Sizing Of An Off-Grid Photovoltaic Power Supply System With Battery Storage

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***Abstract*— In this paper, the sizing of an off-grid photovoltaic power supply system with battery storage is presented. The case study site is located within University of Uyo Main Campus and it has effective daily load demand of 2008.24 kWh per day with annual average of daily solar radiation of 10.58 kWh/m2/day and annual average temperature of 25.36 °C. After the sizing computation, a total number of 763 PV modules and about 5908 of 200Ah batteries are required to meet the daily load demand with three (3) days autonomy. In view of safety factor, a 260 kW inverter was selected along with a 1068.2 A charger controller. Based on the mathematical expressions presented in this paper, MATLAB software was used to study the effect of solar radiation and temperature on the total area of the PV module required to satisfy the given daily load demand and the results show that increase in the solar radiation results in increase in PV energy yield and a decrease in the number of PV modules and hence the PV module area required for a given load demand profile. Conversely, the study on the effect of temperature on module efficiency showed that an increase in the temperature of the module results in decrease in the module efficiency. In all, the parametric analysis results showed that for a given solar radiation value, a rise in temperature leads to a drop in the PV module efficiency, a drop in PV energy yield, a rise in the number of PV module and PV module area required to satisfy a given load demand.**

***Keywords*— Off-Grid Power System, Photovoltaic, Renewable Energy, Solar Radiation, Pv Module Efficiency, Parametric**

1. Introduction

As the global community continues to seek for ways to address the challenges of global warming and the harmful human practices that causes the global warming, researchers continue to explore ways to make renewable energy systems more affordable and easy to deploy [1,2,3,4,5]. Among the renewable energy options, solar photovoltaic power system has continue to gain popularity, especially in the developing countries with endemic acute energy supply shortages but with adequate average daily sunshine hours for significant PV energy harvest [6,7,8,9,10]. Furthermore, the advancements in semiconductor and other technologies have led to continuous drop in the cost of PV power systems components [11,12,13,14,15,16,17]. Accordingly, there are greater future prospects for PV energy system than we have today.

In this paper, the sizing of an off-grid photovoltaic power supply system with battery storage is presented. The study is motivated by the need to provide a simple but effective approach to determine the sizes of various PV power system components for off-grid option that are targeted to users that have no access to the national grid. Specifically, detailed mathematical analysis is presented along with numerical computation using case study data. This approach makes it easier for PV system designers or user to easily apply the ideas presented here in their site specific data. Furthermore, the approach adopted in the sizing is also suitable for comparative analysis of the off-grid photovoltaic power supply system with battery storage and other off-grid photovoltaic power supply system without battery storage or with pumped water storage option.

Finally, apart from the component sizing, the paper also presented parametric analysis that will enable PV system designers or user to understand how changes in their site specific meteorological data can affect the PV system components sizes.

2. Methodology

The procedure used in the sizing of the off-grid photovoltaic power supply system with battery storage includes the following major steps:

i. Estimation of the daily load demand and acquisition of the meteorological data of the case study site
ii. Sizing of the pv array
iii. Sizing of the battery bank
iv. Sizing of the inverter and charge controller

The details of each of the major steps along with the mathematical expressions used to determine the relevant parameter values are presented. Also, sample case study data was used also for numerical computation of the values. Eventually, MATLAB was used to run do the computation for a number of selected scenarios and relevant graphs are generated for parametric analysis of the system. The layout of an off-grid PV system is given in Figure 1.

