Analytical Model For The Selection Of Peak Sun Hour And Days Of Power Autonomy For Pv Solar Power System Components Sizing

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Abstract— **In this paper, an analytical model for the selection of peak sun hour and days of power autonomy for PV solar power system components sizing is presented. The model utilized the mean peak sun hour (PSH) for different days of consecutive low solar radiation to determine the appropriate value to be used in the determination of the required photovoltaic, PV array capacity and the storage bank capacity for different days of power autonomy. The analytical expressions for determination of the requisite parameters are presented. Simulation was done using the solar radiation data of Akwa Ibom State with annual mean of the daily peak sun hour of 6.2933 kWh/m².day . The daily load demand of 480 kWh per day was also used. The results show that the consecutive days of low solar radiation, W, the higher the value of the minimum mean PSH with a value of 4.3500 kWh/m².day at W =1 day to 5.4760 kWh/m².day at W =15 days. Specifically, at PSH of 4.35kWh/m².day, the PV of 138.56 KWp is required and it gives 0 % LoLD and 26.64 % unused energy per year whereas 6.29 kWh/m².day, the PV of 95.97 KWp is required and it gives 5.0 % Loss of Load (LoLD) and 0 % unused energy per year. As such, applications with stringent energy demand will be designed with lower value of PSH which results in negligible LOLD. In addition, with W = 11 and PSH of 5.34kWh/m².day / LOLD of 0 % was achieved for days of power autonomy of 1, 2 and 3, Also, 200 % increase in battery bank only decrease the unused energy by 4.69 % while the LOLD remains at 0%. As such, the 1 day of power autonomy with battery bank of 87,719.30 Ah is still preferred as it will save the cost of battery bank by about 66 %. The ideas presented in this work is relevant for realizing cost effective PV power solutions.**

Keywords— Loss of Load Probability, Peak Sun Hour, Days of Power Autonomy, Photovoltaic, Solar Power System

1. INTRODUCTION

Today, photovoltaic solar (PVS) power systems are dominant alternative power supply systems in Nigeria [1,2]. This is due to the advancements in the solar power system technologies which continues to improve on the system efficiency and also reduce the cost of implementation and maintenance of such systems [3]. Also, due to the large number of population that do not have access to the national grid in Nigeria, standalone PVS power system with battery storage is also mostly adopted in many parts of Nigeria [4,5].

Given the increasing adoption of solar power systems, researchers and designers are looking for ways to minimize cost and improve energy yield and system performance. In this wise, careful selection of PVS power system components is essential. Notably, two key components are the drivers of the standalone PVS power system cost, namely, the PV array and the battery bank [6,7]. Among the two components, battery is always the dominant cost driver given that it has between 3 to 5 years lifespan and so need to be replaced every 3 to 5 years [8,9]whereas the PV modules have about 25 years of lifespan [10,12]. As such, careful selection of the system design parameters is needed to cut down the required battery bank capacity in relation to the required PV array capacity. Accordingly, in this paper, analytical models for the selection of the system parameters for sizing standalone PVS power system components are presented. The model utilized the daily peak sun hour (PSH) dataset of the installation site to determine the suitable value of mean PSH to be used for the sizing of the PV array and the battery bank. The models also help to evaluate the choice of days of autonomy (DoU) as higher DoU courses increase the required battery capacity. The models applicability are demonstrated through sample simulations which are conducted using solar radiation dataset for Akwa Ibom State.

2. METHODOLOGY

The focus of the study is to analytically determine suitable mean peak sun hour along with the appropriate days of autonomy that can be used to size the PV array and the battery bank for a standalone solar power system. The essence is to achieve acceptable loss of load probability value with minimum battery bank and PV array capacities. The model requires sizing of PV array and sizing of the battery bank for the given daily load demand, determination of the expected loss of load and the model for determination of the appropriate mean peak sun hour for the components sizing operations.

