Simplified Approach For Determination Of Optimum PV Module Tilt Angles Using Sun Declination And Elevation Angles At Solar Noon

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***Abstract*— In this work, simplified approach for determination of optimum PV module tilt angles using sun declination and elevation angles at solar noon is presented. The mathematical expression along with the algorithm that utilizes the sun declination angle and the solar noon elevation angle to determine the tilt angle for maximum solar radiation capture on tilted PV module are presented. Furthermore, apart from yearly fixed optimal tilt angle, the algorithm is also employed to determine the monthly fixed optimal tilt angle for each of the twelve months in a year. A case study of a location in Odukpani in cross River State Nigeria with latitude of 5.0825 and longitude of 8.3484 and annual mean daily solar radiation on the horizontal plane of 4.73849863 kW-hr/m^2/day is presented. The results showed that the annual fixed optimum tilt angle is 16.06796° which has the annual mean of daily solar radiation value of 4.931171347 kW-hr/m^2/day. The monthly fixed optimal tilt angle for each of the 12 months are also obtained along with the corresponding optimal monthly mean of daily solar radiation values.**

Keywords— Optimum Tilt Angle, PV Power Plant, Sun Declination Angle, Sun Elevation Angle, Solar Noon

1. INTRODUCTION

Today, solar power system design as gotten many approaches and tools [1,2,3,4,5]. Each approach or tool will however require to provide means of optimizing some aspect of the system. Particularly, energy yield of solar photovoltaic (PV) plant depends on a number of factors which must be considered in order to arrive at optimum value [6,7,8,9].

Over the years, one of the parameters that has attracted attention in the quest for optimal PV power system is the optimal tilt angle. It has been established that proper orientation of the PV module with respect to the sun position is essential for maximum energy yield of PV module [10,11,12,13]. Also, it has been established that the optimal tilt angle is a function of the latitude of the location. However, the exact optimal tilt angle for a given location is influenced by some other factors that may require a more thorough analysis to determine.

Also, the optimal tilt angle is a function of the time range considered. Mostly, yearly fixed optimal tilt angles are needed in PV system design. However, in other cases, monthly adjusted optimal tilt angle can be required. In that case, the optimal tilt angle for each month in a year is needed [14,15,16,17].

Accordingly, in this work, an approach than can be used to determine the yearly fixed and monthly adjusted optimal tilt angle of any given location is presented. The approach is based on the sun declination angle, solar noon elevation angle and the daily solar radiation incident on horizontal surface at the PV installation site [18,19,20]. With these parameters, the optimal tilt angle for any given range of days or months can be computed. Case study dataset is used to demonstrate the application of the method.

2 METHODOLOGY

There are different ways to estimate the optimal tilt angle for PV modules. Some of the methods depends on finding the tilt angle at which maximum cumulative solar energy yield is achieved over a given period of time. Again, some other methods used the cumulative solar radiation incident on the tilted plane of the PV module over a given period. In this work, the second approach is applied. However, rather than employing cumulative solar radiation, a second order polynomial expression trend line equation is fitted on the graph of the solar radiation versus tilt angle and the optimal tilt angle is determined by equating the derivative of the trend line model to zero and solving for the optimal tilt angle over the period considered in the study.

The analytical model for the determination of the optimal tilt angle is a function of the sun elevation angle which in turn is dependent on the day, time and the latitude of the location. In this work the elevation angle (also known as altitude angle) is expressed with respect to the zenith angle at solar noon.

Notably, the sun zenith angle (γ_{Zsun}) at solar noon is given in terms of sun declination angle (δ_{sun}) and the PV installation site latitude (ϕ_{site}) [18];

$$\gamma_{Zenit} = \phi_{site} - \delta_{sun} \quad (1)$$

The sun altitude angle at solar noon (α_{Nsun}) is given as 18,19,20];

$$\alpha_{Nsun} = \begin{cases} 90 - \gamma_{Zenit} \; for\ the\ northern\ hemisphere \\ 90 + \gamma_{Zenit} \; for\ the\ southern\ hemisphere \end{cases} \quad (2)$$

$$\alpha_{Nsun} = \begin{cases} 90 - \phi_{site} + \delta_{sun} \; for\ the\ northern\ hemisphere \\ 90 + \phi_{site} - \delta_{sun} \; for\ the\ southern\ hemisphere \end{cases} \quad (3)$$

The optimal tilt angle (β_{PVopt}) of the PV module at solar noon is given as [21];

$$\beta_{PVopt} = 90 - \alpha_{Nsun} \quad (4)$$

$$\beta_{PVopt} = \begin{cases} \phi_{site} - \delta_{sun} \; for\ the\ northern\ hemisphere \\ \delta_{sun} - \phi_{site} \; for\ the\ southern\ hemisphere \end{cases} \quad (5)$$

The solar radiation incident on the tilted plane of the PV module is denoted as $G_{\beta_{PV}}$ and the solar radiation incident on the horizontal plane is denoted as G_{Hor}, then [22,23]

$$G_{\beta_{PV}} = \frac{(G_{Hor})(Sin(\alpha_{Nsun} + \beta_{PV}))}{Sin(\alpha_{Nsun})} \quad (6)$$

Where β_{PV} is the tilt angle of the PV module. In this work, the altitude angle at solar noon is determined using online Sun Path tool. The Sun path tool requires the following:

i. The PV installation site geo-coordinates (latitude and longitude)
ii. The date
iii. The local time
iv. The GMT time zone

The specific Sun path tool used in this work returns the elevation angle, the azimuth angle and some other details. It also returns values of the angles for each of the 24 hours in a day for all the days in a year. With the information, it is possible to determine the solar radiation on tilted PV plane for each day of the year. Therefore, the approach used to determine the annual fixed optimal tilt angle based on the solar radiation on the tilted PV module is presented in Algorithm 1;

Algorithm 1:

Step 1: Input the longitude and latitude of the PV installation site

Step 2: Retrieve the daily elevation angle and azimuth angle for the case study site for a whole year and extract the sun altitude (elevation) angle only at the solar noon, that is $G_{Hor(n)}$ for n = 1,2,3,…,365. The online sun path tool used in is SUNEARTHTOOLS available at https://www.sunearthtools.com/dp/tools/pos_sun.php#annual.

