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Sun Chart-Based Computation Of Photovoltaic Array Row Spacing For Internal Shading Mitigation At Optimal Fixed Tilt Angle

Silas Abraham Friday[1]
Department of Electrical/ Electronic Engineering
Adekeke University, Ede Osun State
silas.abraham@adelekeuniversity.edu.ng

Kingsley Bassey Clement[2]
Department of Electrical/ Electronic Engineering
University of Uyo, Akwa Ibom State

Anyanime Tim Umoette[3]
Department of Electrical and Electronic Engineering,
Akwa Ibom State University, Nigeria

***Abstract*— In this work, sun chart-based computation of photovoltaic (PV) array row spacing for internal shading mitigation at optimal fixed tilt angle is presented. Specifically, an online sun chart tool was used to determine th relevant sun position angles that are essential for determining the row spacing for internal shading mitigation based on shadow length analysis. Three different PV panels capacities (100 W, 150 W and 200 W) were considered. The study also conducted the analysis for six different locations across Nigeria, which includes locations in following States Akwa Ibom, Abuja, Lagos, Sokoto, Imo and Borno. The required number of PV modules, the row spacing, the row pitch, and the minimum PV array area determined for the 100 W, 150 W and 200 W modules in each of the six locations. In the three PV modules, Akwa Ibom State has the minimum row spacing distance while Sokoto State has the highest row spacing distance, Borno State has the minimum row pitch distance while Lagos State has the highest row pitch distance. Also, in all the three PV modules, Borno State has the lowest required land area while Lagos State has the highest required land area. In essence, for the same set of PV installation, Lagos State will require the highest lad space when compared with the land space required in the other five States considered in the study.**

Keywords*— Sun Chart Tool, Photovoltaic Array, Optimal Fixed Tilt Angle, Row Spacing, Internal Shading Mitigation

1. INTRODUCTION

In recent years, solar large-scale solar power plant are increasingly being adopted across the world. This in pursuant of the cleaner energy system and the need to diversify energy source [1,2,3,4]. Moreover, the depletion of the dominant fossil fuel and the rising cost fossil fuel are also driving the increasing adoption of large-scale solar power plants [5,6,7].

When large scale power plant is being designed, the issue of PV module row spacing is of great concerned [8,9,10,11,12]. One, there is need to avoid inter row shading within the sunshine hours, possibly from 8 am to 5 pm local time. Also, there is need to maximize the utilization of the available land or installation space [10,12,13]. Accordingly, in this work, the focus is to Sun chart-based computation of photovoltaic (PV) array row spacing for internal shading mitigation at optimal fixed tilt angle.

Notably, empirical formulae for yearly fixed optimal tilt angle is used to determine the optimal tilt angle [14,15,16] while the Sun chart tool is used to determine the requisite sun position angles, namely, the elevation angle and the azimuth angle. These parameters are used to determine the minimum row spacing for mitigating inter row shading within the chosen sunshine hours. Furthermore, the row pitch and required minimum area for the installation of the PV array are determined. With these parameters, it will be possible to determine the exact capacity of PV plant that can be installed in a given area having satisfied the inter row shading mitigation criteria.

2. METHODOLOGY

The study focus is to determine the row spacing in a PV power plant installation plant such that internal shading is avoided within the time that meaningful solar radiation is available to be captured. The methodology is broken down into the following;

i. Determination Of PV Module Spacing
ii. Computation Of PV Module Optimal Tilt Angle

iii. Computation Of PV Array Space Requirement
iv. The Case study data set
v. Application of the case study dataset, computation results and discussion

2.1 DETERMINATION OF PV MODULE SPACING

In a PV array with two or more rows, the inter row spacing should be such that the shadow from one row does not fall on the adjacent row, even in the worst case scenario. The worst case is when the shadow length is maximum in a year. In this work, row spacing computation is based on the sun position and shadow analysis.

Specifically, the study considers a PV module with length (Lpv) and width (Wpv) with tilt angle, β_{tilt}. The sun position is given in terms of the sun elevation angle, α and the azimuth angle, ψ. The maximum shadow length occur in June 22 for the Northern hemisphere while it occurs in December 21 for the Southern hemisphere.

