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Modelling And Comparative Evaluation Of Geospatial Location Impact On Land Utilization Factor Of PV Power Plant In Selected States In Nigeria

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Abstract*— In this paper, modelling and comparative evaluation of geospatial location impact on land utilization factor of photovoltaic (PV) power plant in selected States in Nigeria is presented. The PV row spacing determination is based on the principle that the shadow length of the tilted PV module will not cause shading of adjacent PV row with the time frame of 7 am to 5 pm (local time). Within this time frame, the solar radiation on the PV module is to be captured without inter-row shading. The case study PV panel dimensions are 1.65 m (length) by 0.992 m (width). The case study sites are located in Rivers State, Abuja (Federal Capital Territory) and Sokoto State. The row spacing distance and land utilization factor are computed for the three selected locations across Nigeria for different PV tilt angles.In the case where latitude is the optimal tilt angle, Rivers State had the lowest latitude of 4.680392 and a the resultant highest land utilization factor of 81.3635% whereas Sokoto State had the highest latitude of 13.05499 and a the resultant lowest land utilization factor of 65.173%. On the other hand, the results of the PV array land utilization factor computed using the same tilt angle for the three locations show that River State consistently has the lowest land utilization factor while Abuja consistently has the highest land utilization factor. In all, the results show that the PV tilt angle and sun elevation angle are the two key parameters that influence the row spacing and land utilization factor. Again, the elevation angle and tilt angle are both dependent on the location latitude. As such, the latitude of the PV installation site do affect significantly the key parameters that influence the value of the land utilization factor.

***Keywords*— PV Power Plant, Geospatial, Optimal Tilt Angle, Land Utilization Factor, Sun Elevation Angle, PV Tilt Angle**

1. INTRODUCTION

Across the globe, adoption of solar power system has been on the increase [1,2,3]. In addition, there is growing deployment of large-scale Photovoltaic (PV) power plants across the globe [4,5,6,7]. One key factor in large-scale PV plant installation is the required space for the PV array [8,9,10]. Most often, the PV modules are tilted to optimize energy harvest by the PV array [11,12,13]. In that case, the effective area required for a PV module maybe smaller than the actual area of the PV module.

However, in practice, minimum inter row spacing is required to avoid internal shading among the PV rows [14,15]. The conventional approach for determining the inter row spacing is the use of shadow analysis [14,15]. This requires the use of PV tilt angle, the sun altitude angle and the sun azimuth angle to determine the effective row spacing. Furthermore, the row pith and the effective total area required for both the PV modules and the required row spacing are determined. Consequently, the actual area occupied by the PV array is inevitably smaller than the total area required for the PV array installation. This gives rise to land utilization factor which is a measure of the actual area occupied by the PV array when compared to the total area required for the PV array plus the mandatory row spacing requirement. Accordingly, this work is focused on determining the land utilization factor for PV array installation and also to evaluate the impact opf certain parameters on the row spacing and land utilization factor.

2. METHODOLOGY

2.1 THE ANALYTICAL MODELS FOR THE PV ROW SPACING

Let LT denote the local time, LST denote the local solar time, LSTM denote local standard time meridian, $\boldsymbol{\Delta_{UTC}}$ denote the difference between the local time and the universal coordinated time, EoT denote equation of time, TC denote time correction factor and Long denote the longitude of the location, then LST is determined using the following set of equations. In practice, $\boldsymbol{\Delta_{UTC}}$ is given as $\pm \boldsymbol{X}$ where x is an integer value which can be read for each location base on their longitude or specified time zone. In this work, $\boldsymbol{\Delta_{UTC}}$ is approximated using the expression [18];

$$1)\ \boldsymbol{\Delta_{UTC}} \approx \left\lceil \frac{\boldsymbol{Long}}{\boldsymbol{15}} \right\rceil \quad (1)$$

Where $\lceil . \rceil$ *means round up to the nearest upper integer.*

$$2)\ \boldsymbol{LSTM} = (\boldsymbol{15°})(\boldsymbol{\Delta_{UTC}}) \quad (2)$$