Step 3: Retrieve the daily clear sky surface shortwave downward irradiance for the case study site for a whole year, that is $\alpha_{Nsun(n)}$ for n = 1,2,3,…,365.. The data is obtained from the NASA data access viewer portal which is available at https://power.larc.nasa.gov/data-access-viewer/..

Step 4: Input the PV module tilt angle, β

Step 5: Initialize the day number, n =1

Step 6: Initialize the sum of the solar radiation on tilted PV module, $\mathrm{SumG}_{\beta_{PV}} = 0$

Step 7: Compute the solar radiation on tilted PV module for day n, $G_{\beta_{PV(n)}}$ using the Equation 6,

$$G_{\beta_{PV(n)}} = \frac{\left(G_{Hor(n)}\right)\left(Sin\left(\alpha_{Nsun(n)} + \beta_{PV}\right)\right)}{Sin\left(\alpha_{Nsun(n)}\right)}$$

Step 8: Update the sum of the solar radiation on tilted PV module,

$$\mathrm{SumG}_{\beta_{PV}} = \mathrm{SumG}_{\beta_{PV}} + G_{\beta_{PV(n)}}$$

Step 9: Compute the annual mean of the solar radiation on tilted PV module , $\mathrm{AMG}_{\beta_{PV}}$ using the expression;

$$\mathrm{AMG}_{\beta_{PV}} = \frac{\mathrm{SumG}_{\beta_{PV}}}{n} \quad (7)$$

Step 10: Update n: n = n + 1

Step 11: If n < 365 Then Goto Step 7 Else Goto Step 12

Step 12: If there is another tilt angle, then Goto Step 4 Else Goto Step 13

Step 13: Plot the graph of $\mathrm{AMG}_{\beta_{PV}} = \frac{\mathrm{SumG}_{\beta_{PV}}}{n}$ versus β

Step 14: Fit second order polynomial expression of $\mathrm{AMG}_{\beta_{PV}}$ as a function of β on the graph in Step 13 , that is $\mathrm{AMG}_{\beta_{PV}} = f(\beta)$

Step 15: Get the derivative of (β) , that is $\frac{\delta f(\beta)}{\delta \beta}$ and solve for β when $\frac{\delta f(\beta)}{\delta \beta} = 0$

Step 16: Output the value of β obtained when $\frac{\delta f(\beta)}{\delta \beta} = 0$

Step 17: End

The case study is a location in Odukpani in cross River State Nigeria with latitude of 5.0825 and longitude of

8.3484, as shown in Figure 1. The dialogue box for the input data used to obtain the daily elevation angle and azimuth angle for the case study site for a whole year is shown in Figure 2. The data on global radiation on the horizontal surface for the case study site is plotted in the graph of Figure 3 while the graph of the sun elevation angle and sun azimuth angle for a whole year are presented in Figure 4 and Figure 5 respectively.

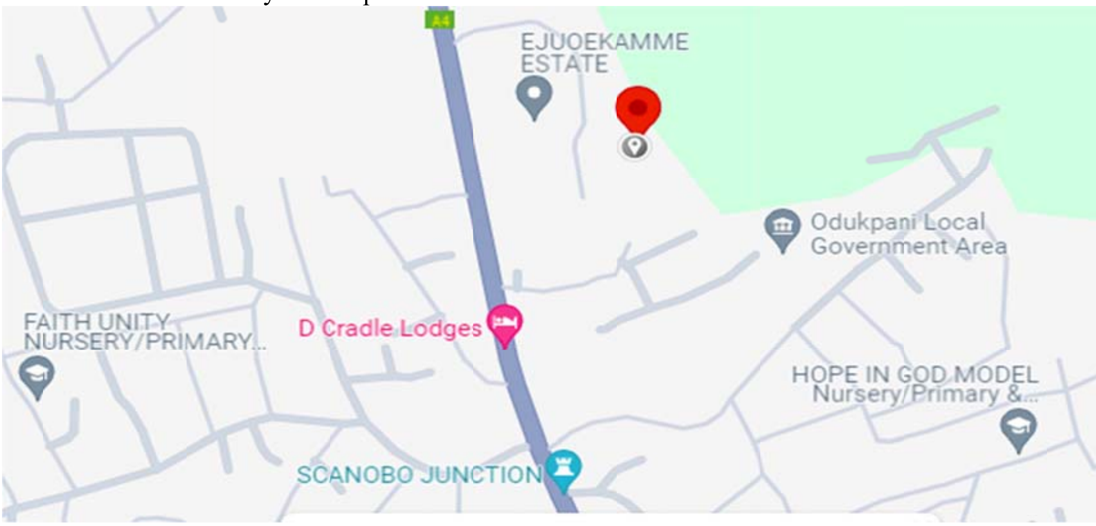


Figure 1 Google maps visualization of the case study site

Figure 2 The dialogue box for the input data used to obtain the daily elevation angle and azimuth angle for the case study site for a whole year