The procedure for the determination of the minimum PV row spacing is based on the schematic diagram in Figure 1. The PV height difference, h of the tilted PV module is given as [10,11,12,13]

$$h = (L_{PV})Sin(\beta_{tilt}) \quad (1)$$

The apparent row spacing, d' is given as;

$$d' = \frac{h}{Tan(\alpha)} \quad (2)$$

The azimuth angle-corrected row spacing, d is given as;

$$d = (d')Tan \quad (\psi) \quad (3)$$

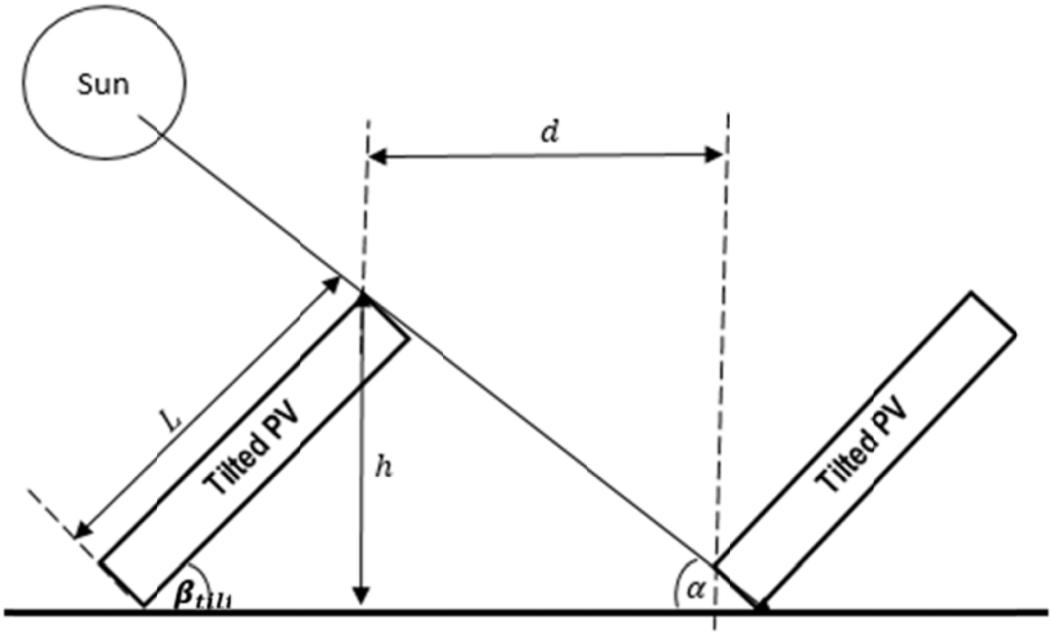

Figure 1 The diagram for row spacing determination using sun position and shadow analysis

2.2 COMPUTATION OF PV MODULE OPTIMAL TILT ANGLE

For a PV array with annual fixed tilt angle, in order to maximize the energy yield of the PV array, the fixed annual tilt angle, β_{tilt} must be optimal. In that case, the following analytical model is used to estimate the annual fixed optimal tilt angle, β_{opt} [16];

$$\beta_{OPT} = 3.7 + 0.69|\phi| \quad (4)$$

Where ϕ is used to indicate the latitude of the PV array installation site.

2.3 COMPUTATION OF PV ARRAY SPACE REQUIREMENT

The area, A_{PV} required for each of the PV module is determined from the knowledge of the row spacing as follows;

$$R_{Pitch} = (L_{PV})Cos(\beta_{tilt}) + d \quad (5)$$

$$R_{Pitch} = (L_{PV})Cos(\beta_{tilt}) + (d')Tan(\psi) \quad (6)$$

$$A_{PV} = (L_{PV})(R_{Pitch}) \quad (7)$$

If there are N_{PV} PV modules in the array, then the minimum area, A_{ARR} required for the entire PV array is given as;

$$A_{ARR} = (A_{PV})(N_{PV}) = (L_{PV})(R_{Pitch})(N_{PV}) \quad (8)$$

2.4 THE CASE STUDY DATA SET

In order to demonstrate the applicability of the analytical models presented in this work for the row spacing analysis, some case study installation sites are considered as shown in Table 1. Specifically, Table 1 shows the site longitude and latitude considered which consist of six different locations across Nigeria. The sun angles (declination angle, elevation angle and azimuth angle) for each of the case study sites are determined using a versatile online sun chart tool which can be accessed at: https://www.sunearthtools.com/dp/tools/. Since all the sites are in the Northern hemisphere, the longest shadow length is expected in the month of June, specifically, on June 22nd. The various parameters associated with the row spacing and required total area of the PV array are presented in the result section for teach of the case study site.

Apart from the case study sites, 100 W, 150 W and 200 W PV module are considered and the dimensions and efficiency are given in Table 2. Also, the technical details of the PV modules are presented in Table 3 while the diagrams specifying the dimensions of the first, second and third PV module are presented in Figure 2, Figure 3 and Figure 4 respectively.

