Analysis Of 400 KW Photovoltaic Plant Array Layout Design With Fixed Tilt Angle And Internal Shading Mitigation Row Spacing

Ubong S. Ukommi[1], Bassey B. Okon[2], Joachim J. Awaka-Ama[3] and Emmanuel A. Ubom[4]
[1&4]Department of Electrical and Electronic Engineering, Akwa Ibom State University, Nigeria
[2]Department of Aerospace Engineering, Federal University of Technology, Ikot Abasi, Nigeria.
[3]Department of Chemistry, Akwa Ibom State University, Nigeria.

A.email: [1]ubongukommi@aksu.edu.ng; [2]engrbasseyokon@gmail.com; [3]j.awaka-ama@aksu.edu.ng; [4]emmanuelubom@aksu.edu.ng
Corresponding email: *ubongukommi@aksu.edu.ng*

Abstract— **In this study analysis of 400 KW photovoltaic plant array layout design with fixed tilt angle and internal shading mitigation row spacing is presented. The case study site geo-coordinates of 4.621437 (latitude) and 7.763922 (longitude) along with the sun elevation angle of 17.82° and azimuth angle of 115.712° for a typical day with the longest shadow angle are obtained. For this study, 2000 units of 200 W photovoltaic (PV) module are used each with dimensions of 1.580m by 0.808 m, PV module area of 1.27664m^2) and PV array area of 2553.28 m^2). The two optimal tilt angles considered are 6.88879153 ° and 4.621437°. The results show that with optimal tilt angle of 6.88879153° the row spacing factor is 1.1546 which is higher than 1.1055 obtained with optimal tilt angle of 4.621437°. The results show that with optimal tilt angle of 6.88879153° the corrected row space of 0.255734 m is needed which resulted in row pitch of 1.824327 m and row spacing factor of 1.1546 while with optimal tilt angle of 4.621437°. The corrected row space of 0.17179 m is needed which resulted in row pitch of 1.746653 m and row spacing factor of 1.1055. This implies that the space requirement for PV installation at the optimal tilt angle of 6.88879153° is higher than that of optimal tilt angle of 4.621437°. Notably, the required PV array area is 2948.113 m^2 for tilt angle of 6.88879153° and 2822.591 m^2 for tilt angle of 4.621437°. Also, the lower tilt angle of 4.621437° has higher (and hence better) land utilization factor of 90.2 % and power density of 141.7 KW/m^2 compared to land utilization factor of 86 % and power density of 135.7 KW/m^2 obtained with tilt angle of 6.88879153°. In all, the case study site and PV module parameters were used to establish the reference row spacing for the case study 400 KW PV power plant such that all through the year, there will not be inter row shading in the array layout.**

Keywords— Photovoltaic Plant, Shading Mitigation, Row Spacing, Internal Shading. Yearly Fixed Tilt Angle

1. Introduction

Nowadays, in Nigeria, the increasing cost of energy from the national grid and the requirement for more environmentally friendly energy generation has triggered renewed effort to install solar photovoltaic (PV) power plants in Nigeria [1,2,3]. This has also drawn the attention of researchers on the land requirement for installation of large number of PV modules that are needed for high capacity PV power plants [4,5,6].

Apart from the increasing cost of land, there is also, the challenge of shading mitigation from adjacent PV rows in a PV array layout design [7,8]. Internal shading will reduce the energy generation from the PV array. On the other hand, row spacing can be done to avoid the inter row spacing. However, excessive row spacing can amount to wastage of land and poor land utilization and low power density [5,6,9,10]. As such, this study is aimed at determining the appropriate row spacing that will have high land utilization factor and at the same time mitigate the incidence of internal row shading. The analysis is conducted for a case study 400 KW PV power plant installation at Akwa Ibom State University main campus. The details of the mathematical models and analysis are presented and two PV tilt angle options are considered.

2 Methodology

The layout design of PV plant array with fixed tilt angle is greatly affected by the row spacing which is a function of the shadow length of adjacent rows [10,11]. In order to mitigate internal shading from adjacent rows, the shadow length of the tilted PV modules is determined such that even in the day with the longest shadow length, the adjacent row is not shaded [12,13]. The study therefore considered the various parameters that can affect the row spacing determination and also the impact of the selected row spacing on the land utilization and power density of the PV array.

2.1 Analytical model for the PV module row spacing

In this work, the adjacent row spacing is analyzed using the diagram in Figure 1 which has β as the PV module tilt angle, α as the sun elevation angle, L as the PV module length, Di as the minimum adjacent row spacing for internal shading mitigation and D as the row pitch.

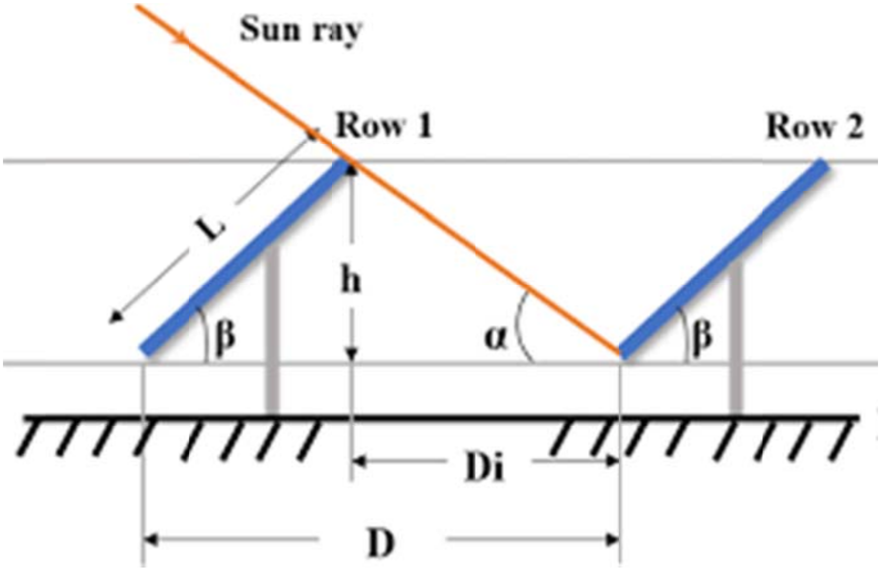

Figure 1 The diagram of two adjacent rows of PV modules [14]