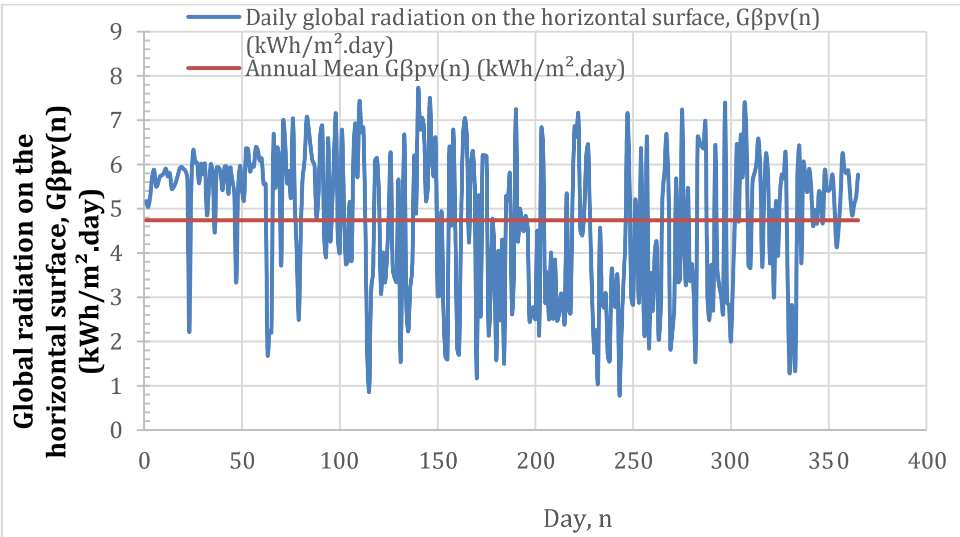


Figure 3 The global radiation on the horizontal surface for the case study site

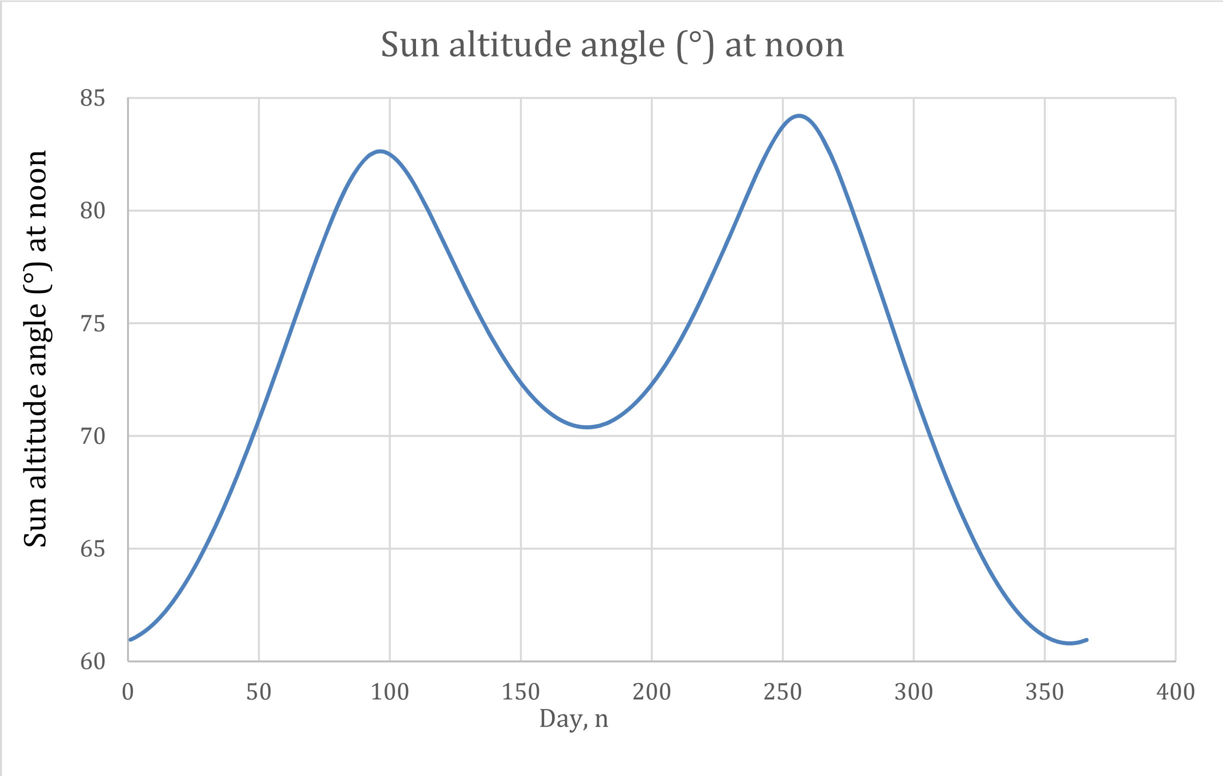


Figure 4 The sun elevation angle for a whole year

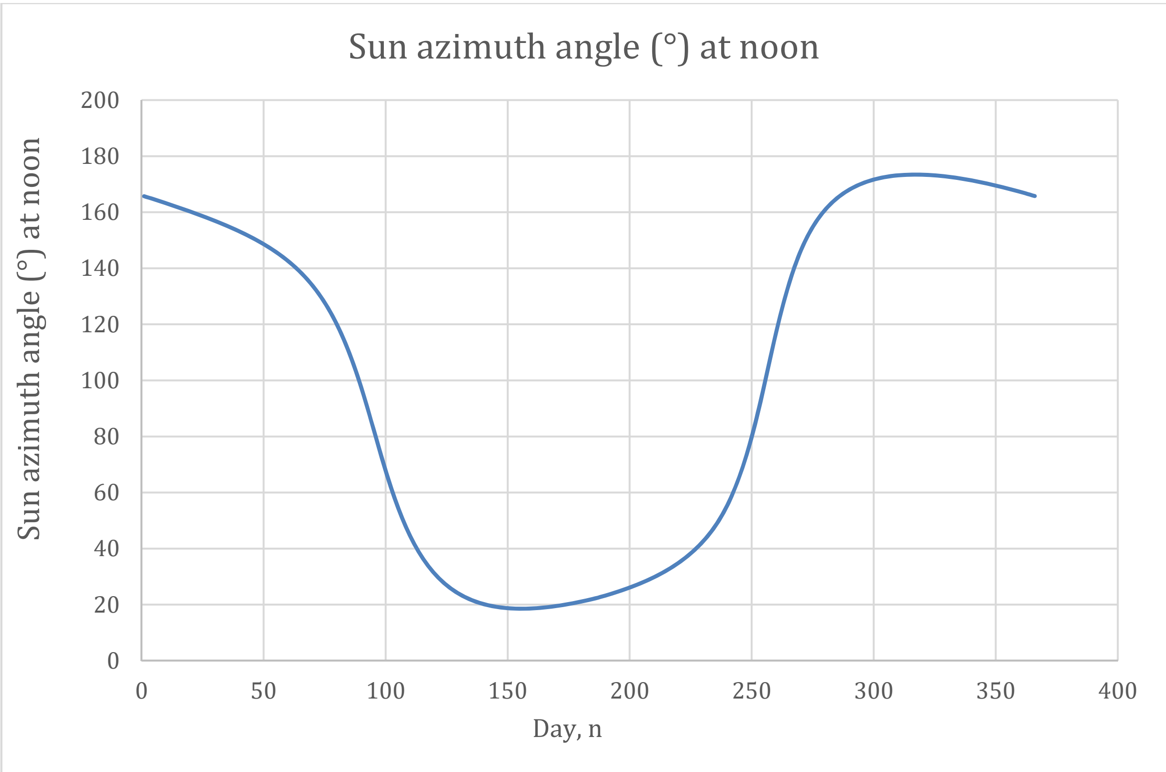


Figure 5 The sun azimuth angle for a whole year

While Algorithm 1 is meant for yearly fixed tilt angle, it is equally used for monthly fixed tilt angles. In this case, the algorithm is run for day number starting from the beginning of each of the months to the end of that same month. The data and formulas for computing day number for each day in a month are presented in Table 1. The beginning day number for each month is obtained by putting 1 =1 in the formulas for the months as shown in Table 1. As such, the first day in June is 151 +1 = 152 while the last day in June is 151 + 30 =181. Hence, the first day in July is 181 + 1=182. So, by using the formulas in Table 1 and the number of days in each month, Algorithm 1 is used to determine the fixed optimal tilt angle for each month.

Table 1 The data and formulas for computing day number for each day in a month

Month	n for i:th Day of the month	For the average day of the month	
		Date	n, day of the year
January	i	17	17
February	31+i	16	47
March	59+i	16	75
April	90+i	15	105
May	120+i	15	135
June	151+i	11	162
July	181+i	17	198
August	212+i	16	228
September	243+i	15	258
October	273+i	15	288