If n denote the day number, then a day number factor denoted as $\boldsymbol{B}$ *can be defined as;*

$$3)\ \boldsymbol{B} = \left(\frac{\boldsymbol{360}}{\boldsymbol{365}}\right)(\boldsymbol{n} - \boldsymbol{81}) \quad (3)$$

$$\boldsymbol{EoT} = \boldsymbol{9.87}\left(\boldsymbol{Sin}(\boldsymbol{2B})\right) - \boldsymbol{7.53}\ \left(\boldsymbol{Cos}(\boldsymbol{B})\right) - \boldsymbol{1.5}\left(\boldsymbol{Sin}(\boldsymbol{B})\right) \quad (4)$$

$$\boldsymbol{TC} = \boldsymbol{4}\,(\boldsymbol{Long} - \boldsymbol{LSTM}) + \boldsymbol{EoT} \quad (5)$$

$$4)\ \boldsymbol{LST} = \boldsymbol{LT} + \frac{\boldsymbol{TC}}{\boldsymbol{60}} \quad (6)$$

The hour angle, ω in degree is given as;

$$\omega = 15\,(LST - 12) \quad (7)$$

The declination angle, δ for day n is given as;

$$\delta = 23.45 \text{ Sin } \left(\frac{360 \text{ x } (284 + \text{n})}{365}\right) \quad (8)$$

The sun elevation angel, θ_{El} and azimuth angle, θ_{Az} for the location with latitude denoted as Lat are given as;

$$\theta_{El} = \sin^{-1}[\text{Sin}\,(\delta)\text{Sin}\,(Lat) + \text{Cos}\,(\delta)\text{Cos}\,(Lat)\text{Cos}\,(\omega)] \quad (9)$$

$$\theta_{Az} = \cos^{-1}\left[\frac{\text{Sin}\,(\delta)\text{Cos}(Lat) - \text{Cos}\,(\delta)\text{Sin}(Lat)\text{Cos}\,(\omega)}{\text{Sin}\,(\theta_{El})}\right] \quad (10)$$

The row spacing (d), for a PV with tilt angle (θ_{tilt}) and length L is given based on the diagram in Figure 1 as;

$$d = \frac{(L)\left(Sin(\theta_{tilt})\right)}{Tan(\theta_{El})} \quad (11)$$

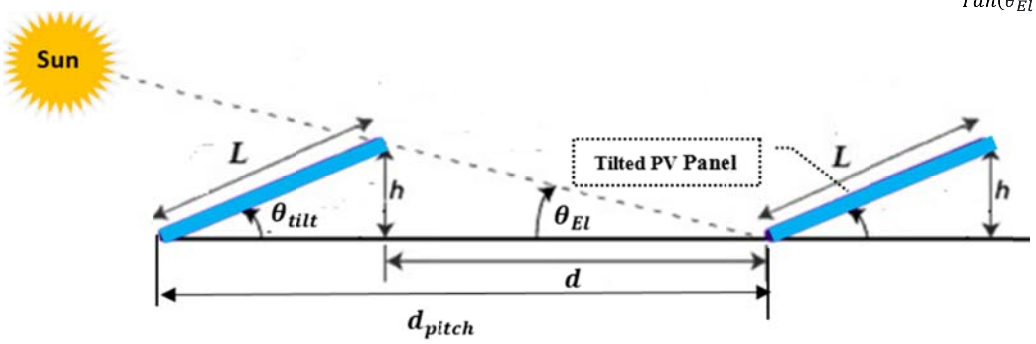


Figure 1 The diagram for computing the PV row spacing

When the azimuth angle correction factor is included, the azimuth angle updated row spacing, daz is given as;

$$daz = d\left(Cos(\theta_{Az})\right) = \left(\frac{(L)\left(Sin(\theta_{tilt})\right)}{Tan(\theta_{El})}\right)\left(Cos(\theta_{Az})\right) \quad (12)$$

