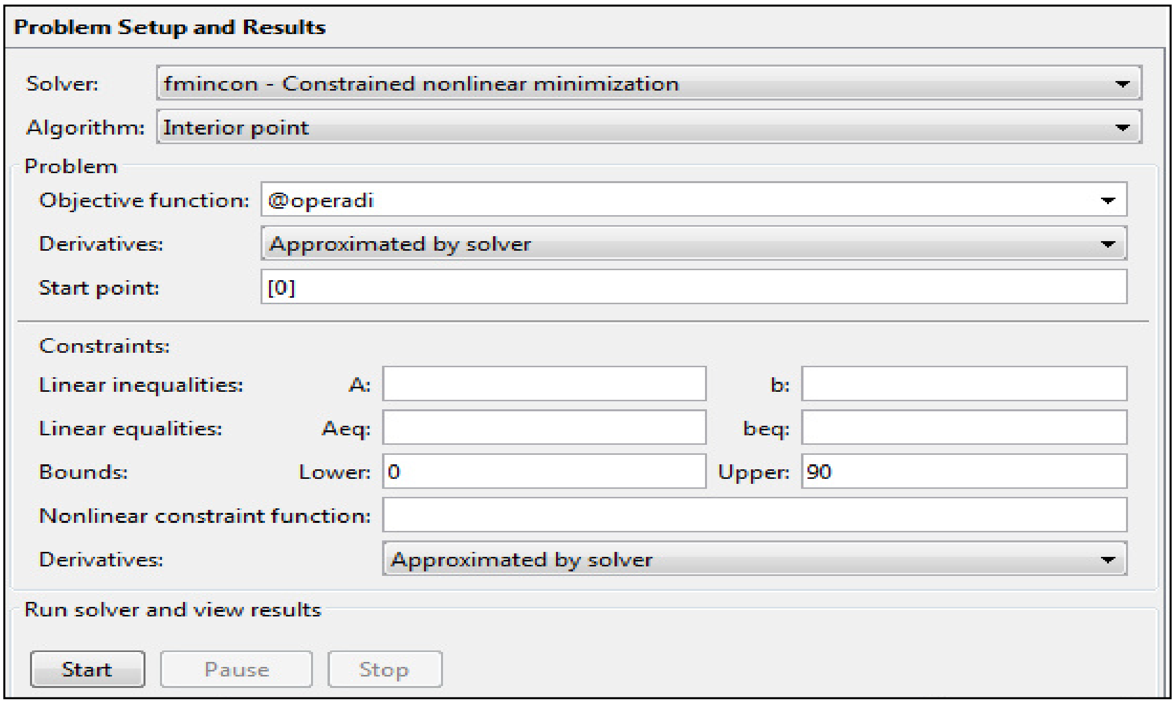
i. Set the options: In the live Editor, set options by entering

$$options = optimoptions('solver','Display','iter',\\ 'Algorithm','interior-point')$$

ii. Pass solver Arguments: Ensure that the options are passed to the solver as follows

[x,fval] = solver (objective function handle, [start point],... ,[Lower limit], [Upper limit], Constraints function handle, options)

iii. Run the script to display the results: This process is reiterated for every month in the annual cycle (January to December) by modifying the Julian days comprising the month denoted by 'j' within the function file '*operadi*'. The matlab script used for the twelve optimization cycles is named *Austin.m*. The lowest values of the target function within the optimization challenge were negated by multiplication with *(-1)* to yield the utmost values. Subsequently, these maximum values were organized in a table alongside the respective months, along with the corresponding optimal tilt angle values.



Problem Setup and Results

Solver: fmincon - Constrained nonlinear minimization
Algorithm: Interior point

Problem
Objective function: @operadi
Derivatives: Approximated by solver
Start point: [0]

Constraints:
Linear inequalities: A: b:
Linear equalities: Aeq: beq:
Bounds: Lower: 0 Upper: 90
Nonlinear constraint function:
Derivatives: Approximated by solver

Run solver and view results

Figure 2: The configured parameters in the Problem Setup procedure

- *Calculation of Solar Energy Received at Fixed Optimum Tilt Angles*

After the calculation of the optimum angles from the optimization process, the monthly variation of average total radiation with the panel tilt angle fixed at the calculated monthly optimum values was also determined on monthly basis using the matlab script 'Optimradiation.m' composed for this study. The days of each month were converted to the Julian equivalent in the calculation. For the purpose of comparison, the matlab script also calculated the monthly variation of average total radiation with respect to daily adjustment of tilt angle in a tracking device.