The value of Di is computed as follows;

$$h = L\,(Sin(\beta)) \quad (1)$$

$$Di = \frac{h}{Tan(\alpha)} = \frac{L\,(Sin(\beta))}{Tan(\alpha)} = L\,(Sin(\beta))\left(\frac{1}{Tan(\alpha)}\right) \quad (2)$$

The PV array considered has fixed tilt angle, β whereas the elevation angle, αvaries with time in hours and in a day. As such, selection of the appropriate time for the elevation angle to be used for the PV array layout design is essential, as indicated in Equation 2. Notably, in Equation 2, the maximum row spacing due to internal shading mitigation concept will occur at the maximum value of $\frac{1}{Tan(\alpha)}$ and this time is within the sunshine hours in a day. To assist in the selection of typical day time hour for the PV array design, the case study site geo-coordinates of 4.621437 (latitude) and 7.763922 (longitude) along with the sun elevation angle and azimuth angle for a typical day time hours ranging from 8 am to 8 pm are obtained and shown in Table 1. Based on the data in Table 1, the graph of sun elevation angle between 8 an and 6 pm is plotted in Figure 2 while the graph of 1/ Tan(Elevation angle) for the sun elevation angle between 8 an and 8 pm is plotted in Figure 3. Figure 2 graph shows that maximum elevation angle occurred at noon (around 12 noon) while minimum elevation angle occur at 8 am. Again, Figure 3 graph shows that maximum value of 1/ Tan(Elevation angle) occurred at 8 am while the minimum value of 1/ Tan(Elevation angle) occurred at noon (around 12 noon). Since, the maximum value of 1/ Tan(Elevation angle) gives the maximum row spacing distance, Di based on Equation 2, the study adopted 8 am as the reference time for solar radiation energy conversion at the site.

Table 1 The sun elevation angle and azimuth angle for a typical day time hours ranging from 8 am to 8 pm of the case study site

Date:	22/06/2024 | GMT1	
coordinates:	4.621437, 7.763922	
location:	4.62143700,7.76392200	
hour	Elevation	Azimuth
8:00:00	8.47°	66.97°
9:00:00	22.22°	66.55°
10:00:00	35.83°	64.3°
11:00:00	49.02°	58.99°
12:00:00	61.08°	47.27°
13:00:00	69.75°	21.02°
14:00:00	69.94°	340.35°
15:00:00	61.49°	313.38°
16:00:00	49.5°	301.3°
17:00:00	36.33°	295.83°
18:00:00	22.72°	293.49°
19:00:00	8.97	293.02