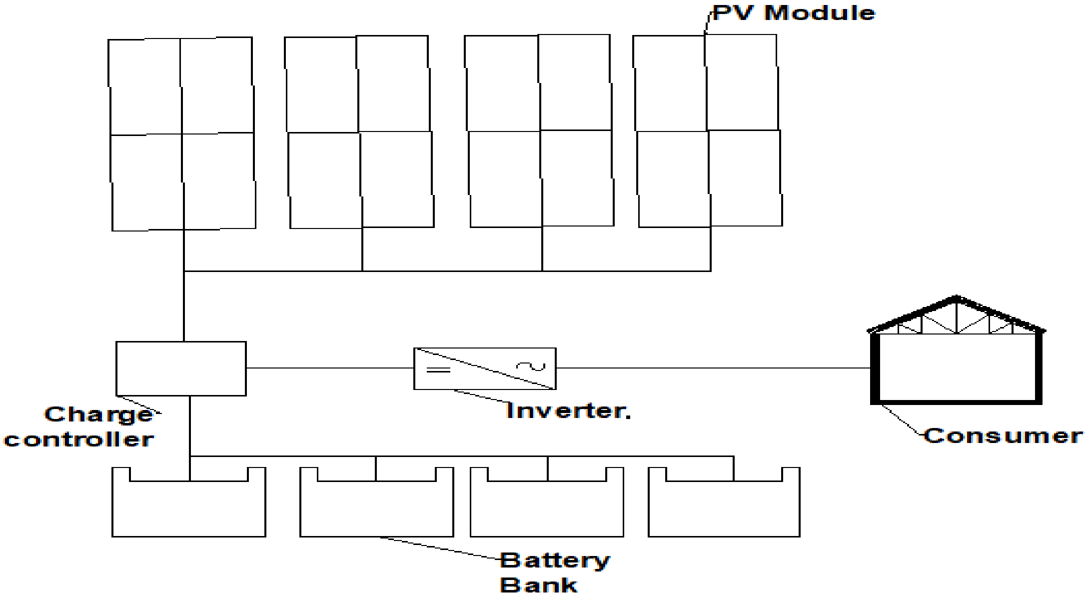

Figure 1: Layout of a simple Off-grid PV system with battery storage

2.1 The daily load demand and the meteorological data of the case study site

The case study site in this paper is University of Uyo Main Campus. The daily load demand obtained from the load profile of the site is 2008.24 kWh. The meteorological data (temperature and the solar radiation incident on the horizontal plane) of the case study site were obtained from NASA portal. The daily average and monthly average solar radiation for a period of one year are shown in Figure 2 and Figure 3 respectively.