2.2. Input Data

The initial dataset used in the study as the foundation for computing the average monthly global solar radiation (H_g) in Lagos (latitude: 6.58°N, longitude: 3.32°E) consists of several parameters. These parameters include sunshine hours (S), regression coefficients (a and b), and the global solar radiation on a tilted plane. These computations were deduced from measurements acquired by the Nigerian Meteorological Authority (NIMET), Oshodi, Lagos, Nigeria, spanning the timeframe from January 2012 to January 2015. The measured parameters encompassed insolation on a horizontal plane, sunshine duration, cloudiness observations, and visibility measurements.

The recorded global solar radiation data, in kWhm^{-2}day^{-1}, can be changed to MJm^{-2}day^{-1} using a conversion factor of 3.6. The input data for the program used in this study can be categorized into two types as stated below:

1. *Fixed input data:* This refers to data that remains unchanged throughout the calculations. They are presented in Table 1 [18].

Table 1. Constant Input Data used for Lagos case study [18]

Parameter	Value
Solar constant (I_{sc})	1.367kW/m^2
Day number	1 – 365
Azimuth angle	assumed 0°
Ground albedo	0.25
Latitude	6.58°N
Longitude	3.32°E

2. *Variable input data:* This refers to the varying data. They are illustrated in Table 2.

Table 2. Variable Input Data Used for the Lagos Case Study [18]

Month	Mean Sun hours (S)	Day Length in hours (S_o)	H_g (MJ/m^2/day)	A	b	$\frac{S}{S_o}$	Clearness Index (K_T)
JAN	5.86	11.67	10.76	0.275	0.575	0.502	0.560
FEB	6.54	11.78	12.34	0.292	0.538	0.555	0.590
MAR	5.82	12.05	13.06	0.269	0.588	0.483	0.550
APR	5.64	12.16	13.29	0.263	0.601	0.464	0.540
MAY	5.82	12.33	11.94	0.265	0.595	0.472	0.540
JUN	3.71	12.41	10.28	0.209	0.715	0.299	0.420
JUL	2.68	12.35	8.14	0.183	0.773	0.217	0.350
AUG	3.12	12.19	7.35	0.196	0.746	0.256	0.380
SEP	3.86	12.02	8.95	0.217	0.700	0.321	0.440
OCT	5.24	11.83	10.32	0.256	0.616	0.443	0.520
NOV	6.28	11.85	11.80	0.286	0.550	0.53	0.580
DEC	6.36	11.61	12.13	0.290	0.543	0.548	0.580

3. RESULTS AND DISCUSSION

This section showcases different sets of results related to the average monthly irradiation. Firstly, it examines the impact of adjusting the tilt angle of a solar panel on the average monthly irradiation. Secondly, it explores the monthly optimum tilt angle for maximizing solar radiation reception. Lastly, it investigates the solar radiation received by the solar panel when the tilt angle is maintained at its optimal value. The values obtained for the optimum tilt angles serve as the basis for implementing a seven-step optimal interval for adjusting the tilt angle of solar panels in Lagos.

3.1. Comparison Between the Geographical Tilt Angle and Declination Angle

The initial series of curves produced via the MATLAB script illustrate the geographical declination angle values juxtaposed with their corresponding tilt angle values. The curves in Fig. 3 compare the daily variation of declination angle and the tilt angle based on the solar angle models stated in (1) and (2). This comparison gives us a guide to the expected optimum tilt angles that will emanate from the optimization process.