2.1 SIZING OF THE PV ARRAY

For a given daily energy demand of E_{DLmd}, daily peak sun hour $of\, PSH_d$, temperature de-rating factor of $\mathrm{f_{td}}$, other de-rating factors of $\mathrm{f_{od}}$, the required solar power capacity to satisfy the load is given as W_{pvc}, where [13,14;

$$W_{pvc} = \frac{E_{DLmd}}{(PSH_d)(\mathrm{f_{td}})(\mathrm{f_{od}})} \quad (1)$$

Where the temperature de-rating factor, $\mathrm{f_{td}}$ is determined from the ambient temperature, T_a , the standard test condition (STC) temperature (which is 25 °C), the nominal operating cell temperature (NOCT), the temperature coefficient (β) of the solar panel and the daily solar irradiance, G_d as follows [15];

$$\mathrm{f_{td}}=1 + \beta\left(\left[T_a + \left(\frac{NOCT-20}{800}\right)\mathrm{G}_d\right] - 25\right) \quad (2)$$

Also,

$$PSH_d = \frac{\mathrm{G}_d}{1\ \mathrm{kW/m2}} \quad (3)$$

Where G_d is given in $\frac{\mathrm{kW}}{\mathrm{m}^2}$.

2.2 SIZING OF THE BATTERY STORAGE

The required battery bank capacity, C_{Bnk} is determined from the given days of power autonomy (da), battery depth of discharge (DoD), battery terminal voltage (V_{Bnk}), battery efficiency (η_{Bnk}) and the daily load demand (E_{DLmd}) with safty factor (sf, usually 1.25). Hence [13,14];

$$C_{Bnk} = \frac{(E_{DLmd})(sf)(da)}{(\mathrm{DoD})(V_{Bnk})(\eta_{Bnk})} \quad (4)$$

2.3 DETERMINATION OF THE LOSS OF LOAD AND THE UNUSED ENERGY

Since the daily solar radiation (G_d) and ambient temperature (Ta) vary over the year, they can be denoted as $\mathrm{G}_{d(k)}$ and Ta(k) respectively for day k. Then, the energy generated from the given solar array capacity (W_{pvc}) in day k is $E_{DePV}(k)$ where [13,14];

$$E_{DePV(k)} = W_{pvc}\left(\left(PSH_{d(k)}\right)\left(\mathrm{f_{td(k)}}\right)\left(\mathrm{f_{od}}\right)\right) \quad (5)$$

$$\mathrm{f_{td(k)}}=1 + \beta\left(\left[T_{a(k)} + \left(\frac{NOCT-20}{800}\right)\mathrm{G}_{d(k)}\right] - 25\right) \quad (6)$$

$$PSH_{d(k)} = \frac{\mathrm{G}_{d(k)}}{1\ \mathrm{kW/m2}} \quad (7)$$

The energy stored in the battery bank on day k is denoted as $E_{Bnk(k)}$. When the battery is fully charged, the maximum energy stored E_{BnkMx} is given as;

$$E_{BnkMx} = (C_{Bnk})(V_{Bnk}) \quad (8)$$

The energy that must be reserved (E_{BnkRsv}) in the battery due to the DoD is given as;

$$E_{BnkRsv} = E_{BnkMx}\,(DoD) \quad (9)$$

The expression for the energy parameters at the end of any day k is given in terms of available energy, $E_{Avl(k)}$, energy supplied to the user , $E_{user(k)}$, missing energy, $E_{miss(k)}$, unused energy, $E_{unused(k)}$ and energy stored in the battery, $E_{Bnk(k)}$ where;

$$E_{Avl(k)} = E_{Bnk(k-1)} + E_{DePV(k)} \quad (10)$$

Where $E_{Bnk(k-1)}$ can be set at 0.

If $E_{Avl(k)} \le E_{BnkRsv}$ then

$$E_{Bnk(k)} = min(E_{Avl(k)}, E_{BnkRsv}) \quad (11)$$

$$E_{user(k)} = 0 \quad (12)$$

$$E_{Miss(k)} = Max(0, E_{Avl(k)} - E_{BnkRsv} - E_{DLmd}) \quad (13)$$

$$E_{Unused} = Max(0, E_{Avl(k)} - E_{DLmd} - E_{BnkMx}) \quad (14)$$

If $E_{BnkRsv} < E_{Avl(k)} \le (E_{BnkRsv} + E_{DLmd})$ then

$$E_{Bnk(k)} = Min(E_{Avl(k)}, E_{BnkRsv}) \quad (15)$$

$$E_{user(k)} = Max(0, E_{Avl(k)} - E_{BnkRsv}) \quad (16)$$

$$E_{Miss(k)} = Max\left(0,\ E_{DLmd} - \left(E_{Avl(k)} - E_{BnkRsv}\right)\right) \quad (17)$$