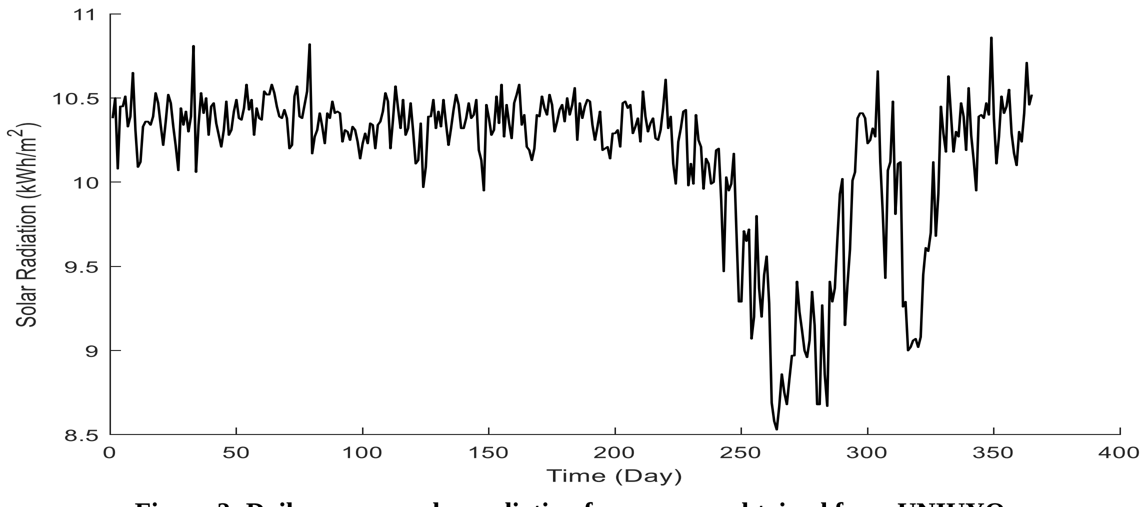

Figure 2: Daily average solar radiation for one year obtained from UNIUYO

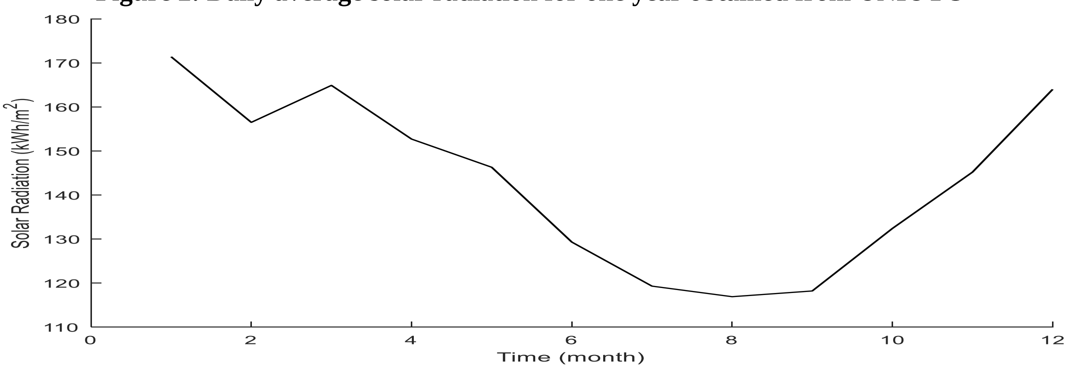

Figure 3: Monthly average solar radiation for one year obtained from UNIUYO

Figure 2 showed that the least solar radiation occurred in the month of August and the highest solar radiation occurred in the month of January. A sample 72 hours (3 days) hourly solar radiation of the case study site is shown in Figure 4 while the 8,760 hours (365 days) hourly solar radiation of the case study site is shown in Figure 5. From Figure 4, it is clear that solar radiation begins from 7:00 hr and ends at 17:00hr. Between the hours of 0:00hr to 6:00hr and 18:00hr to 23:00hr there is no solar radiation. Also, the case study site has an average of 11 hours of solar radiation with peak radiation at 12 noon and 1 pm daily. The annual average of daily solar radiation for the case study site is 10.58 kWh/m^2/day.

Similarly, the monthly average temperature for 12 months is shown in Figure 6. The annual average temperature is 25.36 °C.