The row pitch, d_{pitch} in Figure 1 is given in terms of daz as;

$$d_{pitch} = (L)Cos(\theta_{tilt}) + daz = (L)Cos(\theta_{tilt}) + \left(\frac{(L)\left(Sin(\theta_{tilt})\right)}{Tan(\theta_{El})}\right)\left(Cos(\theta_{Az})\right) \quad (13)$$

$$d_{pitch} = (L)\left[Cos(\theta_{tilt}) + \left(\left(\frac{Sin(\theta_{tilt})}{Tan(\theta_{El})}\right)Cos(\theta_{Az})\right)\right] \quad (14)$$

For each of the locations with attitude, Lat, the optimal tilt angle, $\theta_{tiltOpt}$ is given as;

$$\theta_{tiltOpt} = 3.7 + 0.69|\text{Lat}| \quad (15)$$

Another empirical optimal tilt angle option is to use the latitude of the site while yet another option is to add 15 ° to the latitude of the site. Based on the PV tilt angle the row spacing is determined along with the PV array land requirement and hence, the land utilization factor.

The land utilization factor, U_{lf} is given as the area of space occupied by the tilted PV panel (A_{PVilt}) divided by the total area used for both the PV panel and row spacing ($A_{PViltRwSp}$). Hence, if W is the width of PV panel, then;

$$U_{lf} = \frac{A_{PVilt}}{A_{PViltRwSp}} \quad (16)$$

where;

$$A_{PVilt} = (W)(L)Cos(\theta_{tilt}) \quad (17)$$

$$A_{PViltRwSp} = (W)\left(d_{pitch}\right) \quad (18)$$

$$A_{PViltRwSp} = (W)(L)\left[Cos(\theta_{tilt}) + \left(\left(\frac{Sin(\theta_{tilt})}{Tan(\theta_{El})}\right)Cos(\theta_{Az})\right)\right] \quad (19)$$

Hence,

$$U_{lf} = \frac{Cos(\theta_{tilt})}{\left[Cos(\theta_{tilt}) + \left(\left(\frac{Sin(\theta_{tilt})}{Tan(\theta_{El})}\right)Cos(\theta_{Az})\right)\right]} \quad (20)$$

2.2 THE CASE STUDY DATASET

The names and coordinates of the three locations in Nigeria considered in the study are presented in Table 2. Also, the case study solar panel is a 250W solar panel manufactured by Centurion Systems. The PV panel dimensions are 1.65 m (length) by 0.992 m (width).The row spacing distance and land utilization factor are computed for the three selected locations across Nigeria and their values are compared for a common tilt angle and also for their individual optimal tilt angles. Specifically, the study was conducted at 8 AM local time on 21st of June 2023 and 22nd of December 2023. The day number for 21st of June 2023 is 172 (for Summer solstice) while the day number for 22nd of December 2023 ((for Winter solstice) is 356.

Table 1 The technical specifications for the case study 250W CENTSYS Solar panel [19]

Type Of Module	250W
Maximum Power	250W
Tolerance	± 3%
Open Circuit Voltage	37.8V
Short Circuit Current	8.7A
Maximum Power Voltage	31.5V
Maximum Power Current	7.94A
Module Efficiency	15.3%
Solar Cell Efficiency	17.2%
Series Fuse Rating	15A
Terminal Box	IP65
Maximum system voltage	1000V DC
Operating Temperature	-40°C - 85°C
Dimensions	1650mm x 992mm x 40mm
Weight	17kg