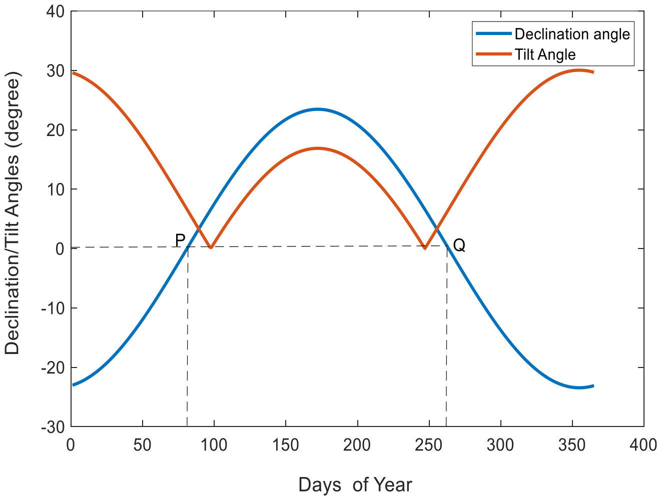


Figure 3: The yearly variance of declination and tilt angles

The thinking is that these values of tilt angle will position the panel to receive the maximum solar radiation. They are mostly applied in the setting of the controller parameters in the tracking device.

The declination angle is zero at two occasions in the year represented by the points P and Q in Fig. 3. These locations correspond to the Julian days 80 and 260 which occur in March and September respectively, while the tilt angle decreases to zero in the month of April, rises and decreases a second time in August. The positive tilt angles occurring within April – August imply that the solar panel shall be inclined at the given angles while facing the northern hemisphere or else placed horizontally for consistency in panel orientation.

3.2. Calculation of average monthly distribution of solar irradiation

The execution of the MATLAB script ‘solar radiation’ produced the mean monthly distribution of total solar radiation received on a horizontal surface in Lagos metropolis at varying tilt angle 0° – 90° in steps of 2°. The results presented in Fig. 4 and 5 show the monthly variation in average total radiation for the first and second halves of the year with 0° – 90° variation in the panel tilt angle. The curves indicate that different peaks occur at different months depending on the season. Higher values of maximum average irradiation occurred during the dry season with the maximum irradiation recorded in the month of December at a tilt angle of 37.63° (see Table 3).

In spite of the 13.29 MJ/m^2 obtained in April as the highest global solar radiation of the year, 16.59 MJ/m2 was obtained in December as the highest value of average monthly radiation (see Table 3). This is as a result of low cloud covering in that month represented by a high value of clearness index 0.58. The shape of the curves provides a guide on the type of optimization technique required to locate the optimum values. The curves showing the average monthly distribution of solar irradiation reveal the possibility of attaining a maximum solar irradiance at negative values of panel tilt angle, which implies an unconventional tilting of solar panel to face the North Pole. The months affected by this phenomenon are from March to August. Negative optimum tilt angle connotes the rotation of the solar panel in opposite direction to face the north instead of south. These regions are not included in the graph because the tilt angle was constrained to values between 0° and 90°. Hence at these seasons, the optimum tilt angle shall be constrained to 0°.

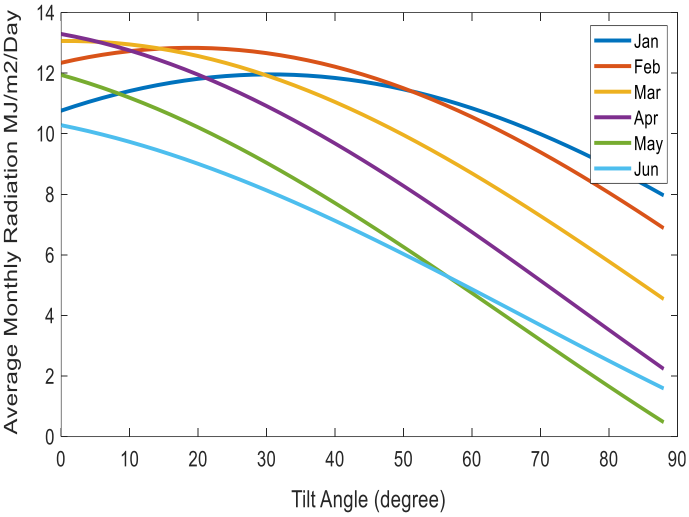


Figure 4: The monthly variation in average monthly radiation for the first half of the year with changes in the panel tilt angle