Table 1 The relocation and other details of the case study sites

S/N	City	State in Nigeria	Latitude	longitude
1	Uyo	Akwa Ibom	5.065901	8.051236
2	Wuse	Abuja	9.071512	7.493711
3	Ebute Metta	Lagos	6.483066	3.374885
4	Tuntube-Tsefe	Sokoto	12.982937	5.244091
5	Mbatoli	Imo	5.630335	7.039271
6	Nganzai	Borno	12.218795	13.105213

Table 2 The dimensions and efficiency of the selected PV modules

S/N	PV module Power rating (watt)	PV module Length (mm)	PV module Width (mm)	PV module Area (mm^2)	PV module Efficiency (%)
1	100	1005	670	673,350	17.2
2	150	1480	670	991,600	17.1
3	200	1320	992	1,309,440	17.2

Table 3 The technical specifications of the three selected PV modules

Type Of Module	100W	150W	200W
Maximum Power	100W	150W	200W
Tolerance	± 3%	± 3%	± 3%
Open Circuit Voltage	22V	22,5V	30V
Short Circuit Current	6,06A	8,56A	8,56A
Maximum Power Voltage	18V	18,5V	24,6V
Maximum Power Current	5,56A	8,11A	8,13A
Module Efficiency	14,9%	15,2%	15,3%
Solar Cell Efficiency	17,2%	17,1%	17,2%
Series Fuse Rating	15A	15A	15A
Terminal Box	IP65	IP65	IP65
Maximum system voltage	1000V DC	1000V DC	1000V DC
Operating Temperature	-40°C - 85°C	-40°C - 85°C	-40°C - 85°C
Dimensions	1005mm x 670mm x 30mm	1480mm x 670mm x 35mm	1320mm x 992mm x 35mm
Weight	8kg	12kg	14,5kg