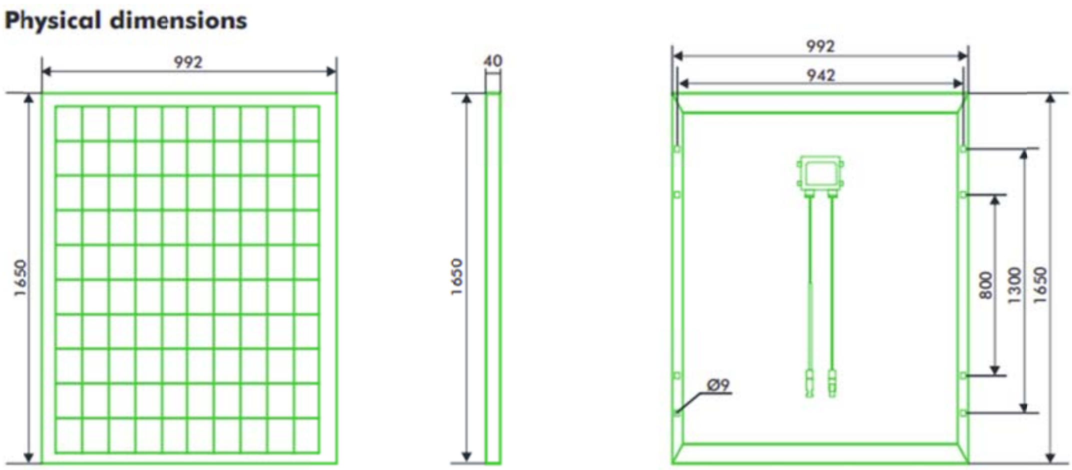


Figure 2 The physical dimensions for the case study 250W CENTSYS Solar panel **[19]**

Table 2 The name and coordinates of the three locations in Nigeria considered in the study

S/N	State in Nigeria	Latitude	Longitude
1	Rivers	4.680392	7.043707
2	Abuja	8.521264	7.331138
3	Sokoto	13.054987	4.942105

3. RESULTS AND DISCUSSION

The results of the optimal tilt angles calculated based on Equation 15 are given in row number 10 of Table 3 for the three locations and they are 6.92947° for Rivers State, 9.579672° for Abuja and 12.70794° for Sokoto State. In this case, the land utilization factors obtained are 0.746255 for Rivers State, 0.726261 for Abuja and 0.65803 for Sokoto State. In essence, with the optimal tilt angle based on Equation 15, River State has the highest land utilization factor of 74.6255% followed by Abuja with value of 72. 6261% while Sokoto has the lowest land utilization factor of 65.803 %.

On the other hand, the results of the PV array land utilization factor, Ulf computed using the same tilt angle for the three locations show that River State consistently has the lowest land utilization factor while Abuja consistently has the highest land utilization factor, as shown in Table 4 and Figure 3.

Again, the results of the PV array land utilization factor, Ulf computed using three different optimal tilt angle options associated with the location latitude are shown in Table 5, Figure 4, Figure 5 and Figure 6. In the case where latitude is the optimal tilt angle (as shown in table 5 and Figure 4), Rivers State had the lowest latitude of 4.680392 and a resultant highest land utilization factor of 81.3635% whereas Sokoto State had the highest latitude of 13.05499 and a the resultant lowest land utilization factor of 65.173%. It is noted from the results that lower tilt angles results in higher land utilization factor.

Similarly, the case where Equation 15, that is, 3.7 + 0.69(Latitude) is the optimal tilt angle (as shown in table 5 and Figure 6), Rivers State had the lowest tilt angle of 6.92947 and a the resultant highest land utilization factor of 74.6255% whereas Sokoto State had the highest latitude of 12.70794 and a the resultant lowest land utilization factor of 65.803 %. Again, it is noted from the results that lower tilt angles results in higher land utilization factor. Even for Sokoto State, the land utilization factor obtained with tilt angle of 12.70794 is higher than the one obtained with tilt angle of 13.05499 .

Table 3 The results for June 21st 2023 based on optimal tilt angle of Equation 15