November	304+i	14	318
December	334+i	10	344

3. RESULTS AND DISCUSSIONS

3.1 Results for the annual fixed optimal tilt angle

The results of the daily solar radiation on the horizontal plane with βtilt = 0 ° and on the tilted PV module with βtilt = 90 ° are shown in Figure 6. The mean daily solar radiation on the horizontal plane is 4.73849863 kW-hr/m^2/day while the mean daily solar radiation on the tilted PV module with βtilt = 90 ° is 1.364947473 kW-hr/m^2/day. Essentially, tilt angle of 90 ° is not good. The mean annual solar radiation capture is worse than that of the horizontal plane layout.

The daily solar radiation is computed for the 365 days in a year and hence the annual mean of daily solar radiation are computed for various PV tilt angles ranging from 1° to 90°. The graph of annual mean of daily solar radiation for $1 \leq \beta \leq 90°$ is shown in Figure 7 while the graph for $1 \leq \beta \leq 30°$ is shown in Figure 8. From Figure 7 and the associated trend line expression in Equation 8, the first estimate of the annual fixed optimum tilt angle is computed as 13.97805 ° which has the annual mean of daily solar radiation value of 4.927887075. However, a more accurate annual fixed optimum tilt angle is computed from Figure 7 and the associated trend line expression in Equation 10 as 16.06796° which has the annual mean of daily solar radiation value of 4.931171347.