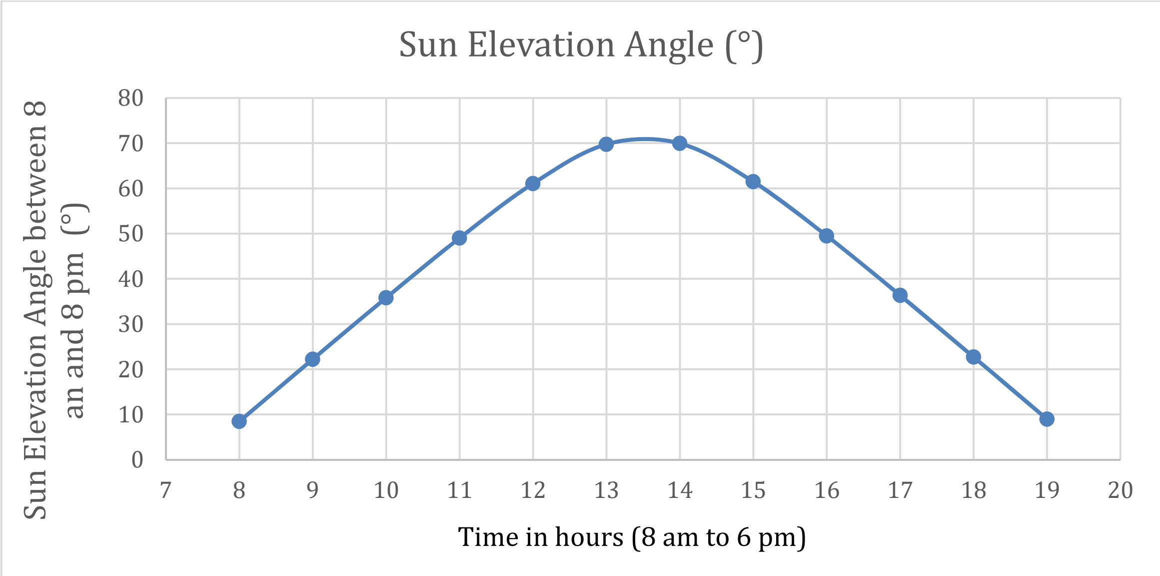

Figure 2 The graph of sun elevation angle between 8 an and 8 pm

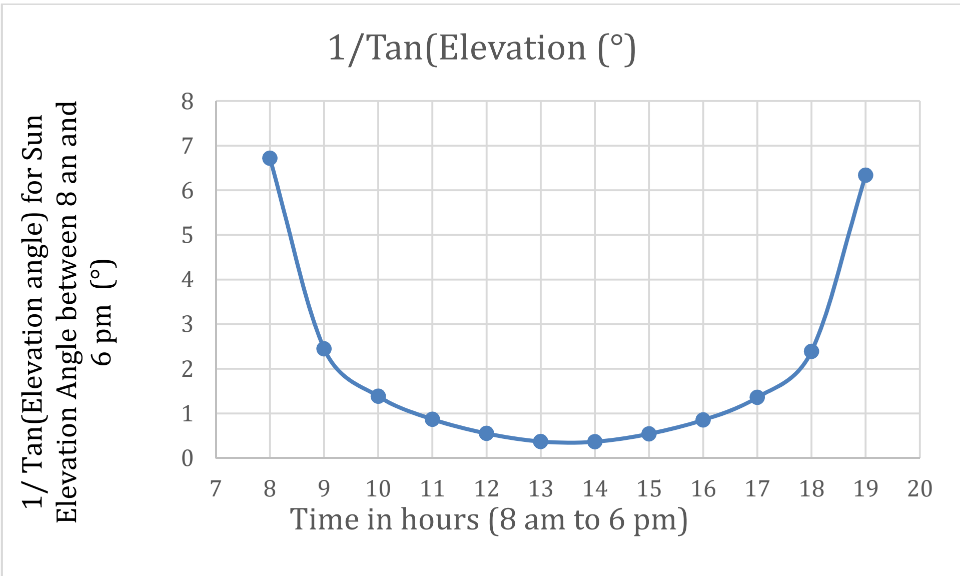

Figure 3 The graph of 1/ Tan(Elevation angle) for the sun elevation angle between 8 an and 8 pm

In many works, the value of Di is corrected using the sun azimuth angle, Υ. If the azimuth angle-corrected Di is denoted as Di_{cor}, then;

$$Di_{cor} = Di\,(Cos(\Upsilon)) = \frac{h(Cos(\Upsilon))}{Tan(\alpha)} = \frac{L\,(Sin(\beta))(|Cos(\Upsilon)|)}{Tan(\alpha)} \quad (3)$$

Hence,

$$D = L\,(Cos(\beta)) + Di_{cor} \quad (4)$$

$$D = L\,(Cos(\beta)) + \frac{L\,(Sin(\beta))(|Cos(\Upsilon)|)}{Tan(\alpha)} \quad (5)$$

$$D = L\left[(Cos(\beta)) + \frac{(Sin(\beta))(|Cos(\Upsilon)|)}{Tan(\alpha)}\right] \quad (6)$$

If the PV module width is denoted as $\bar{L}$, then the effective area, $A_{\beta PV}$ of the tilted PV module is expressed as;

$$A_{\beta PV} = \bar{L}(D) = (\bar{L})\,L\left[(Cos(\beta)) + \frac{(Sin(\beta))(|Cos(\Upsilon)|)}{Tan(\alpha)}\right] \quad (7)$$

Since, $(\bar{L})\,L$ is the actual area, A_{PV} of the PV module with dimension L and $\bar{L}$, then, the $A_{\beta PV}$ can be expressed as,

$$A_{\beta PV} = \bar{L}(L)(f_{rsp}) = A_{PV}(f_{rsp}) \quad (8)$$

Where f_{rsp} is the row spacing factor which is defined as;

$$f_{rsp} = \frac{D}{L} = \frac{A_{\beta PV}}{A_{PV}} = Cos(\beta) + \frac{(Sin(\beta))(|Cos(\Upsilon)|)}{Tan(\alpha)} \quad (9)$$

And

$$A_{PV} = (\bar{L})\,L \quad (10)$$

The higher the value of row spacing factor, the more the ground or land area required to accommodate the given PV array power rating. From the expression for the row spacing factor, the tilt angle, the sun elevation angle and the sun azimuth angle are the key parameters that influence the resultant land utilization factor. Notably, the row spacing factor consists of t6wo components, namely, the land utilization factor (f_{LPV}) which is the fraction of the land that is occupied by the PV module, the shading mitigation cum walkway factor (f_{SW}) which is the fraction of the land that is not occupied by the PV module but reserved for shading mitigation cum walkway. Hence,

$$f_{LPV} = \left(\frac{Cos(\beta)}{frsp}\right)100\ \% \quad (11)$$

$$f_{SW} = \left(\frac{\left(\frac{(Sin(\beta))(|Cos(\Upsilon)|)}{Tan(\alpha)}\right)}{frsp}\right) 100\ \% \qquad (12)$$

For this study, a PV module rated as P_{PVM} is used and given the case study PV plant power capacity as P_{PVArr}, the number of PV modules required, $N_{\beta PV}$ is given as;

$$N_{\beta PV} = \frac{P_{PVArr}}{P_{PVM}} \qquad (13)$$

The total land required for the entire PV array, $A_{\beta Array}$ is given as;

$$A_{\beta Array} = A_{\beta PV}(N_{\beta PV}) = \left(\frac{P_{PVArr}}{P_{PVM}}\right)(A_{PV})\left[(Cos(\beta)) + \frac{(Sin(\beta))(|Cos(\Upsilon)|)}{Tan(\alpha)}\right] \qquad (14)$$

Let A_{Array} denote the actual total area of the PV array where;

$$A_{Array} = \left(\frac{P_{PVArr}}{P_{PVM}}\right)(A_{PV}) \qquad (16)$$

Hence,

$$A_{\beta Array} = A_{Array}(f_{rsp}) = A_{Array}\left[(Cos(\beta)) + \frac{(Sin(\beta))(|Cos(\Upsilon)|)}{Tan(\alpha)}\right] \qquad (17)$$

Again,

$$\frac{A_{\beta Array}}{A_{Array}} = f_{rsp} = \left[(Cos(\beta)) + \frac{(Sin(\beta))(|Cos(\Upsilon)|)}{Tan(\alpha)}\right] \qquad (18)$$

Again, the land utilization factor (f_{LPV}) is given as;

$$f_{LPV} = \left(\frac{Cos(\beta)}{frsp}\right) 100\ \% = \left(\frac{Cos(\beta)}{(Cos(\beta)) + \frac{(Sin(\beta))(|Cos(\Upsilon)|)}{Tan(\alpha)}}\right) 100\ \% \qquad (19)$$

Also, the shading mitigation cum walkway factor (f_{SW}) is given as;

$$f_{SW} = \left(\frac{\left(\frac{(Sin(\beta))(|Cos(\Upsilon)|)}{Tan(\alpha)}\right)}{frsp}\right) 100\ \% = \left(\frac{\left(\frac{(Sin(\beta))(|Cos(\Upsilon)|)}{Tan(\alpha)}\right)}{(Cos(\beta)) + \frac{(Sin(\beta))(|Cos(\Upsilon)|)}{Tan(\alpha)}}\right) 100\ \% \qquad (20)$$