$$E_{Unused} = Max(0, E_{Avl(k)} - E_{DLmd} - E_{BnkMx}) \quad (18)$$

If $(E_{BnkRsv} + E_{DLmd}) < E_{Avl(k)} \le (E_{BnkRsv} + E_{BnkMx})$ then

$$E_{user(k)} = Min(E_{DLmd}, E_{Avl(k)} - E_{BnkRsv}) \quad (19)$$

$$E_{Bnk(k)} = Min(E_{BnkMx}, E_{Avl(k)} - E_{DLmd}) \quad (20)$$

$$E_{Miss(k)} = Max\left(0,\ E_{DLmd} - \left(E_{Avl(k)} - E_{BnkRsv}\right)\right) \quad (21)$$

$$E_{Unused} = Max(0, E_{Avl(k)} - E_{DLmd} - E_{BnkMx}) \quad (22)$$

If $E_{Avl(k)} > (E_{BnkRsv} + E_{BnkMx})$ then;

$$E_{user(k)} = E_{DLmd} \quad (23)$$

$$E_{Bnk(k)} = E_{BnkMx} \quad (24)$$

$$E_{Miss(k)} = 0 \quad (25)$$

$$E_{Unused} = Max(0, E_{Avl(k)} - E_{DLmd} - E_{BnkMx}) \quad (26)$$

The loss of load probability P_{LOLD} and the unused energy P_{Unused} are given in percentage as follows;

$$P_{LOLD} = \left[\frac{\sum_{x=1}^{x=365}(E_{Miss(k)})}{365(E_{DLmd})}\right] 100\% \quad (27)$$

$$P_{Unused} = \left[\frac{\sum_{x=1}^{x=365}(E_{Unused})}{365(E_{DLmd})}\right] 100\% \quad (28)$$

2.4 DETERMINATION OF THE MINIMUM PEAK SUN HOUR FOR VARIOUS CONSECUTIVE DAYS OF LOW SOLAR RADIATION PER YEAR

The peak sun hour for day k is denoted as $PSH_{d(k)}$ and if the consecutive days of low solar radiation is denoted as W, then the mean peak sun hour for every consecutive W days in a year is denoted as $PSH_{W(k)}$ and it is given for k = 1 to k = 365 as ;

$$PSH_{W(k)} = \frac{PSH_{d(k)}+PSH_{d(k+1)}+\cdots+PSH_{d(k+w-1)}}{W} \quad (29)$$

Where $PSH_{d(365+1)} = PSH_{d(1)}, PSH_{d(365+2)} = PSH_{d(2)}, \ldots, PSH_{d(365+W-1)} = PSH_{d(W-1)}$.

The minimum value of $PSH_{W(k)}$ is given as $PSH_{WMIN(k)}$ where;

$$PSH_{WMIN(k)} = Minimum\left(PSH_{W(k)}\right) \; for \; k = 1 \; to \; 365 \quad (30)$$

3. SIMULATION, RESULTS AND DISCUSSION

The essence of the study is to provide an approach that can be used in selecting the peak sun hour value for sizing the PV solar power system. The window size, W (which is consecutive days of low solar radiation) is varied from 1 to 15 and the minimum value of $PSH_{W(k)}$ for each value of W is used to size the PV power system, the PV array and battery bank capacities are captured as well as the loss of load probability and unused energy probability. The simulations are repeated for different days of autonomy and the results are used to draw conclusions on the choice of peak sun hour and days of autonomy for PV power plant. The simulation is done using the solar radiation data of Akwa Ibom State with annual mean of the daily peak sun hour of 6.2933 kWh/m².day or hours/day as shown in Figure 1.