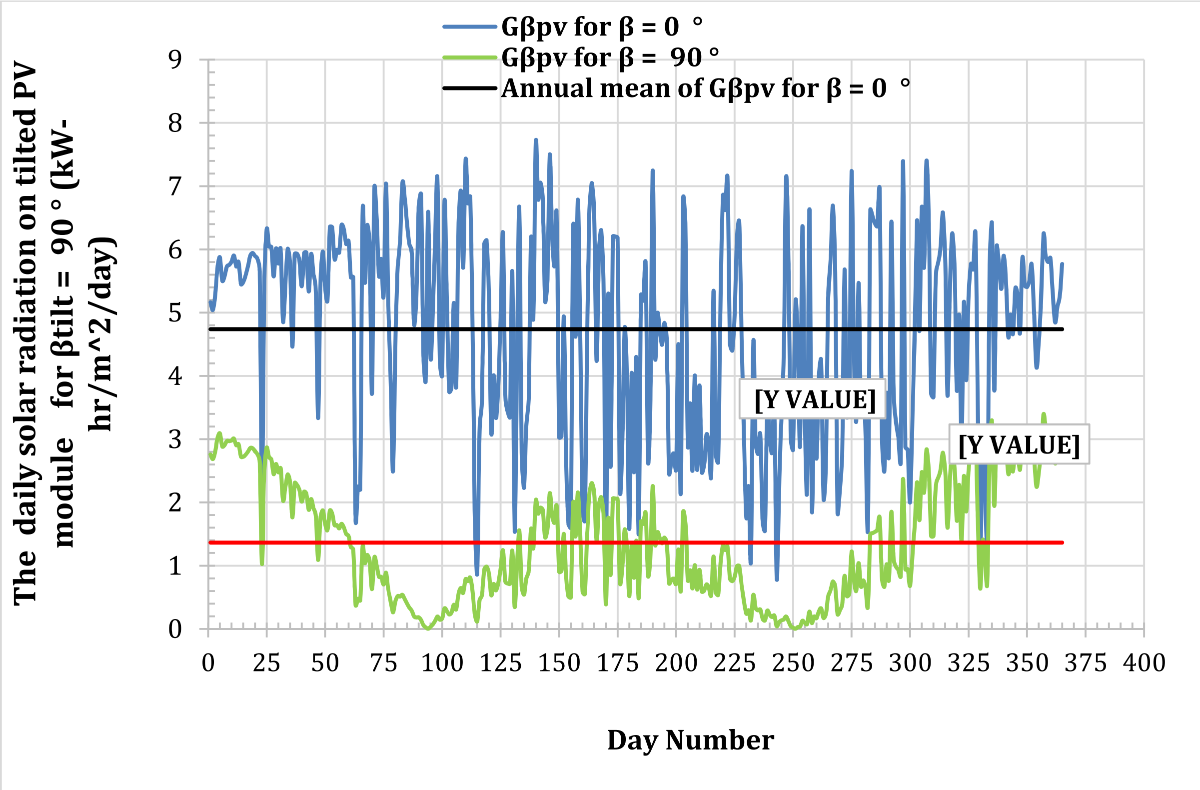


Figure 6 The graph of the daily solar radiation on the horizontal plane with βtilt = 0 ° and on the tilted PV module with βtilt = 90 °

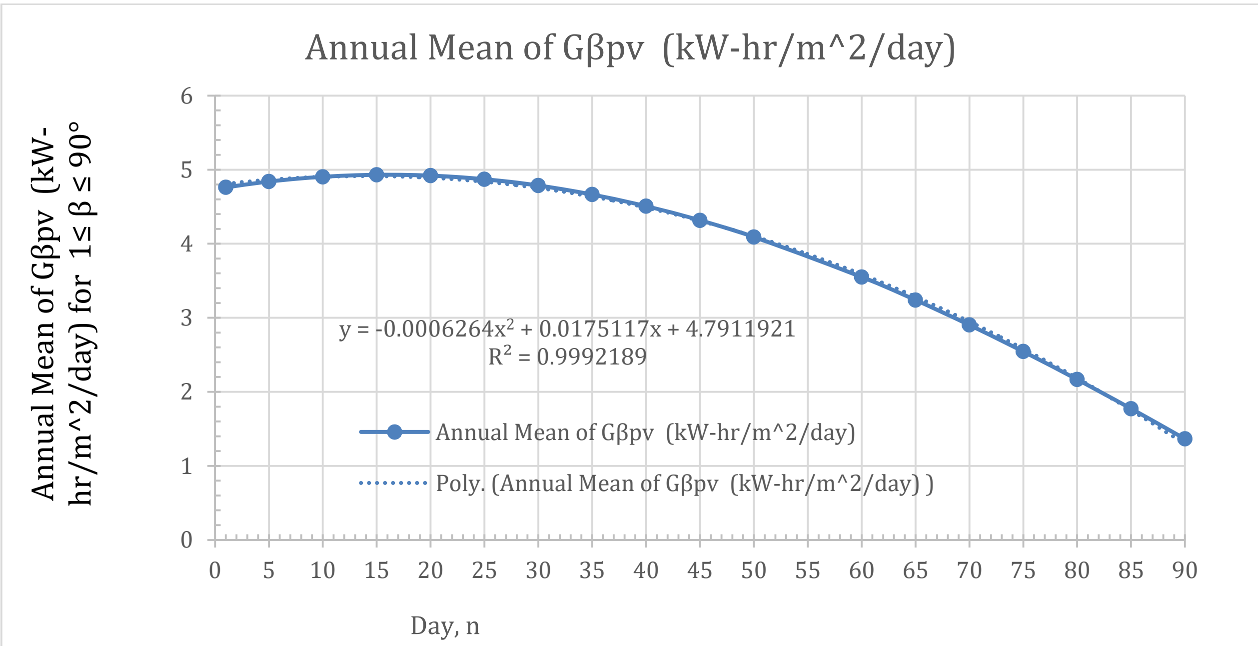


Figure 7 The graph of annual mean of daily solar radiation for $1 \leq \beta \leq 90°$