The power density, $P_{density}$ of the power plant is defined as the KW per m^2 of land area where;

$$P_{density} = \frac{P_{PVArr}}{A_{\beta Array}} \qquad (21)$$

$$P_{density} = \frac{P_{PVArr}}{A_{Array}(frsp)} = \frac{P_{PVArr}}{A_{Array}}\left(\frac{1}{frsp}\right) \qquad (22)$$

$$P_{density} = \frac{P_{PVArr}}{A_{Array}}\left(\frac{1}{\left[(Cos(\beta)) + \frac{(Sin(\beta))(|Cos(\Upsilon)|)}{Tan(\alpha)}\right]}\right) \qquad (23)$$

2.2 THE CASE STUDY SITE AND PV ARRAY DATA

The values of P_{PVArr} in Equation 23 is given from the PV power plant capacity specification. The value of A_{Array} in Equation 23 is obtained from the dimensions (length and width specifications) of the PV module. For this study, 200 W PV module (that is P_{PVM} = 200) is used and given the case study PV plant power capacity as 400 kW (that is $P_{PVArr} = 400{,}000$) , the number of PV modules required, $N_{\beta PV}$ is given as;

$$N_{\beta PV} = \frac{400{,}000}{200} = 2000$$

Specifically, the REDMAX MT-105M-200W PV module with technical specifications in Table 2 and dimensions in Figure 1 is used. It has length of 1580 mm and width of 808 mm with cell efficiency of 19.5 %.

Table 2 The technical specifications of the REDMAX MT-105M-200W PV module

Maximum Power, P_m	200W	**Dimensions (LxWxH)**	1580 x 808 x 35mm
Maximum Power Voltage, V_m	18.0V	**Weight**	15.3kg
Maximum Power Current, I_m	11.11A	**Front Glass**	3.2mm Tempered Glass
Open Circuit Voltage, V_{oc}	22.5V	**Hail Load Test**	Steel ball drop from 1m
Short Circuit Current, I_{sc}	11.35A	**Frame**	Anodised Aluminium Alloy
Cell Efficiency	19.5%	**Junction Box Type**	IP65 rated
Fill Factor, FF	≥74%	**Temp. Coeff. @ V_{oc}**	-0.24% to -0.33% / °C
Working Temperature	-40°C to +85°C	**Temp. Coeff. @ P_m**	-0.37% to -0.42% / °C
Power Tolerance	±3%	**Temp. Coeff. @ I_{sc}**	-0.03% to -0.04% / °C

(Available https://www.rjbatt.com.au/media/m4zjjdhk/pds-mt-105m-200w-solar-panel.pdf)

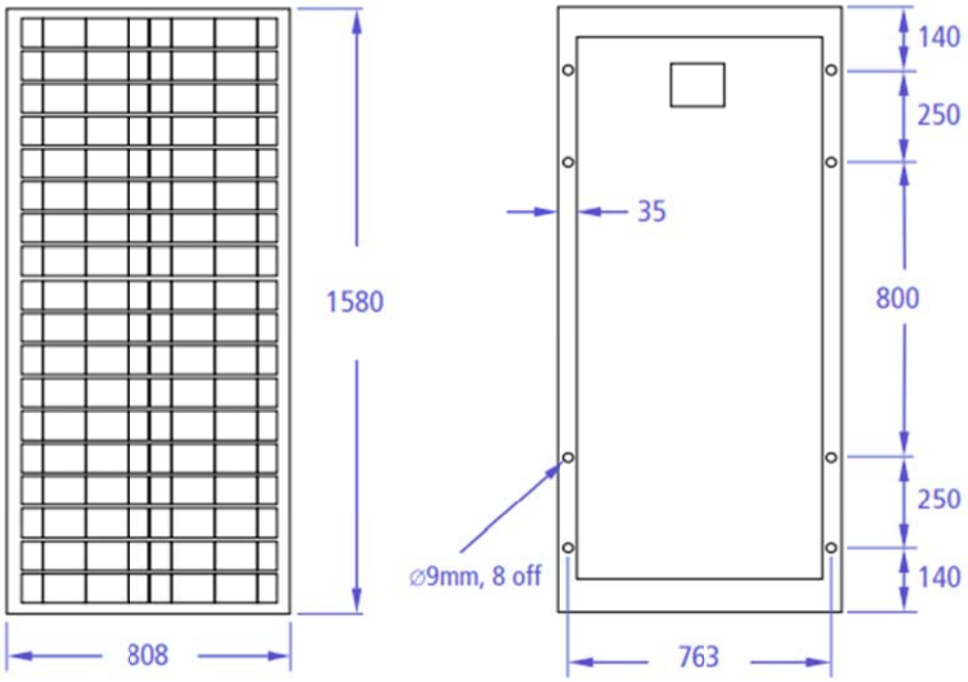

Figure 1 The dimensions of the REDMAX MT-105M-200W PV module
(Available https://www.rjbatt.com.au/media/m4zjjdhk/pds-mt-105m-200w-solar-panel.pdf)

The value of tilt angle, β in Equation 23 is selected for optimal yearly fixed tilt angle (β_{optyr}). Two options are used in this study.

$$\beta_{optyr} = \begin{cases} latitude & Option\ 1 \\ 0.69(latitude) + 3.7 & Option\ 2 \end{cases} \quad (24)$$

For the case study site with latitude of 4.621437, the optimal yearly fixed tilt angle (β_{optyr}) options are;

$$\beta_{optyr} = \begin{cases} 4.621437 & Option\ 1 \\ 0.69(l4.621437) + 3.7 = 6.79636279 & Option\ 2 \end{cases}$$

The value of the elevation angle and azimuth angle in Equation 23 are obtained by selecting a typical day in a year with the maximum value of azimuth angle-corrected Di which is denoted as Di_{cor} and given in Equation 6. Notably, the maximum value of Di_{cor} occurs in the day at the selected 8 am time when $\frac{|Cos(\Upsilon)|}{Tan(\alpha)}$ is maximum. The graph of the elevation angle (°) at 08:00:00 for the whole year is shown in figure 4 while The graph of the azimuth angle (°) at 08:00:00 for the whole year is shown in figure 5. Hence, the plot of $\frac{|Cos(\Upsilon)|}{Tan(\alpha)}$ versus day number for elevation and azimuth angle extracted for each of the 365 days at 8 am is given in Figure 6. The results showed that the maximum value of 1.34449301 for $\frac{|Cos(\Upsilon)|}{Tan(\alpha)}$ occurred at 8 am on the 4th day which is in January. Hence, the elevation angle and azimuth at 8 am on the 4th day which is in January are used in Equation 23.