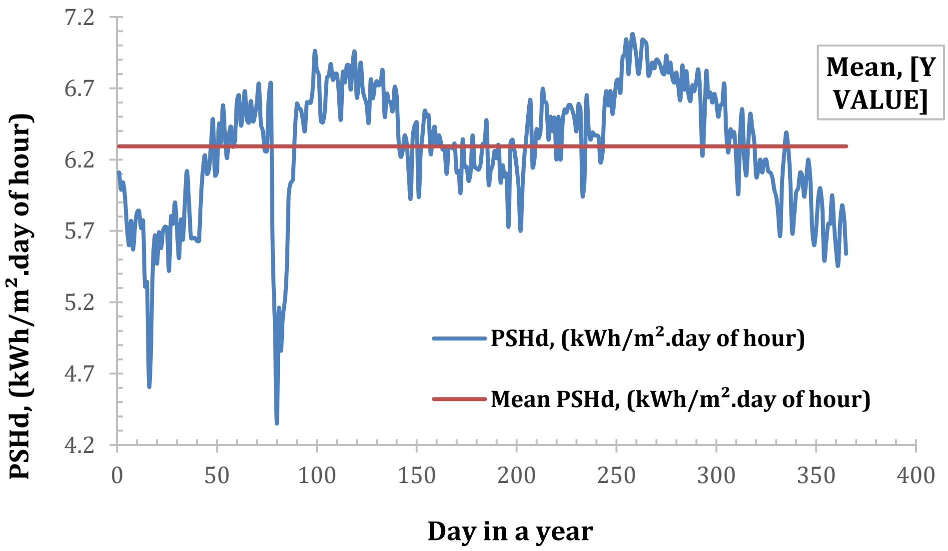

Figure 1 The solar radiation data of Akwa Ibom State with annual mean of the daily peak sun hour of 6.2933 kWh/m².day or hours/day

The minimum mean PSH (kWh/m².day) for different consecutive days of low solar radiation, W (day) is shown in Table 1 and Figure 2 while Figure 3 shows the solar radiation data of Akwa Ibom State with annual mean of the daily peak sun hour and minimum mean PSH for different consecutive days of low solar radiation, W.

According to the results in Table 1, figure 2 and Figure 3, the higher the value of W, the higher the value of the minimum mean PSH with a value of 4.3500 kWh/m².day at W =1 to 5.4760 kWh/m².day at W =15. Also, the annual mean of the daily peak sun hour, 6.2933 kWh/m².day is much higher than the value of 5.4760 kWh/m².day at W =15.

Table 1 The minimum mean PSH (kWh/m².day) for different consecutive days of low solar radiation, W (day)

Consecutive days of low solar radiation, W (day)	Minimum mean PSH (kWh/m².day)	Annual Mean (kWh/m².day)	Mean for 1-15 consecutive days of low solar radiation, (kWh/m².day)
1	4.3500	6.293315	5.022532
2	4.7050	6.293315	5.022532
3	4.7867	6.293315	5.022532
5	4.9040	6.293315	5.022532
7	5.0243	6.293315	5.022532
9	5.1822	6.293315	5.022532
11	5.3400	6.293315	5.022532
13	5.4346	6.293315	5.022532
15	5.4760	6.293315	5.022532

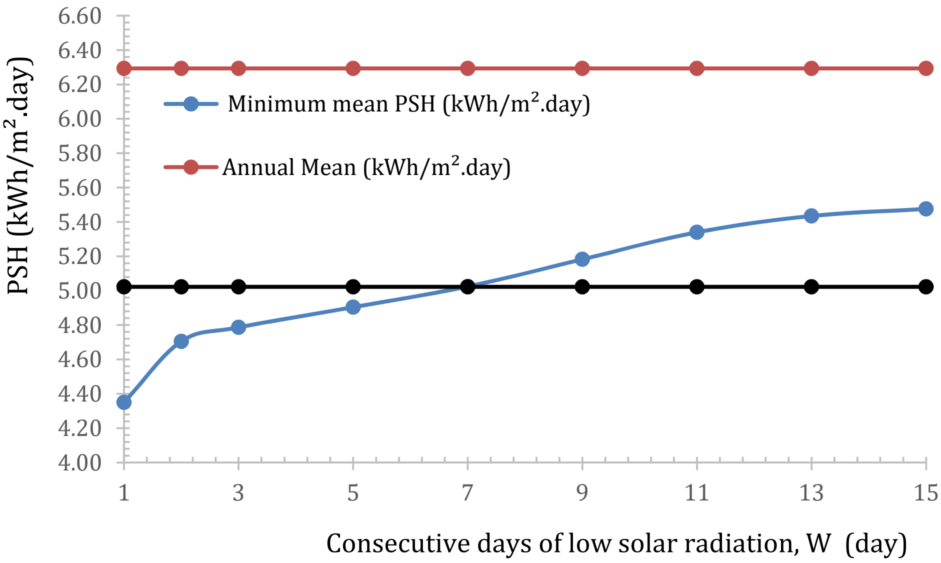

Figure 2 The minimum mean PSH (kWh/m².day) for different consecutive days of low solar radiation, W (day)