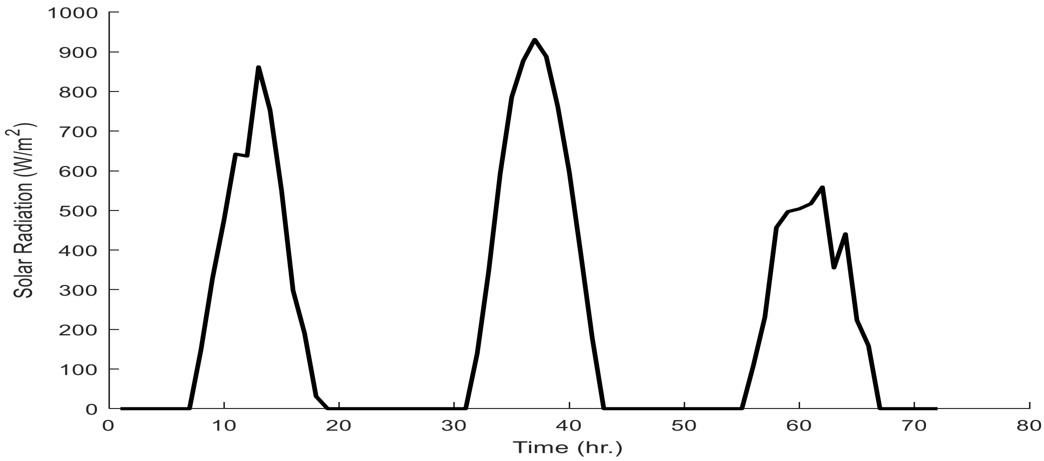

Figure 4: Hourly solar radiation in W/m^2 for 72 hours obtained from UNIUYO

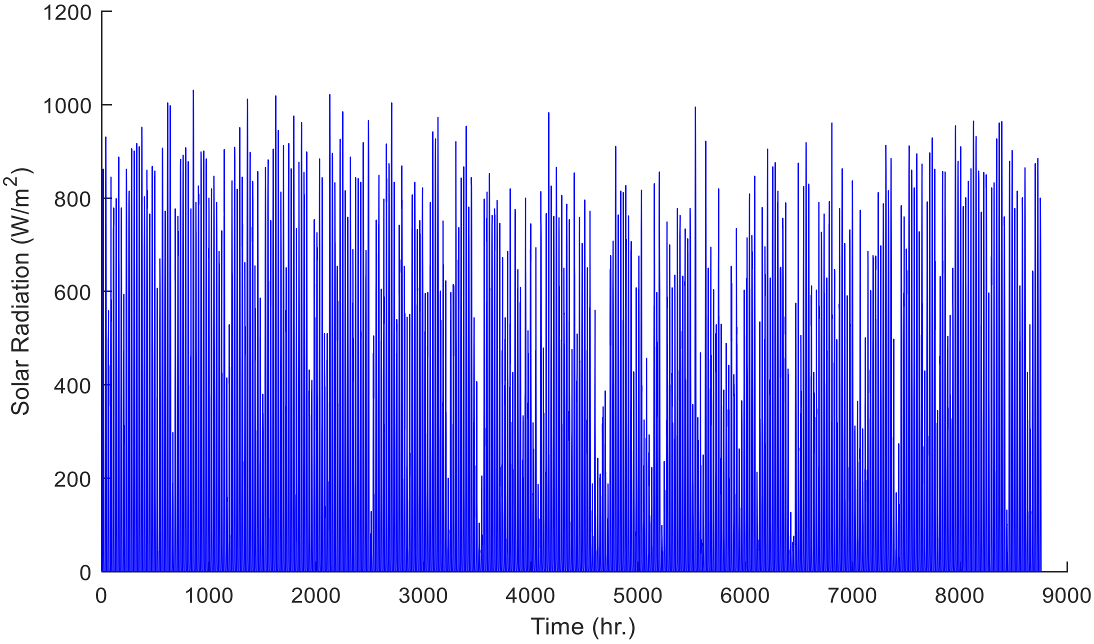

Figure 5: Hourly solar radiation in W/m^2 for one year obtained from UNIUYO

2.2 Sizing of the PV Array for Off-grid Photovoltaic System with Battery Storage

According to standard practice, when sizing the PV array in an off-grid system it is important to account for the charge controller losses, losses due to wiring connections and battery losses. These system component losses are accommodated in the sizing procedure by scaling up the daily load demand by 30%. Hence, given that the daily load demand is2008.24 kWh, then;

$$E_{PV} = 2008.24 \text{ x } 1.3 = 2610.71 \text{ kWh}$$

The PV array output energy is calculatedas;

$$P_{PV} = \eta(T_{op}, S_r)(S_r)(A_{tm}) \quad (1)$$

Where: P_{PV} is the output power of the PV array, A_{tm} is the total area of PV array, $\eta(T_{op}, S_r)$ is the operating efficiency of the PV array (which is a function of the operating cell temperature and solar radiation) and S_r is the solar radiation. Now, $\eta(T_{op}, S_r)$ is is computed as;

$$\eta(T_{op}, S_r) = \eta(25\,°C, S_r)[1 + K(T_{op} - 25\,°C)] \quad (2)$$

Where: $\eta(25\,°C, S_r)$ is the module efficiency under standard test condition (STC), K is the PV cell temperature coefficient, T_{op} is the PV cell operating temperature.