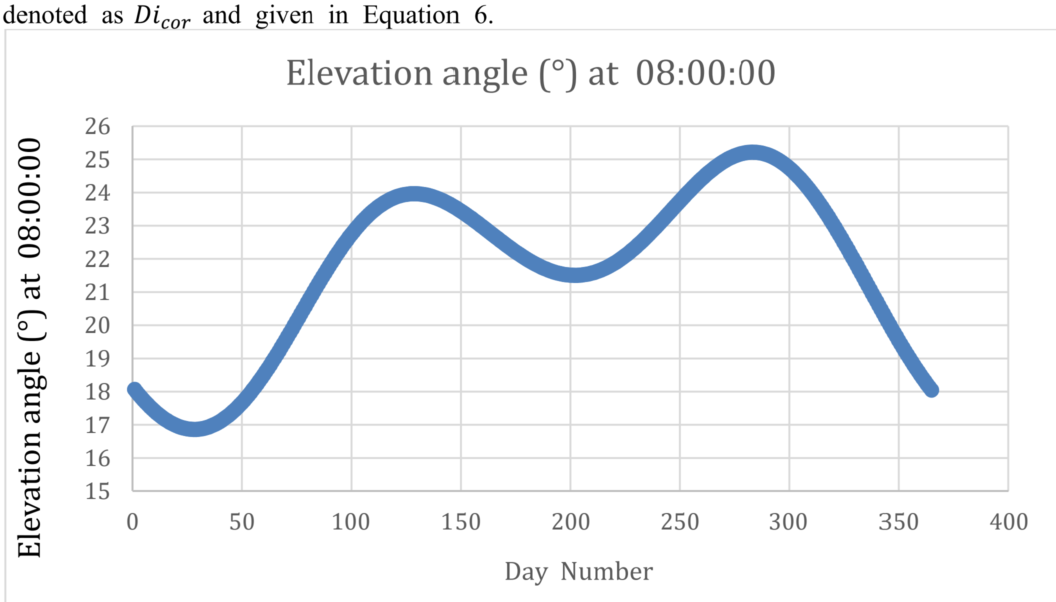

Figure 4 The graph of the elevation angle (°) at 08:00:00 for the whole year while