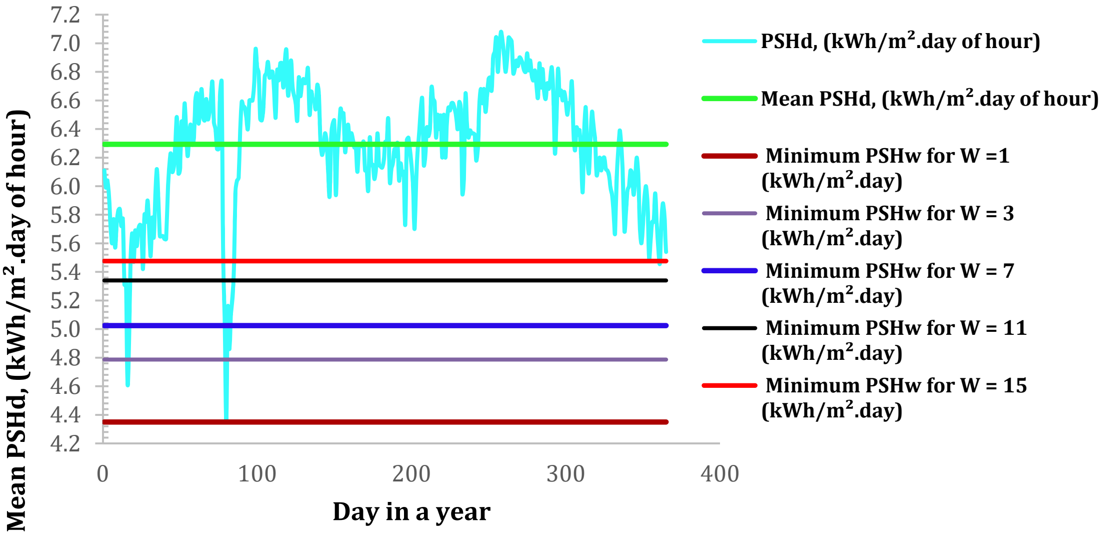

Figure 3 The solar radiation data of Akwa Ibom State with annual mean of the daily peak sun hour and minimum mean PSH for different consecutive days of low solar radiation, W

The daily load demand of 480 kWh per day which is obtained from a 20 kW power running for 24 hours each day is used in the sizing of the PV solar power system for different mean PSH determined from the different consecutive days of low solar radiation, W ranging from 1 to 15 days and for different days of power autonomy. The results of the PV array power rating , battery bank rating, loss of load probability, PLoLD and unused energy probability, PUnused for days of autonomy, DoU =3 are shown in Table 2 while those for DoU =2 and DoU =1 are shown in Table 3 and Table 4 respectively. The results in Tables 2, 3 and 4 show that the required PV array power rating (KWp) decreases with increase in the mean PSH (kWh/m².day) used in the sizing calculations, as shown in Figure 4. However, the battery bank capacity required remained constant for the given days of autonomy, DoU , as shown in Figure 5. Specifically, at PSH of 4.35kWh/m².day, the PV of 138.56 KWp is required and it gives 0 % LoLD and 26.64 % unused energy per year whereas 6.29 kWh/m².day, the PV of 95.97 KWp is required and it gives 5.0 % LoLD and 0 % unused energy per year. As such, applications with stringent energy demand will be designed with lower value of PSH which results in negligible LOLD.