$$y = -0.0006264x^2 + 0.0175117x + 4.7911921 \quad (8)$$

$$\frac{dy}{dx} = -0.0012528\, x + 0.0175117 \quad (9)$$

$$x = 13.97805 \quad \text{for } \frac{dy}{dx} = 0$$

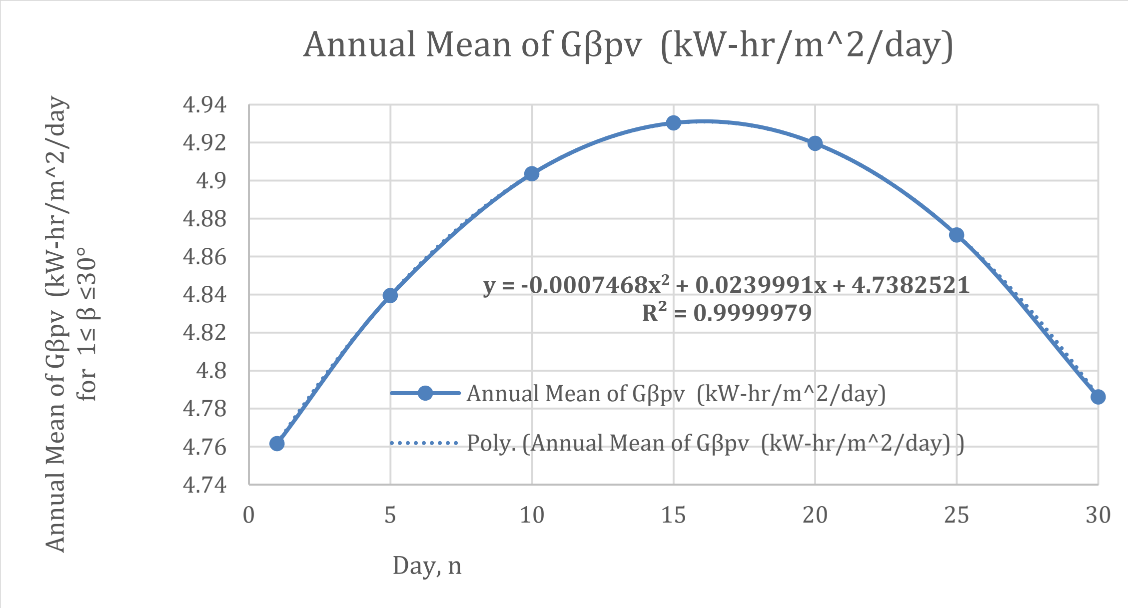


Figure 8 The graph of annual mean of daily solar radiation for $1 \leq \beta \leq 30°$

$$y = -0.0007468x^2 + 0.0239991x + 4.7382521 \quad (10)$$

$$\frac{dy}{dx} = -\ 0.0014936x + 0.0239991 \quad (11)$$

$$x = 16.06796 \ \text{ for } \frac{dy}{dx} = 0$$

3.2 Results of the monthly fixed optimal tilt angle

Again, the daily solar radiation is computed for each of the 12 months in a year and hence the monthly mean of daily solar radiation are computed for various PV tilt angles ranging from 1° to 90°. The results of the monthly mean of daily solar radiation for the 12 months are given in Table 2 for the various tilt angles.

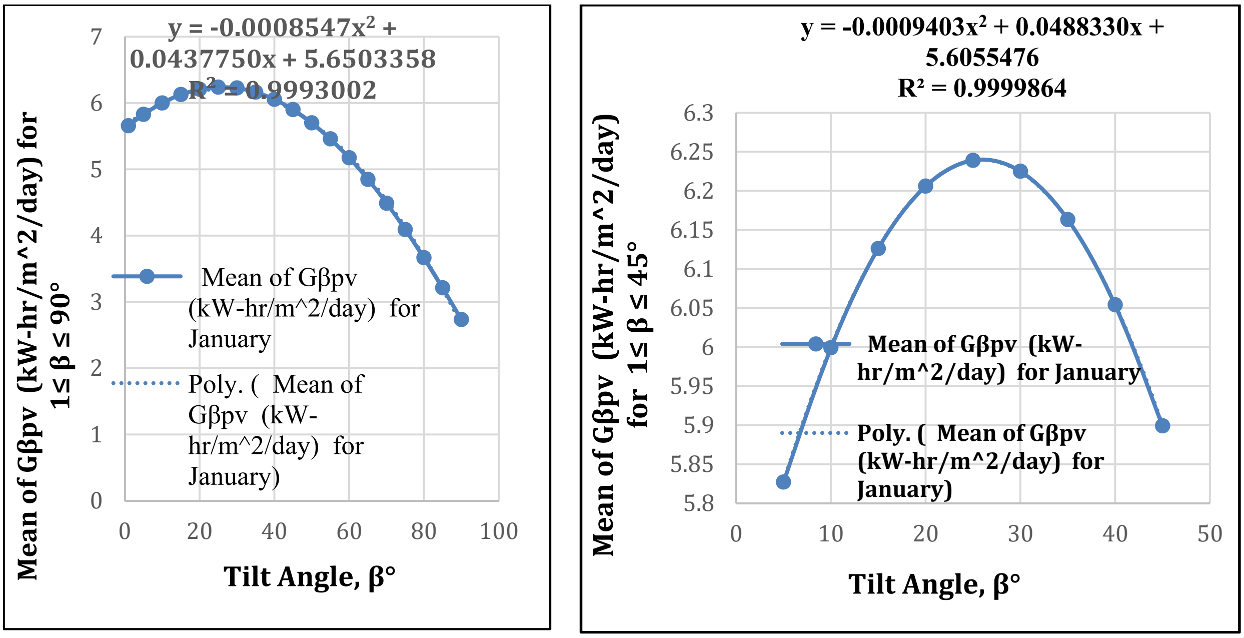
Table 2 The monthly mean of daily solar radiation , Gβpv (kW-hr/m^2/day) for the 12 months for various tilt angles ranging from 1° to 90°