The selected PV module is the MONO SOLAR MODULE TW345MW-72 which is a Monocrystalline solar panel with Maximum Power (Pmax) of 345 Wp, the PV cell temperature coefficient (K) = -0.41%℃ , the area of each module (A_m) = 1.77 m^2 and $\eta(25\,℃, S_r)$ = 18.3%. Also, the meteorological data obtained from NASA portal for the study site shows that T_{op} = 25.36 °C and S_r = 10.58 kWh/m^2/day. Hence,

$$\eta(T_{op}, S_r) = 18.3\% \, [1 - 0.0041(25.36\,℃ - 25\,℃)] = 17.8\%$$

Now,

$$A_{tm} = (A_m) N_{PV} = \frac{P_{PV}}{\eta(T_{op}, S_r)(S_r)} \quad (3)$$

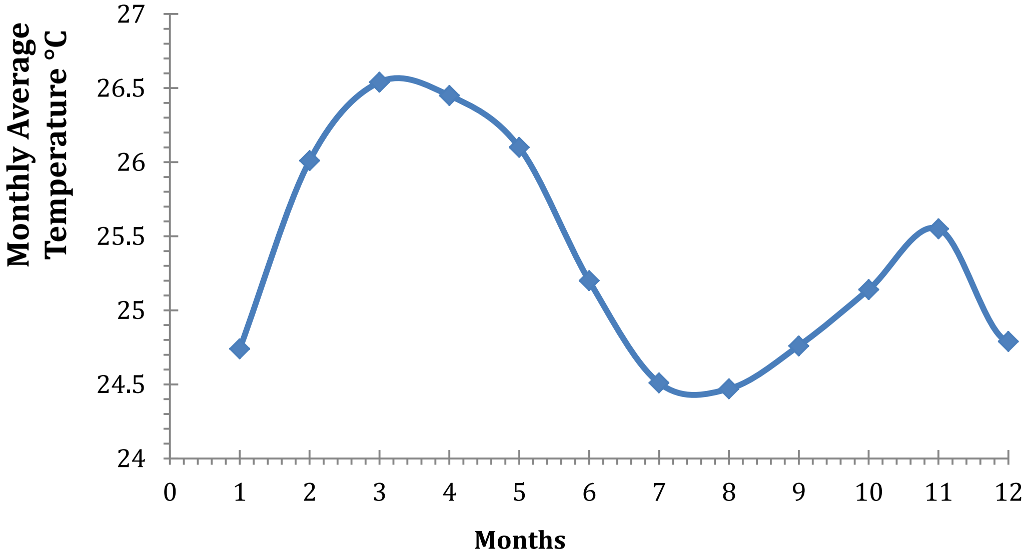

Figure 6. The monthly average temperature for 12 months

Where N_{PV} is the number of PV module required to supply the required electrical energy and A_m is the area of each module. Therefore, from Equation 1 and Equation 3, the number of PV module required to supply electrical energy to the system is given as;

$$N_{PV} = \frac{P_{PV}}{\eta(T_{op}, S_r)(S_r)(A_m)} \quad (4)$$

Hence, with the available dataset,

$$N_{PV} = \frac{2610.71}{0.178 \ \text{x} \ 10.85 \ \text{x} \ 1.77} = 763.72$$
$$\approx 763 \text{PV modules}$$

N_{SPV} is the number of PV modulein series and N_{PVP} is the number of PV modules in parallel and also that the system bus voltage is 168 V dc while the selected PV module nominal voltage is 24 V dc, then;

$$N_{SPV} = \frac{168}{24} = 7 \quad (5)$$

$$N_{PVP} = \frac{N_{PV}}{N_{SPV}} = \frac{763}{7} = 109 \quad (6)$$

About 763 PV modules are used, with 7 panels connected in series while 109 string in parallel.