Table 2 The results of the PV array power rating , Battery bank rating, Loss of Load Probability, PLoLD and Unused Energy Probability, PUnused for days of autonomy, DoU =3

Consecutive days of low solar radiation, W (day)	Minimum mean PSH (kWh/m².day)	Days of power autonomy (days)	PV array power rating (KWp)	Battery bank rating (Ah)	Loss of Load Probability, PLoLD (%)	Unused Energy Probability, PUnused (%)
1	4.35	3	138.56	263,157.89	0.00	26.64
2	4.71	3	128.15	263,157.89	0.00	20.66
3	4.79	3	125.98	263,157.89	0.00	19.28
5	4.90	3	122.98	263,157.89	0.00	17.30
7	5.02	3	120.05	263,157.89	0.00	15.27
9	5.18	3	116.41	263,157.89	0.00	12.61
11	5.34	3	112.99	263,157.89	0.00	9.95
13	5.43	3	111.03	263,157.89	0.12	8.48
15	5.48	3	110.20	263,157.89	0.18	7.86
365	6.29	3	95.97	263,157.89	5.00	0.00

Table 3 The results of the PV array power rating , Battery bank rating, Loss of Load Probability, PLoLD and Unused Energy Probability, PUnused for days of autonomy, DoU =2

W	PSH (kWh/m².day)	Days of power autonomy (days)	PV array power rating (KWp)	Battery bank rating (Ah)	Loss of Load Probability, PLoLD (%)	Unused Energy Probability, PUnused (%)
1	4.35	2	138.56	175,438.60	0.00	26.84
2	4.71	2	128.15	175,438.60	0.00	20.87
3	4.79	2	125.98	175,438.60	0.00	19.50
5	4.90	2	122.98	175,438.60	0.00	17.53
7	5.02	2	120.05	175,438.60	0.00	15.50
9	5.18	2	116.41	175,438.60	0.00	12.85
11	5.34	2	112.99	175,438.60	0.00	10.20
13	5.43	2	111.03	175,438.60	0.12	8.72
15	5.48	2	110.20	175,438.60	0.18	8.11
365	6.29	2	95.97	175,438.60	5.00	0.00

Table 4 The results of the PV array power rating , Battery bank rating, Loss of Load Probability, PLoLD and Unused Energy Probability, PUnused for days of autonomy, DoU =1

W	PSH (kWh/m².day)	Days of power autonomy (days)	PV array power rating (KWp)	Battery bank rating (Ah)	Loss of Load Probability, PLoLD (%)	Unused Energy Probability, PUnused (%)
1	4.35	1	138.56	87,719.30	0.00	27.04
2	4.71	1	128.15	87,719.30	0.00	21.09
3	4.79	1	125.98	87,719.30	0.00	19.72
5	4.90	1	122.98	87,719.30	0.00	17.75
7	5.02	1	120.05	87,719.30	0.00	15.73
9	5.18	1	116.41	87,719.30	0.00	13.08
11	5.34	1	112.99	87,719.30	0.00	10.44
13	5.43	1	111.03	87,719.30	0.12	8.97
15	5.48	1	110.20	87,719.30	0.18	8.36
365	6.29	1	95.97	87,719.30	5.09	0.10

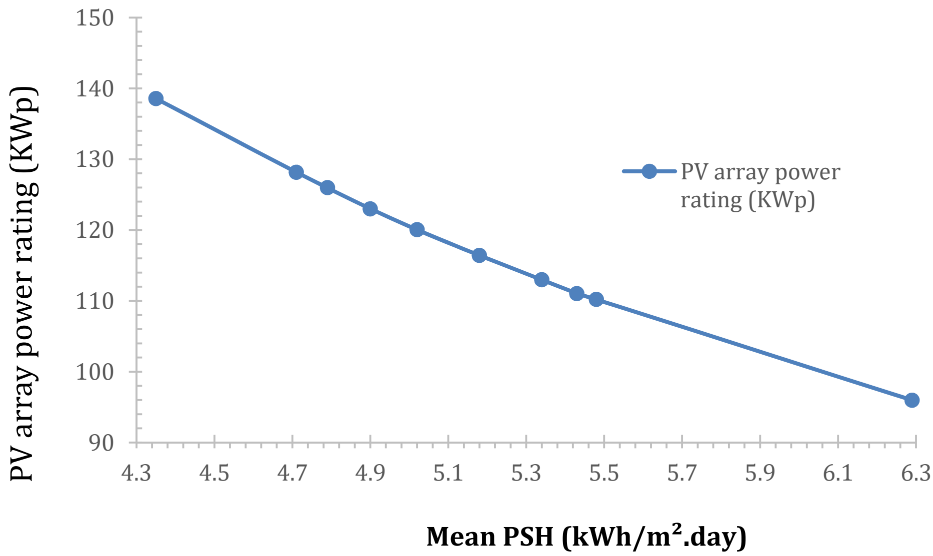

Figure 4 The graph of PV array power rating (KWp) versus mean PSH (kWh/m².day)