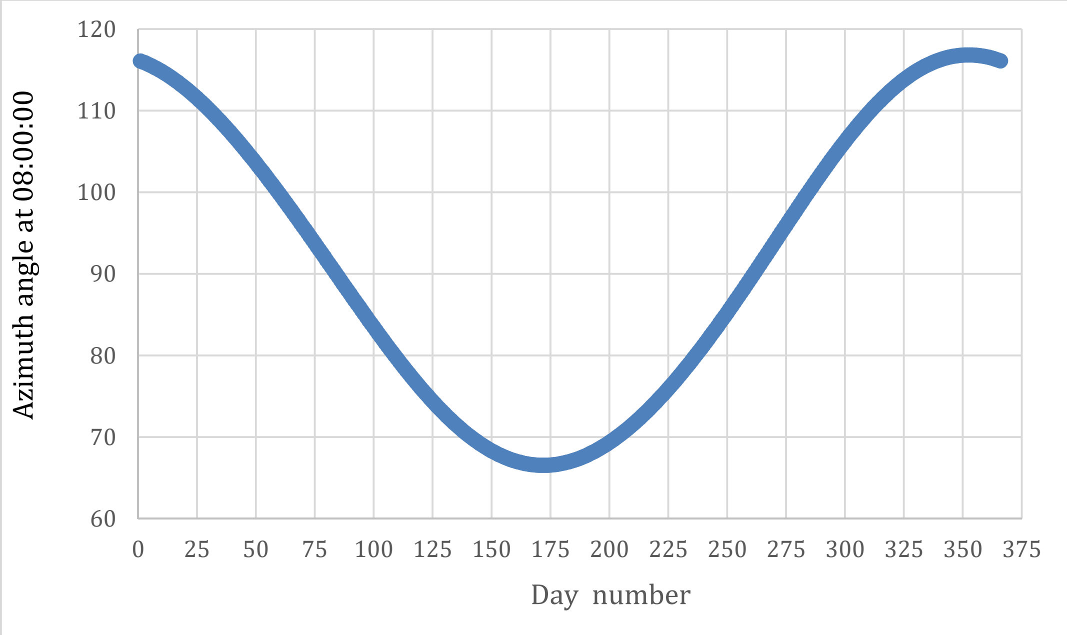

Figure 5 The graph of the azimuth angle (°) at 08:00:00 for the whole year

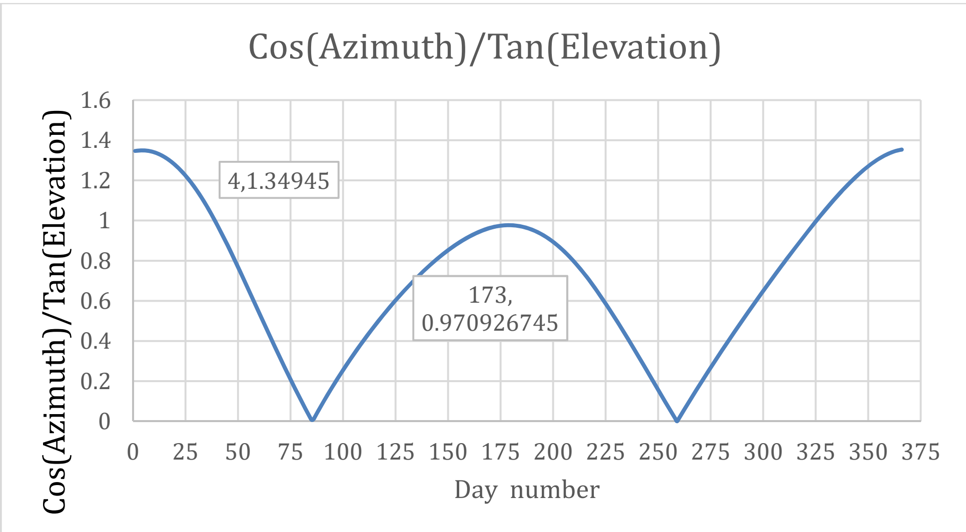

Figure 6 The graph of Cos(Azimuth)/Tan(Elevation) versus day number where the elevation angle and azimuth angle are taken at 8 am per day

3. RESULTS AND DISCUSSION

The case study site geo-coordinates and the results of the sun position angles and the resultant row spacing factor, f_{rsp} based on the sun angles are shown in Table 3 for the two selected optimal tilt angle options. It is seen from the results that with optimal tilt angle of 6.88879153° the row spacing factor is 1.1546 which is higher than that obtained with optimal tilt angle of 4.621437°.

The PV module dimension and the resultant PV module area, PV array area are shown in Table 4. The dataset in Table 4 shows that there are 200 PV module in the array. Also, the actual PV module area is 1.27664 m^2) and the actual PV array area is 2553.28 m^2) . The same PV module and PV array data in Table 4 are used in the analysis for the two optimal tilt angle options.

The results for the row spacing and the resultant row spacing factor, f_{rsp} based on the PV module are and row spacing distance are shown in Table 5. The results show that with optimal tilt angle of 6.88879153° the corrected row space of 0.255734 m is needed which resulted in row pitch of 1.824327 m and row spacing factor of 1.1546 while with optimal tilt angle of 4.621437°. the corrected row space of 0.17179 m is needed which resulted in row pitch of 1.746653 m and row spacing factor of 1.1055. This implies that the space requirement for PV installation at the optimal tilt angle of 6.88879153° is higher than that of optimal tilt angle of 4.621437° as can be seen in Table 6, where required PV array area is 2948.113 m^2 for tilt angle of 6.88879153° and 2822.591m^2 for tilt angle of 4.621437°.

Also, the lower tilt angle of 4.621437° has higher (and hence better) land utilization factor of 90.2 % and power density of 141.7 KW/m^2 compared to land utilization factor of 86 % and power density of 135.7 KW/m^2 obtained with tilt angle of 6.88879153°, as shown in Figure 7, Figure 8 and Table 6.

Evaluation of the effectiveness of the selected reference row spacing parameters in mitigating inter row shading at the optimal tilt angle of 6.88879153° is shown in Figure 9 and at the optimal tilt angle of 4.621437° is shown in Figure 10. As can be seen in Figure 9 and Figure 10, the row spacing required for each day of the year is less or equal to the selected reference row spacing obtained from the set of input dataset. None of the row spacing requirement is above the reference row spacing obtained. As such, there will not be inter row spacing in the PV array layout if the parameter specifications stated in this study are maintained for the PV plant installation.

Table 3 The sun position angles and the resultant row spacing factor, f_{rsp} based on the sun angles

$\boldsymbol{\beta_{optyr}}$ **(°)**	**Latitude**	**Longitude**	**Date**	**Day Number**	**Time**	**Elevation angle, $\boldsymbol{\alpha}$ (°)**	**Azimuth angle, $\boldsymbol{\alpha}$ (°)Υ**	$f_{rsp} = Cos(\beta_{optyr}) + \frac{(Sin(\beta))\lvert Cos(\Upsilon)\rvert}{Tan(\alpha)}$
6.88879153	4.621437	7.763922	4th January. 2024	4	8:00:00 (AM)	17.82	115.712	1.1546
4.621437	4.621437	7.763922	4th January. 2024	4	8:00:00 (AM)	17.82	115.72	1.1055

Table 4 **The PV module dimension and the resultant PV module area, PV array area**

PV module length, L (m)	PV module width, $\bar{L}$ (m)	PV module power rating, P_{PVM} (Watt)	PV Array Power Rating, P_{PVArr} (KW)	Number of PV modules required, $N_{\beta PV}$	Actual area of PV module, A_{PV} (m^2)	Actual area of PV array, A_{Array} (m^2)
1.580	0.808	200	400	2000	1.27664	2553.28

Table 5 The results for the row spacing and the resultant row spacing factor, f_{rsp} based on the PV module are and row spacing distance

$\boldsymbol{\beta_{optyr}}$ **(°)**	h (m)	Di (m)	Dicor (m)	Row pitch, D (m)	$A_{\beta PV}$ (m^2)	$f_{rsp}==\frac{D}{L}\frac{A_{\beta PV}}{A_{PV}}$
6.88879153	0.189509	0.589377	0.255734	1.824327	1.474057	1.154638
4.621437	0.127304	0.395916	0.17179	1.746653	1.411296	1.105477

Table 6 The results for the required PV array area, land utilization factor, walkway/ shading mitigation factor and power density

$\boldsymbol{\beta_{optyr}}$ **(°)**	Required PV array area, $A_{\beta Array}$	Land Utilization Factor, f_{LPV} (%)	Walkway/ Shading Mitigation Factor, f_{SW} (%)	Power Density, $P_{density}$, (KW/m^2)
6.88879153	2948.113	86.0	14.0	135.7
4.621437	2822.591	90.2	9.8	141.7