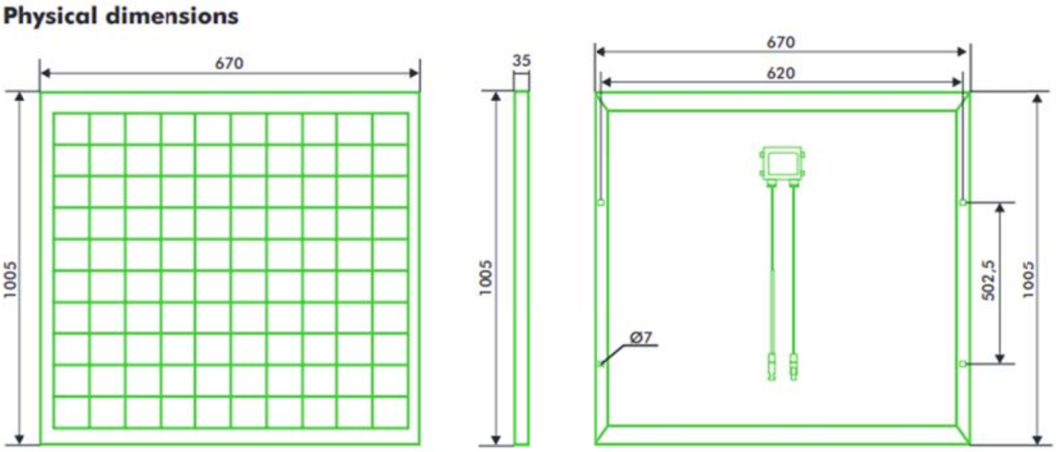

Figure 2 The physical dimensions of the CENTSYS 100W Solar panel

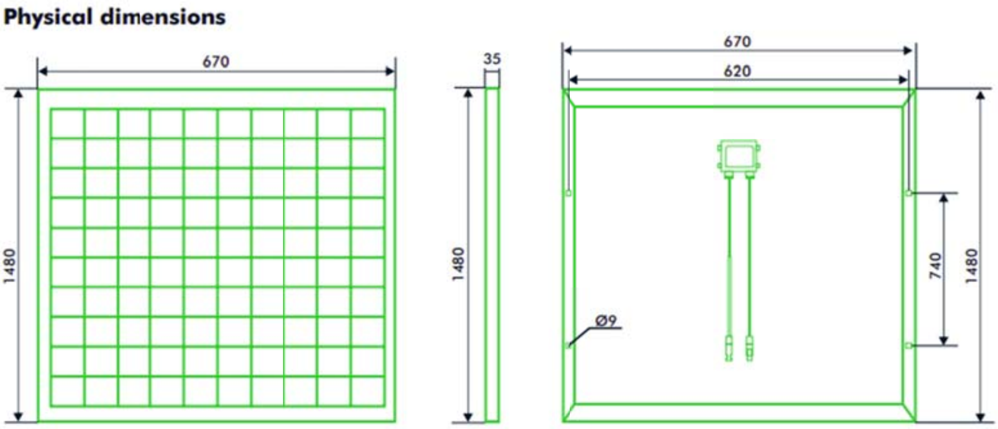

Figure 3 The physical dimensions of the CENTSYS 150W Solar panel

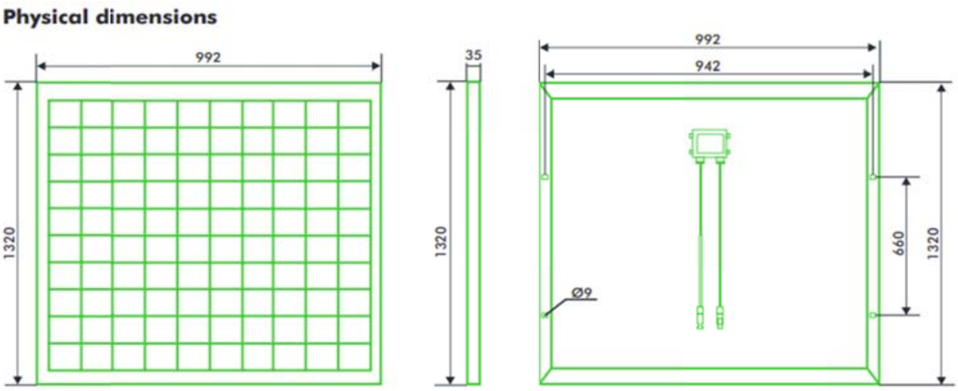

Figure 4 The physical dimensions of the CENTSYS 200W Solar panel

3. RESULTS AND DISCUSSION

The online sun path tool was used to determine the requisite sun angles for each of the case study locations. The results returned from the sun path tool for the location in Uyo at latitude of 5.065901 and longitude of 8.051236 are shown in Figure 5 and it is taken at 9: 00 Am on June 22nd 2024. The results in Figure 5 show elevation angle of 35.83 ° and azimuth angle of 64.3 ° for the location in Uyo.

Again, the results returned from the sun path tool for the location in Wuse at latitude of 9.071512 and longitude of 7.493711 are shown in Figure 6 and it is taken at 9: 00 Am on June 22nd 2024. The results in Figure 6 show elevation angle of **37.50** ° and azimuth angle of **67.33**° for the location in Wuse. The rest of the results of the sun angles and row spacing for all the locations obtained using the sun path online tool and 100 W PV module are shown in Table 4.

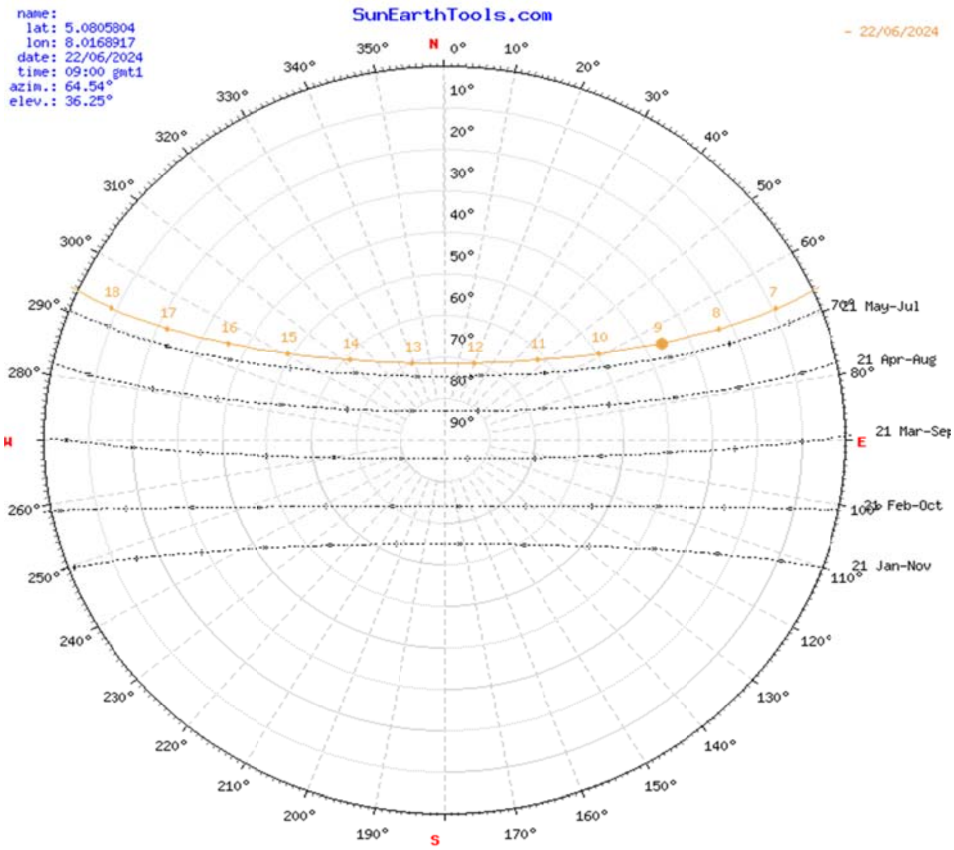

Figure 5 The results returned from the sun path tool for the location in Uyo at latitude of 5.065901 and longitude of 8.051236