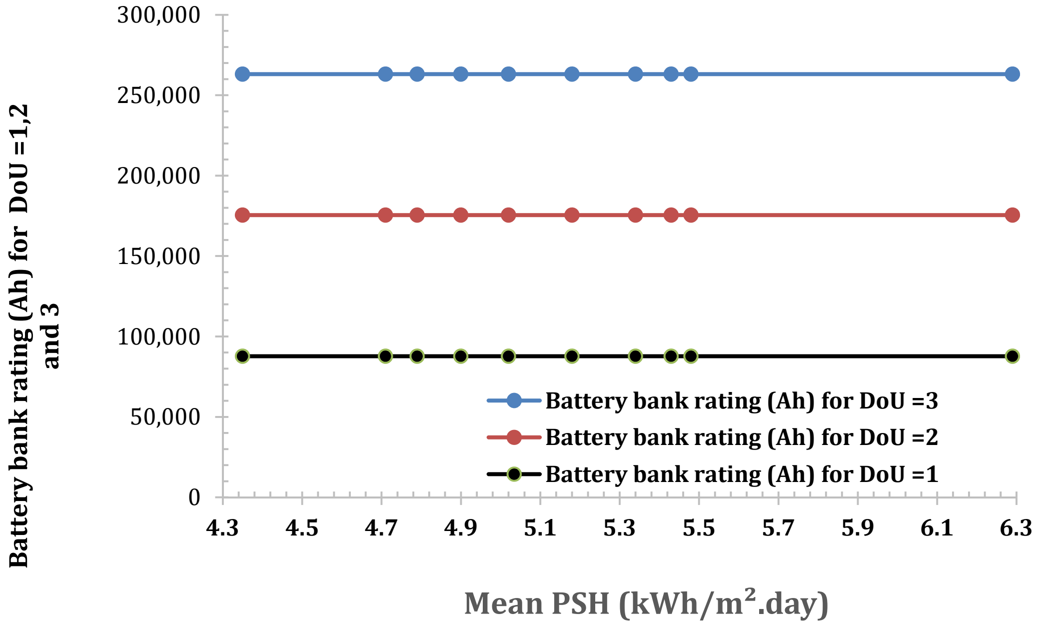

Figure 5 The graph of battery bank rating (Ah) for DoU =1,2 and 3 versus mean PSH (kWh/m².day)

Furthermore, the results of the percentage increase in battery bank capacity (%) and percentage decrease in unused energy (%) with respect to battery bank rating are presented in Table 5. Also, the graph of loss of load probability, PLoLD (%) and unused energy probability, PUnused (%) versus battery bank rating (Ah) are presented in Figure 6 while the graph of ppercentage decrease in unused energy (%) versus percentage increase in battery bank capacity (%) are presented in Figure 7. The results in Table 5 , Figure 6 and figure 7 are for W = 11 with PSH of 5.34kWh/m².day and DoU varied from 1 to 3 days. The results show that for the three DoU and same PSH value, the PV array power capacity remained constant at 112.99 kWp whereas the battery bank capacity rose from 87,719.30 Ah with DoU of 1day to 263,157.89 Ah with DoU of 3 days, which is about 200 % increase. The 200 % increase in battery bank only decrease the unused energy by 4.69 %. As such, the 1 day of power autonomy with battery bank of 87,719.30 Ah is still preferred as it will save the cost of battery by about 66 %.

Table 5 Percentage increase in battery bank capacity (%) and Percentage decrease in unused energy (%) with respect to Battery bank rating

W (days)	Days of power autonomy, DoU (days)	PV array power rating (KWp)	Battery bank rating (Ah)	Loss of Load Probability, PLoLD (%)	Unused Energy Probability, PUnused (%)	Percentage increase in battery bank capacity (%) with respect to DoU of 1	Percentage decrease in unused energy (%) with respect to DoU of 1
11	3	112.99	263,157.89	0.0	9.95	200	-4.69
11	2	112.99	175,438.60	0.0	10.20	100	-2.30
11	1	112.99	87,719.30	0.0	10.44	0	0.00