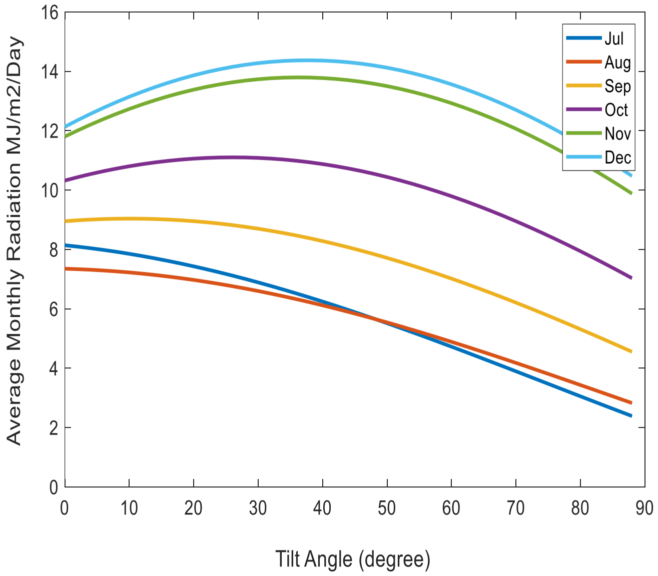


Figure 5: The monthly variation in average monthly radiation for the second half of the year with changes in the panel tilt angle

3.3. Calculation of optimum values of tilt angle and average total radiation

This section presents the findings regarding the optimal tilt angle required for maximizing solar irradiation on solar panels on monthly basis. The monthly optimal tilt angle values, calculated using the Optimization App, along with the corresponding average monthly total radiation, are respectively presented in columns four and five of Table 3. These values are also visualized through the curves in Figure 6.

From the data presented in Table 3, it is evident that the maximum incident energy (global radiation) differs from the energy received on an inclined plane with the optimal monthly tilt angle. To fully utilize solar irradiation, it becomes necessary to periodically adjust the tilt angle of the solar panels, either on monthly basis or alternatively on a seasonal basis. By optimizing the orientation and inclination of the solar panels, the capture efficiency can be improved, leading to more efficient utilization of solar radiation and reduction in the cost associated with solar energy usage.

Table 3: Results of the calculations from optimization App showing the monthly values of finest tilt angle and maximum solar radiation

Months	**H_g(MJ/m^2/day)**	**K_T**	**B_{opt}**	**H_{tmax}**	**H_{topt}**
JAN	10.760	0.560	30.520	11.960	15.840
FEB	12.340	0.590	18.820	12.830	16.270
MAR	13.060	0.550	0.800	13.060	15.110
APR	13.290	0.540	0.000	13.290	17.190
MAY	11.940	0.540	0.000	11.940	16.280
JUN	10.280	0.420	0.000	10.280	14.540
JUL	8.140	0.350	0.000	8.140	13.100
AUG	7.350	0.380	0.000	7.360	13.420
SEPT	8.950	0.440	10.050	9.040	14.370
OCT	10.320	0.520	26.050	11.100	15.070
NOV	11.800	0.580	36.270	13.790	16.490
DEC	12.130	0.580	37.630	14.370	16.590
Average					**15.340**

Htmax– maximum total radiance which occurs as we vary the tilt angle from 0° – 90°, Htopt– the total radiance achieved by keeping the value of tilt angle constant and equal to the optimum value throughout the duration of any particular month.