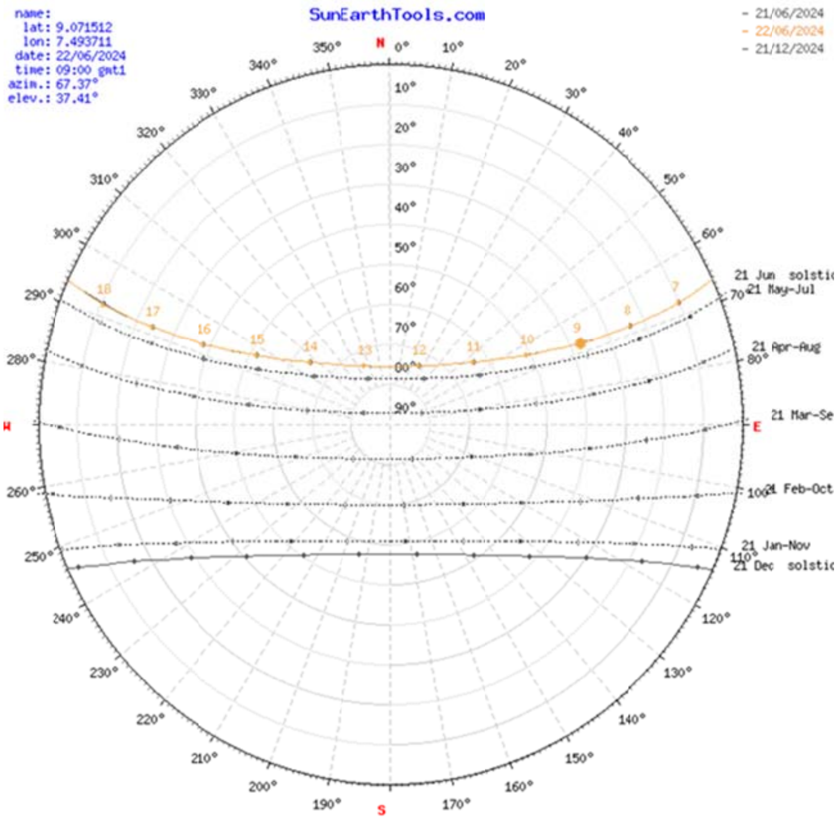

Figure 6 The results returned from the sun path tool for the location in Wuse at latitude of 9.071512 and longitude of 7.493711

Table 4 The results of the sun angles and row spacing for all the locations obtained using the sun path online tool and 100 W PV module

	1	2	3	4	5	6
City	Uyo	Wuse	Ebute Metta	Tuntube-Tsefe	Mbatoli	Nganzai
State in Nigeria	**Akwa Ibom**	**Abuja**	**Lagos**	**Sokoto**	**Imo**	**Borno**
Latitude	**5.065901**	**9.071512**	**6.483066**	**12.98294**	**5.630335**	**12.2188**
Time on June 22nd	**9:00 AM**	**9:00 AM**	**9:00 AM**	**9:00 AM**	**9:00 AM**	**9:00 AM**
Sun Elevation Angle (°)	**36.37**	**37.50**	**32.73**	**36.86**	**35.70**	**43.79**
Sun Azimuth Angle (°)	**64.48**	**67.33**	**66.23**	**70.27**	**65.07**	**69.12**
Fixed optimal tilt angle, β_{opt} (°)	**7.2**	**9.96**	**8.17**	**12.66**	**7.58**	**12.13**
PV module length, Lpv („)	**1005**	**1005**	**1005**	**1005**	**1005**	**1005**
PV module Width, Wpv (mm)	**670**	**670**	**670**	**670**	**670**	**670**
Corrected row spacing, d (mm)	**73.64**	**87.30**	**89.60**	**99.17**	**77.82**	**78.53**

The computed number of PV modules, the corrected row spacing, the row pitch, and the minimum PV array area are shown in Table 7 for the 100 W PV module, in Table 8 for the 150 W PV module and in Table 9 for the 200 W PV module. In the three PV modules, Akwa Ibom State has the minimum row spacing distance while Sokoto State has the highest row spacing distance, Borno State has the minimum row pitch distance while Lagos State has the highest row pitch distance. Also, in all the three PV modules, Borno State has the lowest required land area while Lagos State has the highest required land area. In essence, for the same set of PV installation, Lagos State will require the highest lad space when compared with the land space required in the other five States considered in the study.