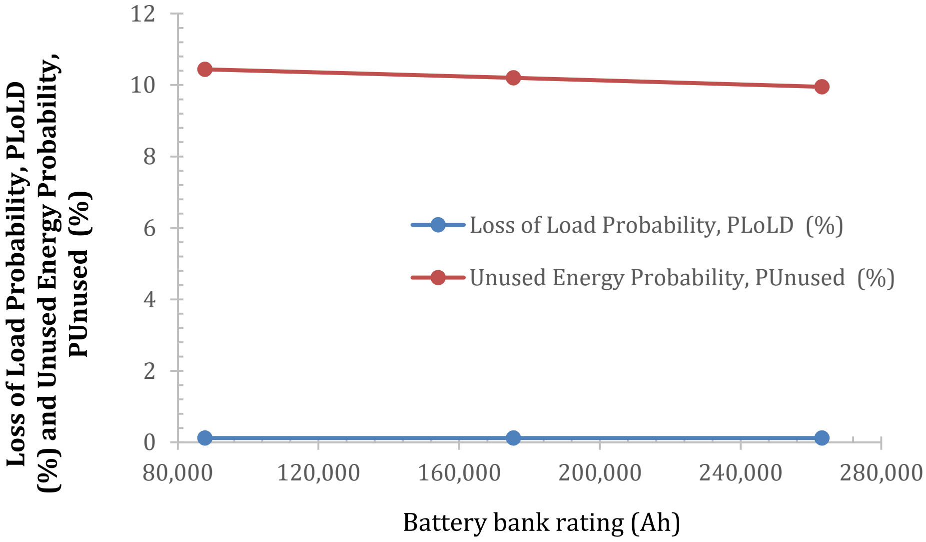

Figure 6 Loss of Load Probability, PLoLD (%) and Unused Energy Probability, PUnused (%) versus Battery bank rating (Ah)

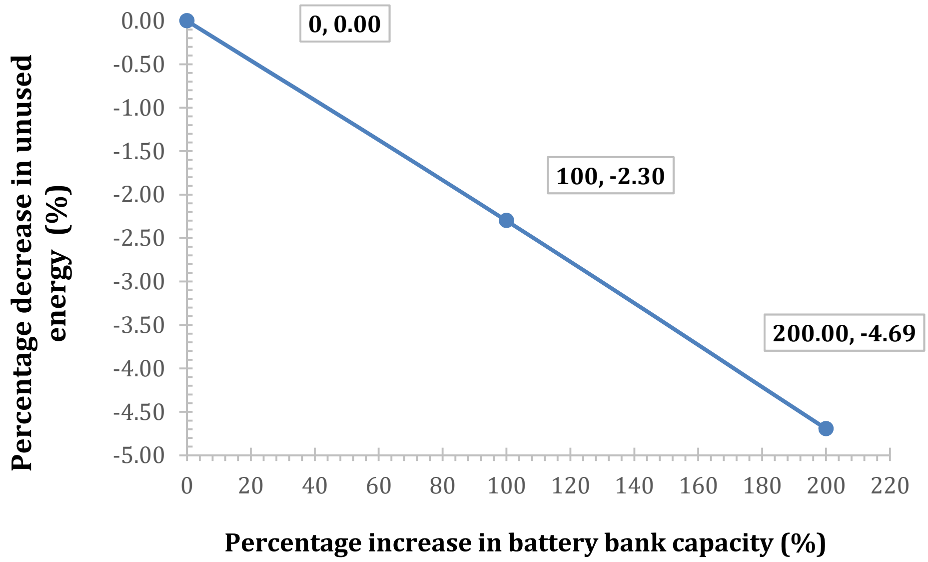

Figure 7 Percentage decrease in unused energy (%) versus Percentage increase in battery bank capacity (%)

4. CONCLUSION

An approach for determining the appropriate peak sun hour (PSH) to choose in sizing PV solar power system is presented. The study considered the size of the required PV array, the size of the battery bank , the loss of load probability and the probability of unused energy per annum. The analytical expressions for determination of the listed parameters are presented. The solar radiation data and a fixed daily demand data were used in some sample numerical computations and the results show that the Pv array capacity increases with decrease in PSH values whereas the battery bank capacity increases with increase in the days of power autonomy. Also, cost effective sizing can be achieved by appropriate selection of the PSH value which can give negligible LOLD with low required battery bank capacity.

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