S/N	The Parameters	Rivers State	Abuja (Federal Capital Territory)	Sokoto State
1	Latitude	4.680392	8.521264	13.05499
2	Longitude	7.043707	7.331138	4.942105
3	Day Number	172	172	172
4	Declination angle Angle	23.44913	23.44913	23.44913
5	Local Time (AM)	7	7	7
6	Solar Time	6.44458	6.463743	6.304474
7	Hour Angle (°)	-83.3313	-83.0439	-85.4329
8	Elevation Angle (°)	7.969901	9.720703	9.26787
9	Azimuth Angle (°)	66.93981	67.50696	67.91031
10	PV Tilt Angle (°)	6.92947	9.579672	12.70794
11	Azimuth corrected row space, daz (m)	0.556941	0.613237	0.836481
12	Row pitch, dpitch (m)	2.194889	2.240228	2.446062
13	Actual area of the PV module based on it dimensions, APVAct (m^2)	1.6368	1.6368	1.6368
14	Actual land area occupied by titled PV, Apvtilt (m^2)	1.624844	1.613975	1.596705
15	Titled PV area on land with row pitch, ApviltRwSp (m^2)	2.17733	2.222307	2.426494
16	Land utilization factor, U_{lf}	0.746255	0.726261	0.65803

Table 4 The results for June 21st 2023 based on same tilt angle for all the locations

Same PV Tilt Angle (°)	Land utilization factor, U*lf* for River State	Land utilization factor, Ulf for Abuja (FCT)	Land utilization factor, Ulf for Sokoto State
4	0.836374	0.864928	0.861215
8	0.717774	0.761112	0.755354
12	0.627086	0.678105	0.67121
16	0.554865	0.609614	0.602113

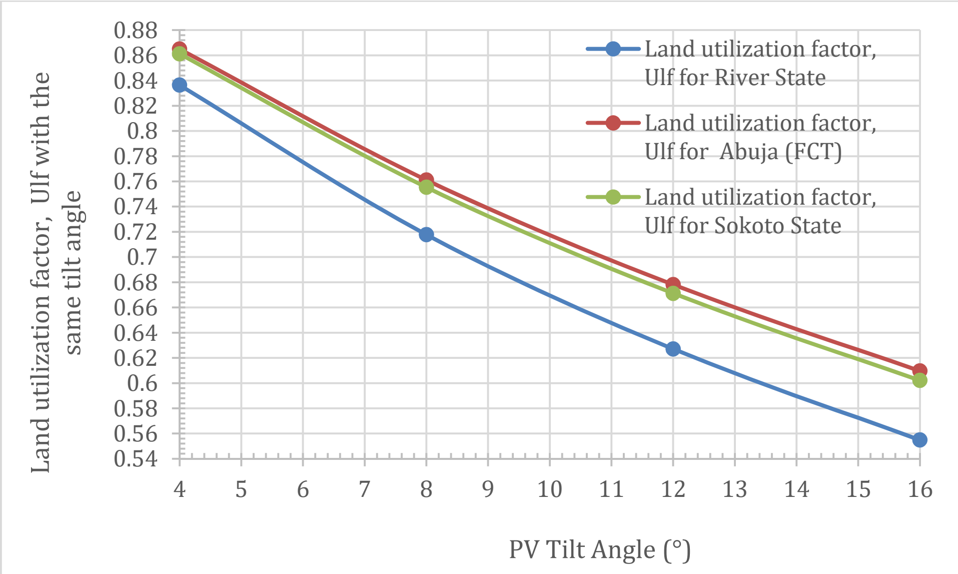


Figure 3 The PV array land utilization factor, Ulf computed using the same tilt angle for the three locations

Table 5 The results for June 21st 2023 based on three different optimal tilt angle options associated with the location latitude

State	Latitude as the Optimal Tilt Angle (°)	Land utilization factor, Ulf with Latitude as the PV Optimal Tilt Angle	PV Optimal Tilt Angle (°)	Land utilization factor, Ulf with Latitude + 15 as the PV Optimal Tilt Angle	PV Optimal Tilt Angle (°)	Land utilization factor, Ulf with 3.7 + 0.69(Latitude) as the PV Optimal Tilt Angle
Rivers	4.680392	0.813635	19.68039	0.499836	6.92947	0.746255
Abuja	8.521264	0.749281	23.52126	0.507089	9.579672	0.726261
Sokoto	13.05499	0.65173	28.05499	0.448795	12.70794	0.65803