Table 7 The computed number of PV modules, the corrected row spacing, the row pitch, and the minimum PV array area for the 100 W PV module with length, Lpv (1005 mm) and width, Wpv 670(mm)

State	**Number of PV modules, N_{PV}**	**Corrected row spacing, d (mm)**	**Row pitch, R_{Pitch} (mm)**	**Minimum PV array area, A_{ARR} (mm^2)**
Akwa Ibom	30	73.64433	1070.73	21,521,664.0
Abuja	30	87.30178	1077.157	21,650,858.9
Lagos	30	89.5957	1084.387	21,796,188.0
Sokoto	30	99.167	1079.74	21,702,774.8
Imo	30	77.82337	1074.03	21,588,001.2
Borno	30	78.52521	1061.083	21,327,775.5
	Minimum	73.64433 (Akwa Ibom)	1061.083 (Borno)	21327775.5 (Borno)
	Maximum	99.167 (Sokoto)	1084.387 (Lagos)	21796188 (Lagos)

Table 8 The computed number of PV modules, the corrected row spacing, the row pitch, and the minimum PV array area for the 150 W PV module with length, Lpv (1480 mm) and width, Wpv 670(mm)

State	Number of PV modules, N_{PV}	Corrected row spacing, d (mm)	Row pitch, R_{Pitch} (mm)	Minimum PV array area, A_{ARR} (mm^2)
Akwa Ibom	20	108.4513	1576.79576	21,129,063.2
Abuja	20	128.5638	1586.261291	21,255,901.3
Lagos	20	131.9419	1596.9089	21,398,579.3
Sokoto	20	146.037	1590.064933	21,306,870.1
Imo	20	114.6056	1581.655991	21,194,190.3
Borno	20	115.6391	1562.590418	20,938,711.6
	Minimum	108.4513 (Akwa Ibom)	1562.59 (Borno)	20938711.6 (Borno)
	Maximum	146.037 (Sokoto)	1596.909 (Lagos)	21398579.3 (Lagos)

Table 9 The computed number of PV modules, the corrected row spacing, the row pitch, and the minimum PV array area for the 200 W PV module with length, Lpv (1480 mm) and width, Wpv 670(mm)

State	Number of PV modules, N_{PV}	Corrected row spacing, d (mm)	Row pitch, R_{Pitch} (mm)	Minimum PV array area, A_{ARR} (mm^2)
Akwa Ibom	15	96.72688	1406.331354	20,926,210.5
Abuja	15	114.665	1414.773584	21,051,830.9
Lagos	15	117.6779	1424.2701	21,193,139.1
Sokoto	15	130.2492	1418.166022	21,102,310.4
Imo	15	102.2158	1410.666154	20,990,712.4
Borno	15	103.1376	1393.661724	20,737,686.5
	Minimum	96.72688 (Akwa Ibom)	1393.661724 (Borno)	20,737,686.5 (Borno)
	Maximum	130.2492 (Sokoto)	1424.27 (Lagos)	21193139.1 (Lagos)

Comparison of the length of the three PV modules (100 W, 150 W and 200 W) used in the study is presented in Figure 7. The 150 W PV module has the highest PV length of 1480 mm while the 100 W PV module has the lowest length of 1005 mm.

Comparison of the row spacing distance for the three PV modules (100 W, 150 W and 200 W) for six case study sites is presented in Figure 8. The results show that in all the sites, the 150 W PV module has the highest row spacing distance while the 100 W PV module has the lowest row spacing distance. Also, among the six States considered in the study, Sokoto State has the highest row spacing distance with the 150 W PV module while Akwa Ibom State has the lowest row spacing distance with the 100 W PV module.

Comparison of the row pitch distance for the three PV modules (100 W, 150 W and 200 W) for six case study sites is presented in Figure 9. The results show that in all the sites, the 150 W PV module has the highest row pitch distance while the 100 W PV module has the lowest row pitch distance. Also, among the six States considered in the study, Lagos State has the highest row pitch distance with the 150 W PV module while Borno State has the lowest row pitch distance with the 100 W PV module.

Also, comparison of the minimum land area requirement for the three PV modules (100 W, 150 W and 200 W) for six case study sites is presented in Figure 10. The results show that in all the sites, the 100 W PV module has the highest required land space while the 200 W PV module has the lowest required land space. Also, among the six States considered in the study, Lagos State has the highest required land space with the 100 W PV module while Borno State has the lowest required land space with the 200 W PV module.