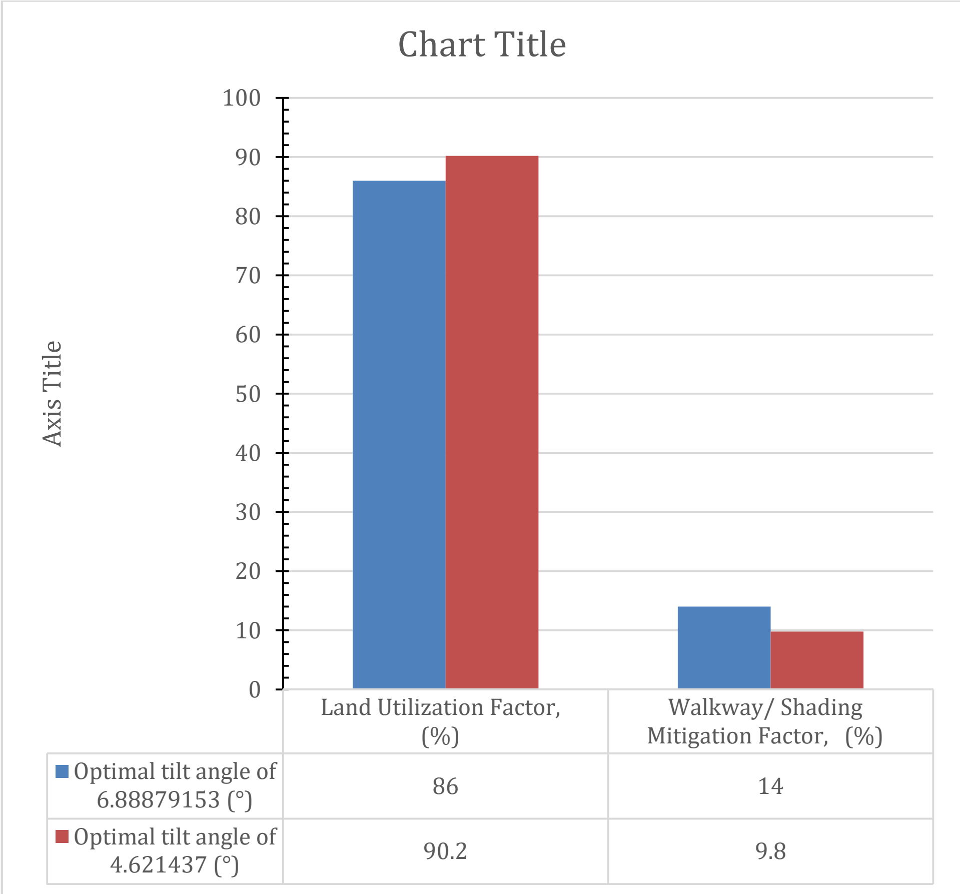

Figure 7 The land utilization factor, walkway/ shading mitigation factor for the two optimal tilt angle options