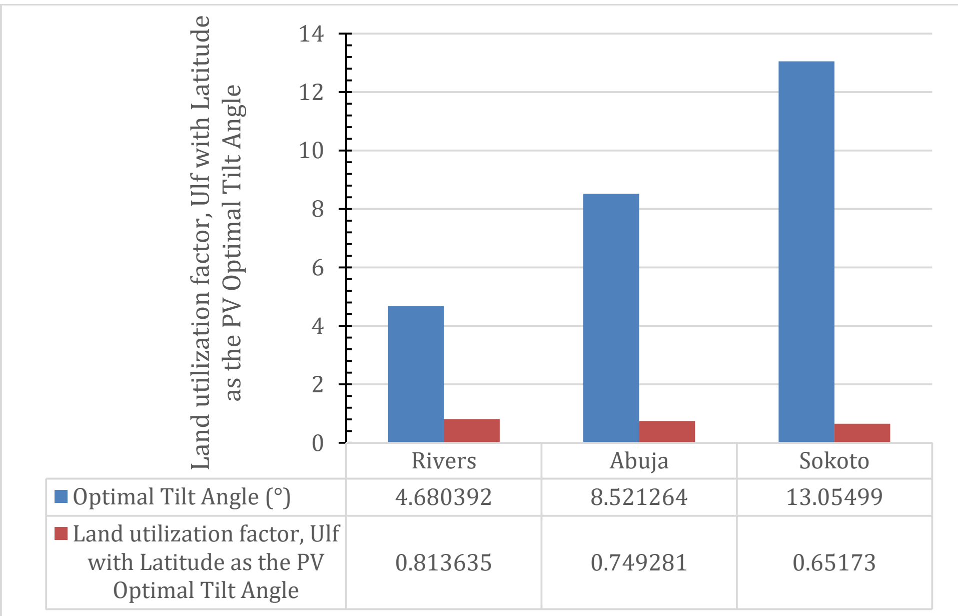
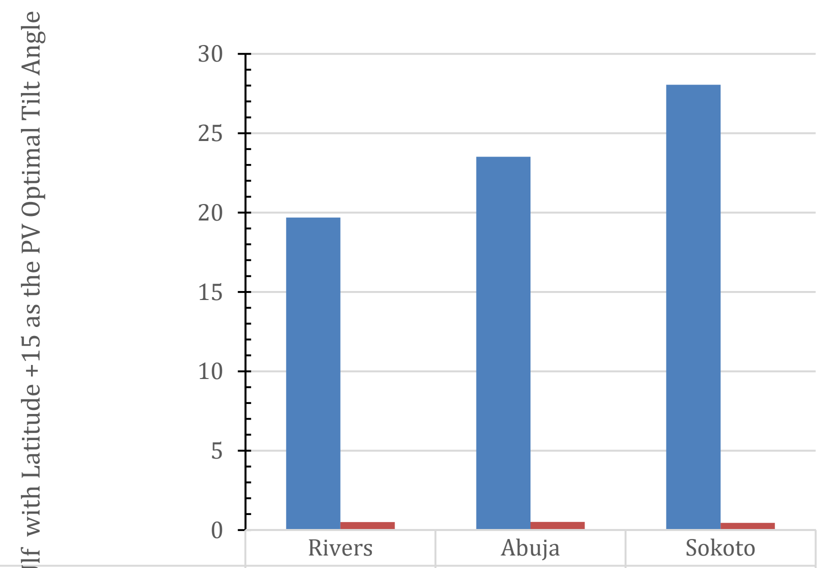
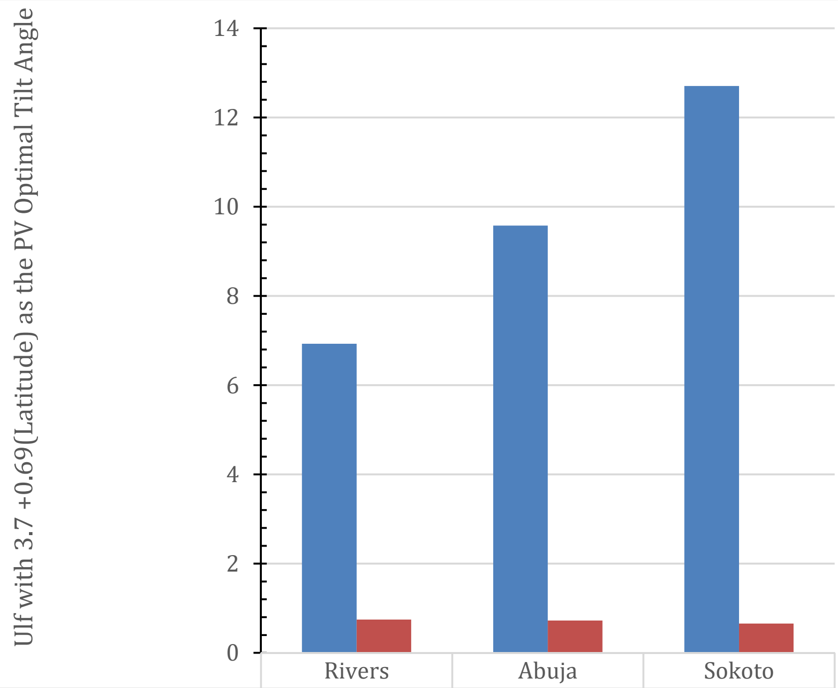