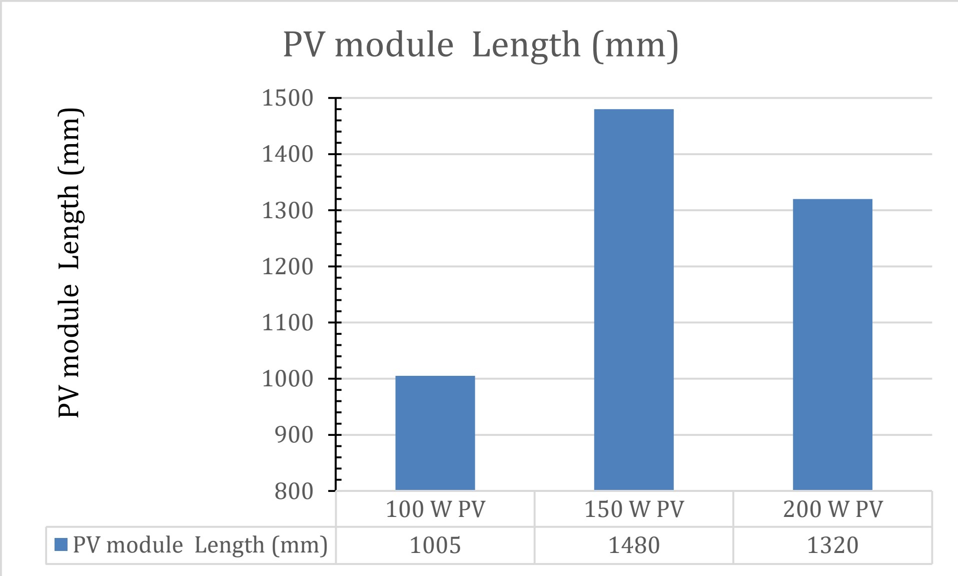

Figure 7 Comparison of the length of the three PV modules (100 W, 150 W and 200 W) used in the study

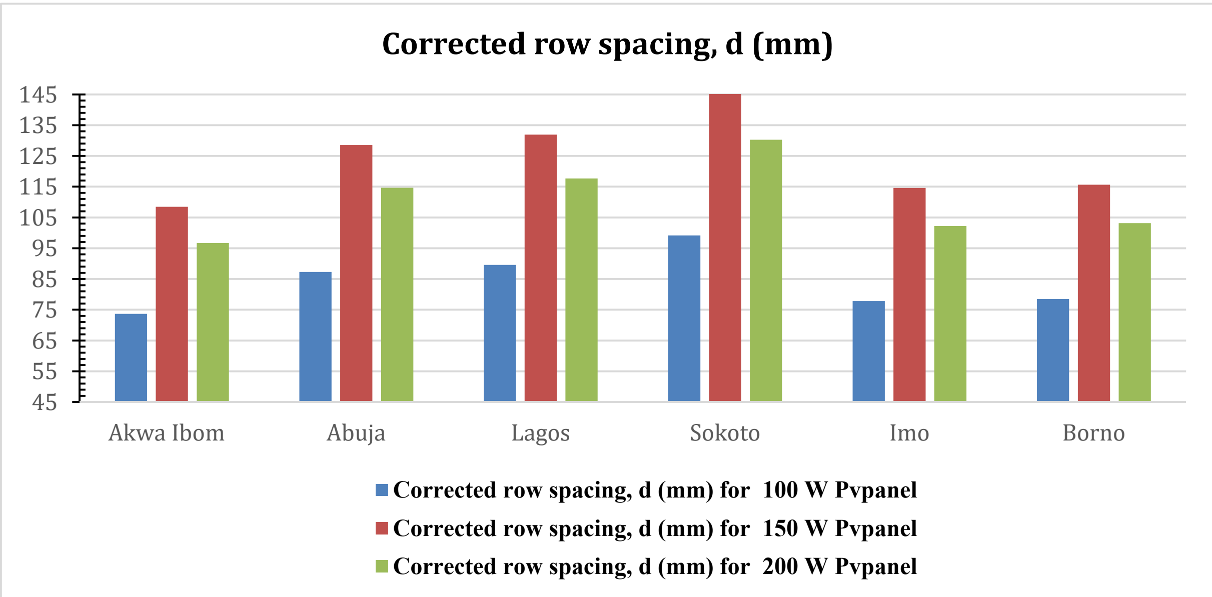

Figure 8 Comparison of the row spacing distance for the three PV modules (100 W, 150 W and 200 W) for six case study sites