β (°)	Gβpv for Jan	Gβpv for Feb	Gβpv for March	Gβpv for Apr	Gβpv for May	Gβpv for Jun	Gβpv for July	Gβpv for Aug	Gβpv for Sept	Gβpv for Oct	Gβpv for Nov	Gβpv for Dec
1	5.657	5.692	5.361	5.096	4.800	4.384	3.909	3.700	4.014	4.339	4.877	5.379
5	5.827	5.803	5.389	5.104	4.865	4.467	3.974	3.726	4.017	4.403	5.007	5.558
10	5.999	5.901	5.388	5.080	4.914	4.540	4.027	3.734	3.994	4.452	5.137	5.745
15	6.126	5.955	5.345	5.017	4.925	4.579	4.050	3.714	3.940	4.467	5.227	5.887
20	6.206	5.964	5.262	4.915	4.899	4.582	4.042	3.665	3.856	4.448	5.277	5.985
25	6.239	5.927	5.139	4.777	4.835	4.551	4.003	3.589	3.743	4.396	5.287	6.037
30	6.225	5.845	4.977	4.601	4.735	4.485	3.934	3.485	3.601	4.310	5.257	6.043
35	6.163	5.718	4.776	4.391	4.598	4.385	3.835	3.354	3.432	4.191	5.187	6.003
40	6.054	5.548	4.540	4.148	4.427	4.252	3.707	3.198	3.237	4.040	5.077	5.918
45	5.899	5.336	4.269	3.873	4.222	4.086	3.550	3.018	3.017	3.858	4.929	5.787
50	5.700	5.083	3.965	3.568	3.984	3.889	3.367	2.815	2.774	3.648	4.743	5.612
55	5.457	4.792	3.631	3.236	3.717	3.663	3.158	2.590	2.510	3.409	4.522	5.395
60	5.172	4.464	3.270	2.880	3.421	3.408	2.924	2.346	2.227	3.144	4.265	5.137
65	4.848	4.102	2.883	2.502	3.099	3.128	2.669	2.084	1.927	2.856	3.977	4.839

70	4.487	3.708	2.475	2.104	2.753	2.824	2.393	1.805	1.613	2.546	3.658	4.505
75	4.092	3.287	2.048	1.691	2.387	2.498	2.099	1.514	1.286	2.216	3.311	4.136
80	3.666	2.840	1.605	1.265	2.002	2.154	1.789	1.210	0.949	1.870	2.939	3.736
85	3.212	2.372	1.150	0.829	1.602	1.793	1.466	0.898	0.605	1.509	2.544	3.308
90	2.733	1.886	0.687	0.387	1.190	1.418	1.131	0.578	0.257	1.137	2.131	2.854

3.2.1 Fixed monthly optimal tilt angle for the month of January

From the results in Table 2, the graph of Gβpv versus tilt angle β (°) for the month of January is plotted as shown in Figure 9 for 1≤ β ≤ 90° and 1≤ β ≤ 45°.



(a) (b)

Figure 9 The graph of Gβpv versus tilt angle β (°) for the month of January

$$y = -0.0009403x^2 + 0.0488330x + 5.6055476 \quad (12)$$

$$\frac{dy}{dx} = -0.0018806x + 0.0488330 \quad (13)$$

$$x = 25.96671275 \text{ for } \frac{dy}{dx} = 0$$

The optimal tilt angle obtained from Figure 9 a is 25.60840061° for the graph with range of 1≤ β ≤ 90° which has monthly mean of daily solar radiation value of 6.240220791 kW-hr/m^2/day. Again, the optimal tilt angle obtained from Figure 9b, Equation 12 and Equation 13 for 1≤ β ≤ 45° is 25.96671275° which has monthly mean of daily solar radiation value of 6.240348657 kW-hr/m^2/day for the month of January. Hence, the more accurate optimal tilt angle for the month of January is 25.96671275°.

3.2.2 Fixed monthly optimal tilt angle for the month of February

From the results in Table 2, the graph of Gβpv versus tilt angle β (°) for the month of February is plotted as shown in Figure 10 for 1≤ β ≤ 45°. The optimal tilt angle obtained from Figure 10, Equation 14 and Equation 15 is 18.43096396 ° which has monthly mean of daily solar radiation value of 5.91447 kW-hr/m^2/day for the month of February.