Figure 4 The PV array land utilization factor, Ulf computed using the location latitude as the PV optimal tilt angle



	Rivers	Abuja	Sokoto
PV Optimal Tilt Angle (°)	19.68039	23.52126	28.05499
Land utilization factor, Ulf with Latitude +15 as the PV Optimal Tilt Angle	0.499836	0.507089	0.448795

Figure 5 The PV array land utilization factor, Ulf computed using the location latitude + 15 ° as the PV optimal tilt angle



	Rivers	Abuja	Sokoto
PV Optimal Tilt Angle (°)	6.92947	9.579672	12.70794
Land utilization factor, Ulf with 3.7 +0.69(Latitude) as the PV Optimal Tilt Angle	0.746255	0.726261	0.65803

Figure 6 The PV array land utilization factor, Ulf computed using Equation 15, that is 3.7 + 0.69 (location latitude) as the PV optimal tilt angle

To further examine the factors that affect the land utilization factor, the computation for land utilization factor based on same tilt angle of 4° for all the locations is performed and the results are shown in Table 6. The results show that with the same PV dimensions and same tilt angle, the same PV row height of 0.115098 m is obtained for all the three locations. However, the row space results in table 6 show that the smaller elevation angle has higher row space. Notably, Rivers State with the smallest elevation angle of 7.969901 has highest row space distance of 0.822099 m whereas Abuja with the highest elevation angle of of 9.720703 has lowest row space distance of 0.67189 m. As such, apart from tilt angle, the elevation angle plays significant role in the determination of the row spacing and the land utilization factor.

Table 6 The results for June 21st 2023 based on same tilt angle of 4° for all the locations

State	Elevation Angle	PV Row Height (m)	PV Row Space (m)	Azimuth Angle	Azimuth Angle corrected PV Row Space (m)	Land utilization factor
Rivers State	7.969901	0.115098	0.822099	66.939801	0.322015	0.836374
Abuja (Federal Capital Territory)	9.720703	0.115098	0.67189	67.506964	0.257046	0.864928
Sokoto State	9.26787	0.115098	0.705343	67.910314	0.265249	0.861215

4. CONCLUSION

The PV row spacing and land utilization factor are considered in this work. The analytical approach for computing the row spacing and the land utilization for PV power installation in three locations in Nigeria is presented along with sample case study computations. The study focused on determining the key parameters that effect the row spacing ad the land utilization factor.

In all, the PV tilt angle and sun elevation angle are the two key parameters that influence the row spacing and land utilization factor. Again, the elevation angle and tilt angle are both dependent on the location latitude. As such, the latitude of the PV installation site do affect significantly the key parameters that influence the value of the land utilization factor.

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