According to Table 3, the optimum tilt angle adjustments of the solar panel which lead to the maximum energy production for the year are 30.52˚, 18.82˚, 0.8˚, 0˚, 0˚, 0˚, 0˚, 0˚, 10.05˚, 26.05˚, 36.27˚ and 37.63˚. The maximum value of optimum tilt angle of 37.63˚ occurs in December when the sunshine hours is long. The value decreases towards zero at March as the rainy season approaches until August where it begins to increase as the year advances towards December. Between the months of September and February, the maximum values of total irradiation were achieved at tilt angles 10.05°, 26.05˚, 36.27˚, 37.63˚, 30.52˚ and 18.82˚ respectively. Zero tilt angles were recorded as optimum value for all months from March to August which correspond to the rainy season periods in Nigeria. Zero tilt angle depicts a horizontal placement of solar panel, where the total irradiation is comprised of the beam and diffused radiation components while the reflected component plays no significant role. The entire period of the raining season therefore becomes an optimal interval. The optimum tilt angle curve is almost flattened in this period showing that a fixed value of the panel tilt in this period cannot make any difference. Based on these results, a combination of monthly and seasonal adjustments is being proposed in this study as optimal adjustment interval for solar panels located in Lagos metropolis required to produce the desired result in terms of maximizing solar energy incident on the panel. A seasonal approach could be adopted during the rainy season when there is no significant variation in optimum tilt angle while monthly adjustment is necessary in dry season where the case is otherwise. Precisely, this study proposes a Seven-Step optimal interval adjustment of tilt angles for Lagos metropolis. These includes: January, February, March – August, September, October, November and December. The corresponding values of tilt angles at these periods are 30.52˚, 18.82˚, 0˚, 10.05˚, 26.05˚, 36.27˚ and 37.63˚ respectively.

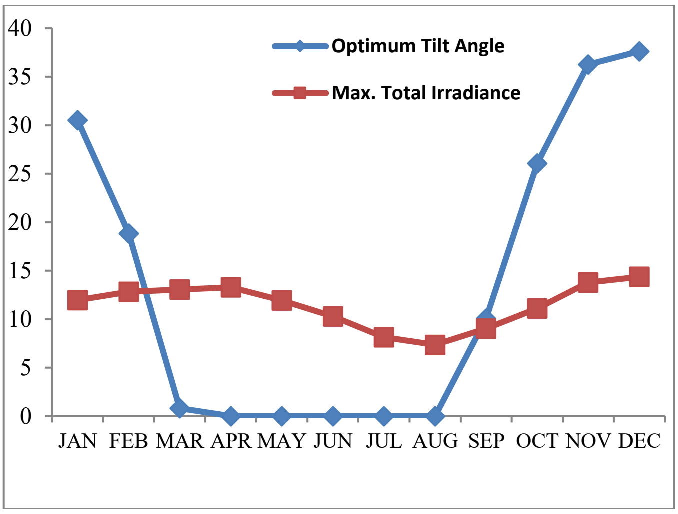


Figure 6: Comparison in the values of peak tilt angle and maximum PV radiation for per month of year

3.4. Calculation of Solar radiation and energy received with fixed peak tilt angle

This part presents and examines results on the effect of panel tilt angle on the yielded solar energy when the daily value of tilt angle is fixed at the monthly optimum value. When the panel tilt angle was adjusted to the monthly optimum values, the maximum radiation that corresponds to the optimum tilt angles are stated in the last column of Table 3 as well as the plot in Fig. 7. The estimated average annual energy yield is 15.34 MJ/m^2/ Day. Fig. 8

emphasizes the importance of installing PV systems at their optimal tilt angles for a better performance as reflected in the increased daily values of total solar radiation captured by the panel. Fig. 8 on the other hand compares the monthly total radiation for seven-step adjustment of tilt angle with that of daily adjustment of panel tilt angle.

It is observed from Fig. 8 that the proposed seven-step optimal adjustment interval produces almost a similar result as that of the daily adjustment of tilt angle in terms of the effective solar radiation received. For the seven-step approach, the total radiation received per day is 15.34 MJ/m^2 while the daily adjustment with tracking device produced 15.09 MJ/m^2. Both quantities are significantly higher than the radiation to be received by a fixed horizontal surface. Accumulating the energy produced over a year cycle to see the advantage of one approach over the other, it is observed that the total solar energy generated per year on the seven-step adjustment of tilt angle surface is 1555.3 kWh per annum while that of daily adjustment is 1530 kWh per annum.

The comparison of annual total radiation or generated solar electricity for varying values of tilt angle (synonymous with the operation of a tracking device) and that obtained for seven-step adjustment of tilt angle shows that the quantity of electricity generated in both cases annually are approximately the same but the proposed approach yielded an improved result in the given location. This proves that the use of the seven-step optimal adjustment interval outweighs the use of tracking device in daily adjustment. A single value of tilt angle is therefore sufficient to cover the months between March and September giving rise to seven-step optimum adjustment intervals comprising January, February, March – August, September, October, November and December.