$$y = -0.0009403x^2 + 0.0488330x + 5.6055476 \quad (14)$$

$$\frac{dy}{dx} = -0.0018092x + 0.0488330 \quad (15)$$

$$x = 18.43096396 \text{ for } \frac{dy}{dx} = 0$$

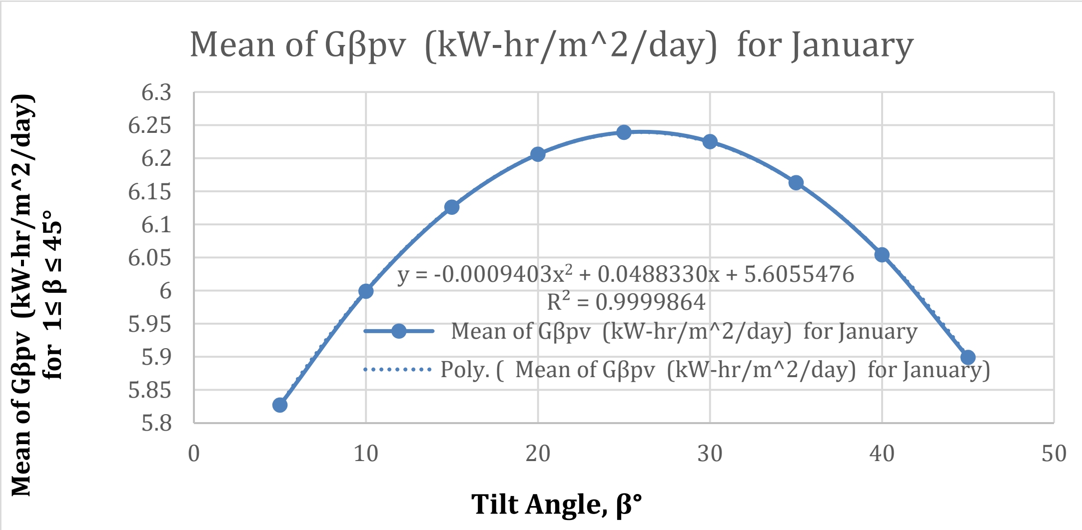


Figure 10 The graph of Gβpv versus tilt angle β (°) for the month of January

3.2.3 Fixed monthly optimal tilt angle for the month of March

From the results in Table 2, the graph of Gβpv versus tilt angle β (°) for the month of March is plotted as shown in Figure 11 for 1≤ β ≤ 45°. The optimal tilt angle obtained from Figure 11, Equation 16 and Equation 17 is 7.316103864 ° which has monthly mean of daily solar radiation value of 5.393870682 kW-hr/m^2/day for the month of March.

$$y = -0.0008203x^2 + 0.0120028\ x + 5.3499580 \quad (16)$$

$$\frac{dy}{dx} = -\ 0.0016406\ x + 0.0120028 \quad (17)$$

$$x = 7.316103864 \text{ for } \frac{dy}{dx} = 0$$

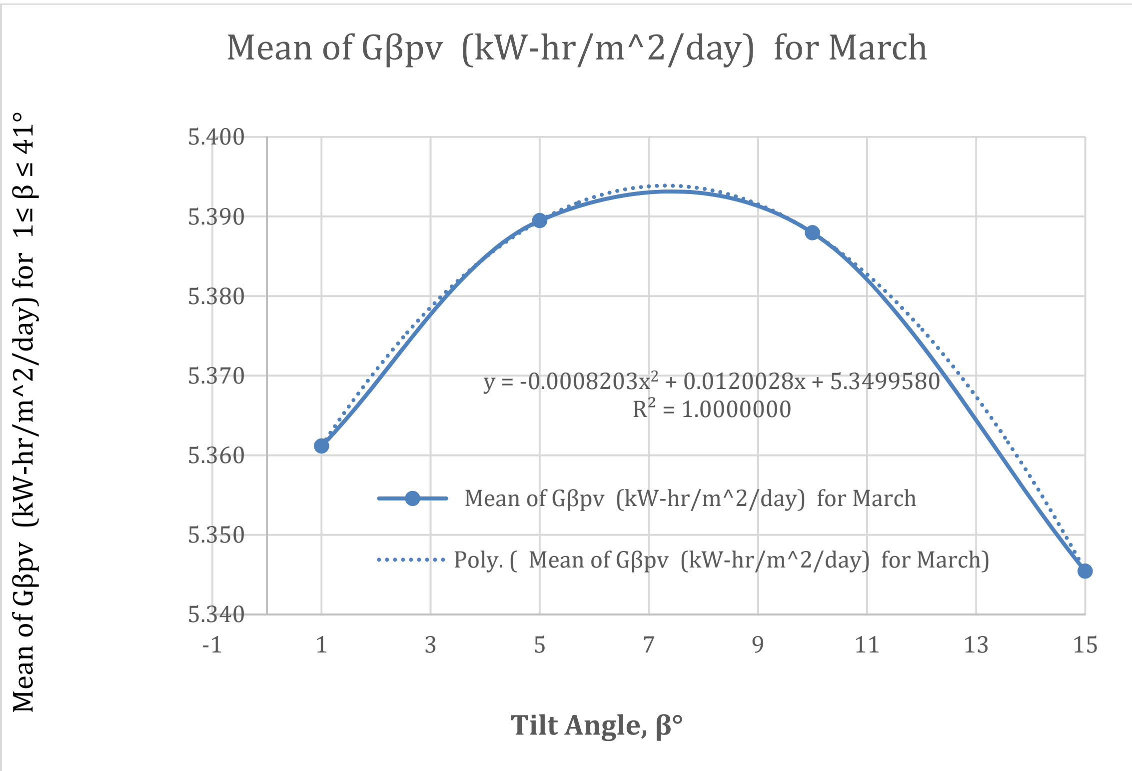


Figure 11 The graph of Gβpv versus tilt angle β (°) for the month of March

3.2.4 Fixed monthly optimal tilt angle for the 12 months

Similar approach was adopted for the rest of the months and the results obtained for the monthly fixed optimal tilt angle and the corresponding monthly mean solar radiation are presented in Table 3.

Table 2 The monthly fixed optimal tilt angle and the corresponding monthly mean solar radiation

S/N	Month	Monthly Fixed Optimal Tilt Angle (°)	Mean of Gβpv (kW-hr/m^2/day)
1	January	25.96671275°.	6.240348657
2	February	18.43096396	5.965983849
3	March	7.316103864	5.393870682
4	April	4.344574591	5.104699419
5	May	13.9848262	4.925897146
6	June	18.01912843	4.584907201
7	July	16.21198307	4.051039861
8	August	8.905897887	3.735130224
9	September	3.662986588	4.018310032
10	October	14.74405026	4.467025551
11	November	23.75450676	5.288343658
12	December	28.16368	6.046006752
	Annual	16.06796	4.931171347

4. CONCLUSION

An approach for determine the yearly annual fixed optimal tilt angle and also the monthly fixed optimal tilt angle for PV array in a given geo-location is presented. The approach utilizes the sun declination and elevation angles at solar noon to determine the solar radiation on tilted PV panel for the given period of interest and then determine at which tilt angle the PV panel capture the highest amount of solar radiation. With this approach the optimal annual fixed and optimal monthly fixed tilt angles are determined with the aid of trend line quadratic equations and their derivatives. The optimal tilt angles obtained are validated using sample computations based on the available case study dataset.

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