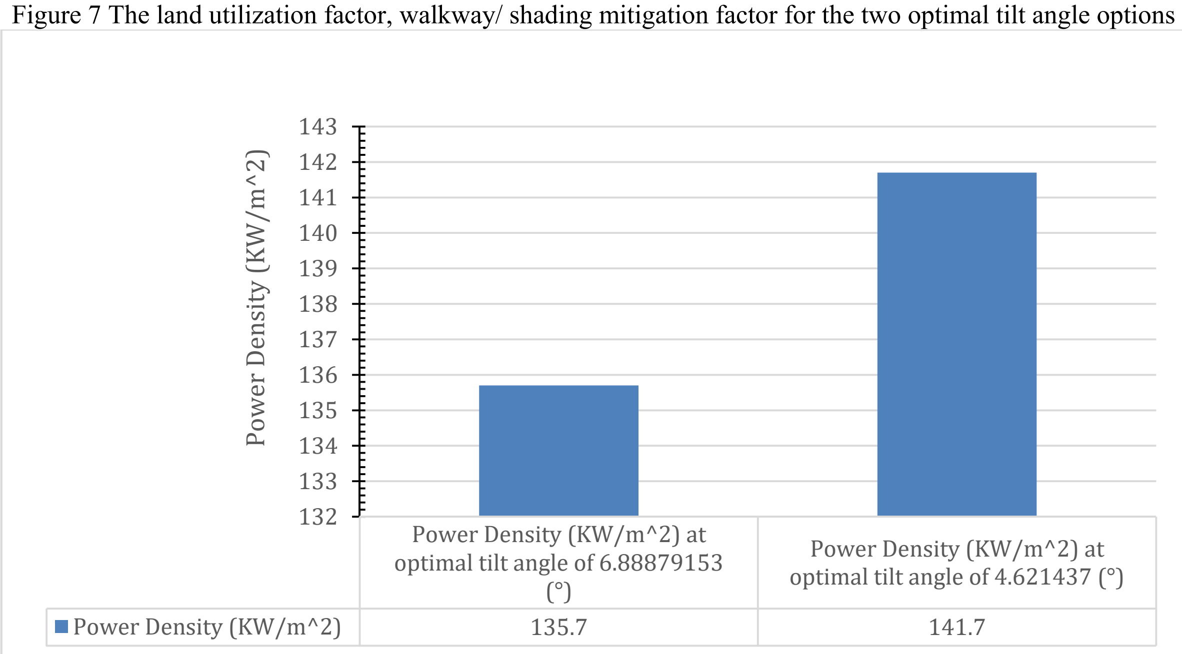

Figure 8 Power Density (KW/m^2) at the two optimal tilt angle options

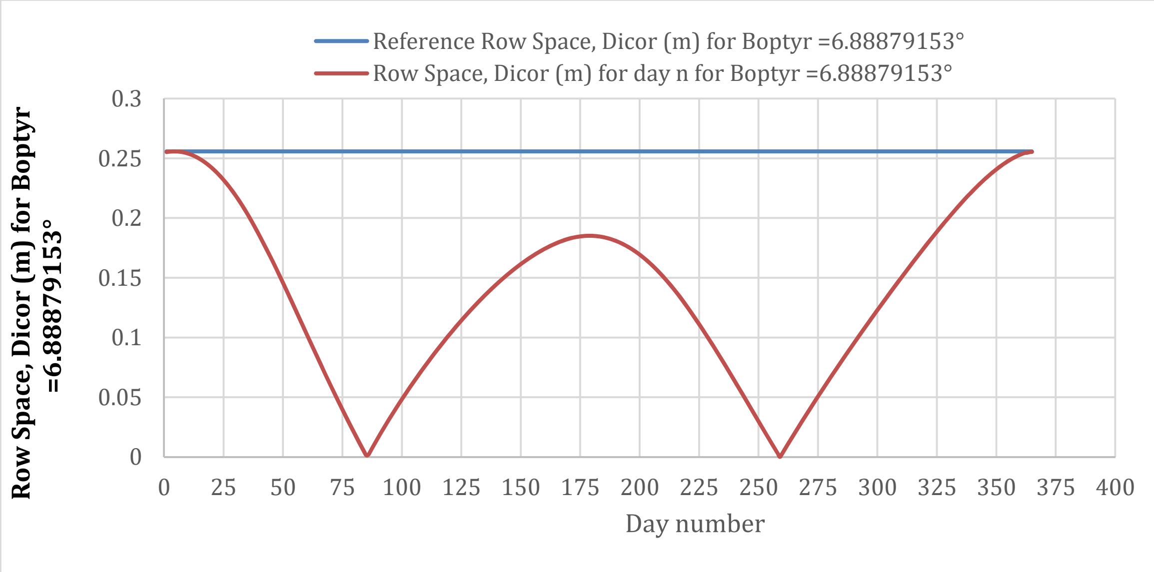

Figure 9 Evaluation of the effectiveness of the selected reference row spacing parameters in mitigating inter row shading at the optimal tilt angle of 6.88879153°

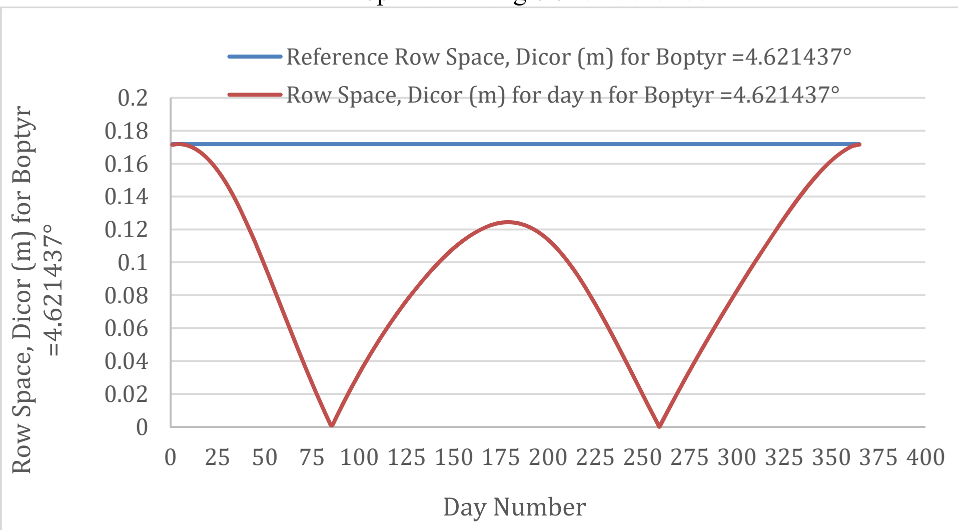

Figure 10 Evaluation of the effectiveness of the selected reference row spacing parameters in mitigating inter row shading at the optimal tilt angle of 4.621437°

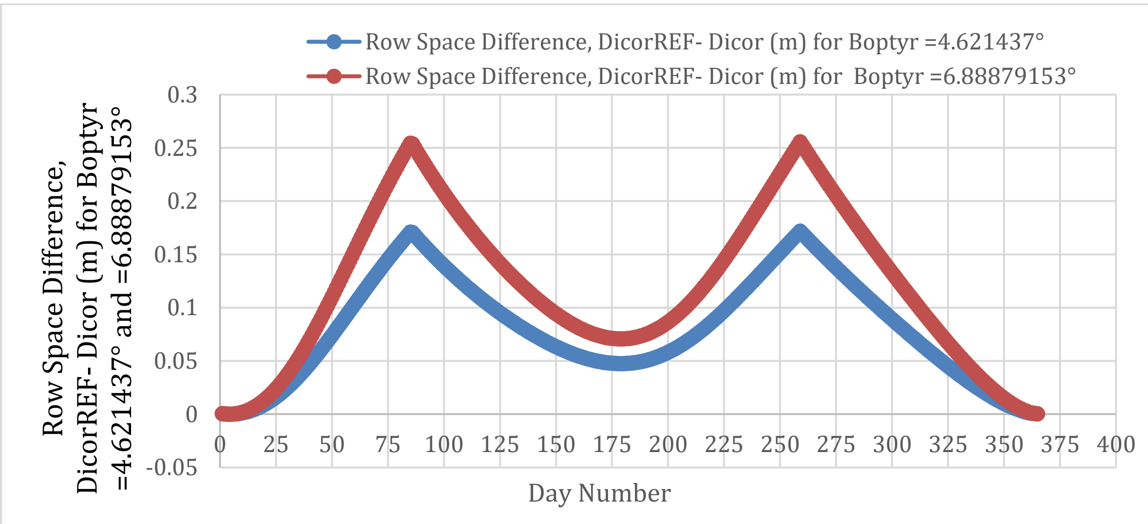

Figure 11 Row Space Difference

4. CONCLUSION

The analysis for proper row spacing determination in the layout design of a PV plant is presented. The analysis considered the tilt angle of the PV modules and the appropriate sun angles selection for effective row spacing that will mitigate inter row shading throughout the year. The choice of the parameters are based on the installation site geo-coordinates, the PV module dimensions and insight on the sun angle analytical models.

In all, the case study site and PV module parameters were used to establish the reference row spacing for the case study 400 KW PV power plant. The study considered two optimal tilt angle options and the results showed that the lower tilt angle has better land utilization factor and also better power density value.

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