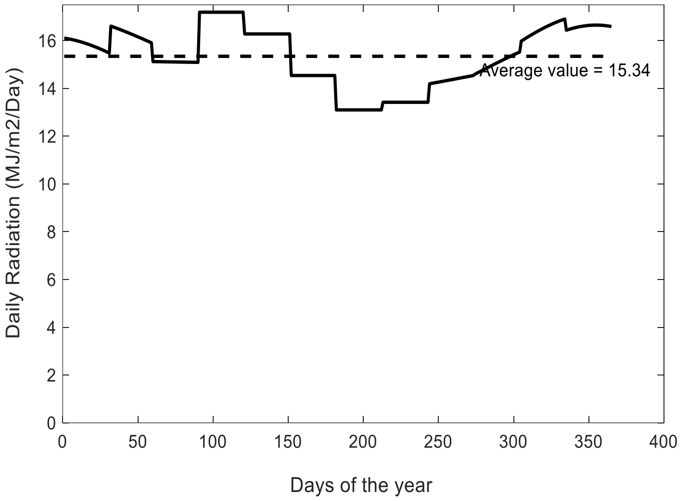


Figure 7: Monthly variation of total radiation with the panel angle fixed at the calculated optimum value

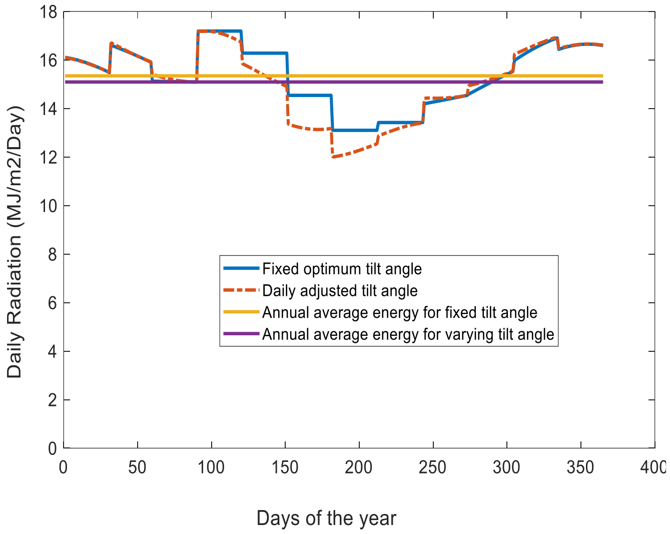


Figure 8: Comparison between monthly total radiation for seven-step adjustment of tilt angle and that of daily varying tilt angle

4. CONCLUSION

In this paper, appropriate frequency for manual adjustment of PV panel tilt angle required to achieve optimal generation of solar electricity within an equatorial region, using Lagos state in Nigeria as a case study, is presented. The monthly optimal value of tilt angle and the corresponding maximum value of solar radiation required to maximize the output of the PV module was estimated. This was carried out using various isotropic models of solar angles and solar radiation parameters in the MATLAB environment as the optimization tool. The problem was formulated as an optimization problem using average monthly solar radiation as the objective function. The results obtained showed that with the monthly optimum tilt angle that yielded the optimum irradiation as a fixed value for the panel tilt angle for the month, a substantial increase in solar energy was produced. Furthermore, it was shown that the same objective is achievable when the PV panel tilt angle was adjusted from January -March and October- December at a constant value between March – August. Consequently, a combination of monthly and seasonal adjustment intervals termed in this study as 'Seven-Step Adjustment Interval' is recommended for Lagos location in Nigeria. The optimal values of tilt angles for these monthly and seasonal adjustment intervals were obtained as the recommended adjustment angles for solar panels located in Lagos. This approach substantially improved the energy generation of a PV module at any location within the study area. It requires less intervention from manual operators and yet guarantees the intended maximization of solar radiation on the PV module. The daily adjustment could be so strenuous when applied manually. A possible future research work on this topic is to consider the applicability of the proposed method in other regions of the world taking into cognizance their unique climate and weather condition.

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