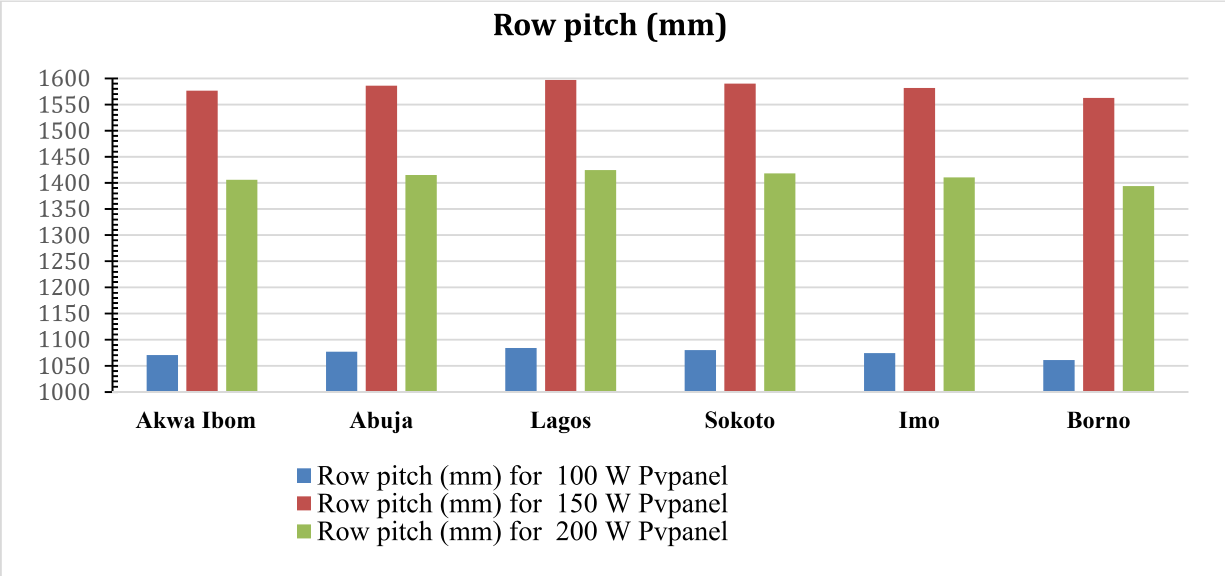

Figure 9 Comparison of the row pitch distance for the three PV modules (100 W, 150 W and 200 W) for six case study sites

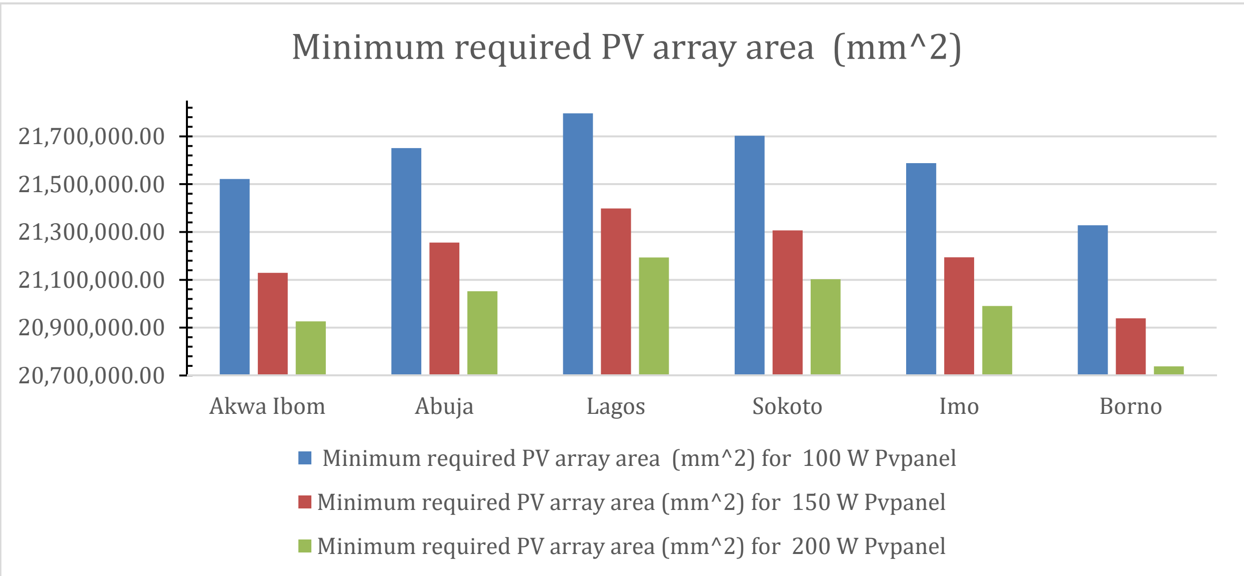

Figure 10 Comparison of the minimum land area requirement for the three PV modules (100 W, 150 W and 200 W) for six case study sites

4 CONCLUSION

The analysis of row spacing for the installation of PV plant in six different locations across Nigeria is presented. The study examined the issue of row spacing that will ensure that there is no internal shading among the PV rows for a given time period, which in this study is between 8 am and 5 pm. The study considered three different PV panel sizes and the land space requirement for the three different PV panels and six different locations were determined and compared.

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