2.3 Sizing of the Battery for the PV System with Battery Storage

In this paper, a 12 Vdc, 200 Ah battery deep cycle battery was used in the battery bank and 3 days of autonomy is adopted. The battery bank capacity (E_{bb}) in Ampere-hour (Ah) of the battery bank was calculated as follows;

$$E_{bb} = \frac{\text{Total watt-hour per day x Days of autonomy}}{0.85 \text{ x DoD x nominal battery voltage}} \quad (7)$$

where E_{bb} is the battery capacity in Ampere-hour (Ah), DoD is the depth of discharge and the value of 50% was used, 0.85 is the recommended operating capacity of the battery which is adopted to prolong the life of the battery, the nominal battery voltage is 168 Vdc. Substituting the values into Equation 7 gives:

$$E_{bb} = \frac{2008.24 \ \text{x} \ 1000 \ \text{x} \ 3}{0.85 \ \text{x} \ 0.5 \ \text{x} \ 168} = 84388.66 \text{ Ah}$$

Hence, with the selected 12Vdc, 200 Ah battery and 168 V system bus voltage, the number of batteries in series(N_{Sbat}) in the battery bank is given as;

$$N_{pbat} = \frac{168}{12} = 14 \quad (8)$$

Also, the number of batteries in parallel (N_{pbat}) in the battery bank is given as;

$$N_{sbat} = \frac{E_{bb}}{200} = 421.9433 \cong 422 \quad (9)$$

Hence, the total number of batteries in (N_{Tbat}) in the battery bank is given as;

$$N_{Tbat} = (N_{pbat})(N_{sbat}) = 14\,(422) = 5908 \quad (10)$$

2.4 Sizing of the Inverter and Charge Controller for the PV System with Battery Storage

An inverter is required to convert the DC voltage at the terminal of the battery bank into appropriate AC power. The input voltage of the inverter must be the same as the nominal voltage of the battery bank. It is recommended that the inverter size should be about 20 to 30% larger than the total connected load of the consumer as shown in Equation 11.

$$\text{Inverter Size} = \text{Total connected load (kW)} + (30\% \text{ of total connected load}) \quad (11)$$

where the total connected load is 200 kW. Hence,

$\text{Inverter Size} = 200 + (0.3 \text{ x } 200) = 260 \text{ kW}$

This will enable the inverter handle inductive loads safely. Therefore, the parameters of the inverter required for the off-grid system is as follows; Capacity = 260 kW, Input voltage (D.C side) = 168 Vdc and Output voltage (A.C side) = 230/400 Vac.

In an Off-grid PV system, the charge controller is referred to as the battery manager. It manages the battery voltage and current. The charge controller is a device that is used to limit the rate of charge and discharge of a battery bank. It is used to check overcharging and over-discharging of a battery bank which is capable of reducing the lifespan and performance of the system. The charge controller was selected to match the current and voltage characteristic of the battery bank and PV array. In determining the appropriate size of the solar charge controller for the PV system, the module short circuit current, I_{sc} was multiplied by the number of modules in parallel and by a safety or sizing factor of 1.25. Hence,

$$\text{Charge Controller Rating} = I_{sc} \text{x PV modules in parallel x } 1.25 \quad (12)$$

For the selected PV module, I_{sc} = 7.84 A and the number of PV modules in parallel = 109. Hence, the charge controller rating = 7.84 x 109 x 1.25 = 1068.2 A

3. Results and discussion

The summary of the sizing results for the off-grid photovoltaic power supply system with battery storage is shown in Table 1.

Based on the mathematical expressions presented in this paper, MATLAB software was used to study the effect of solar radiation and temperature on the total area of the PV module required to satisfy the given daily load demand and the results are shown in Figure 7. The results in Figure 7 showed that an increase in the solar radiation results in a decrease in the module area required for a given load demand profile. This means that, for a given module area, an increase in the solar radiation results in an increase in the output power of the PV module.

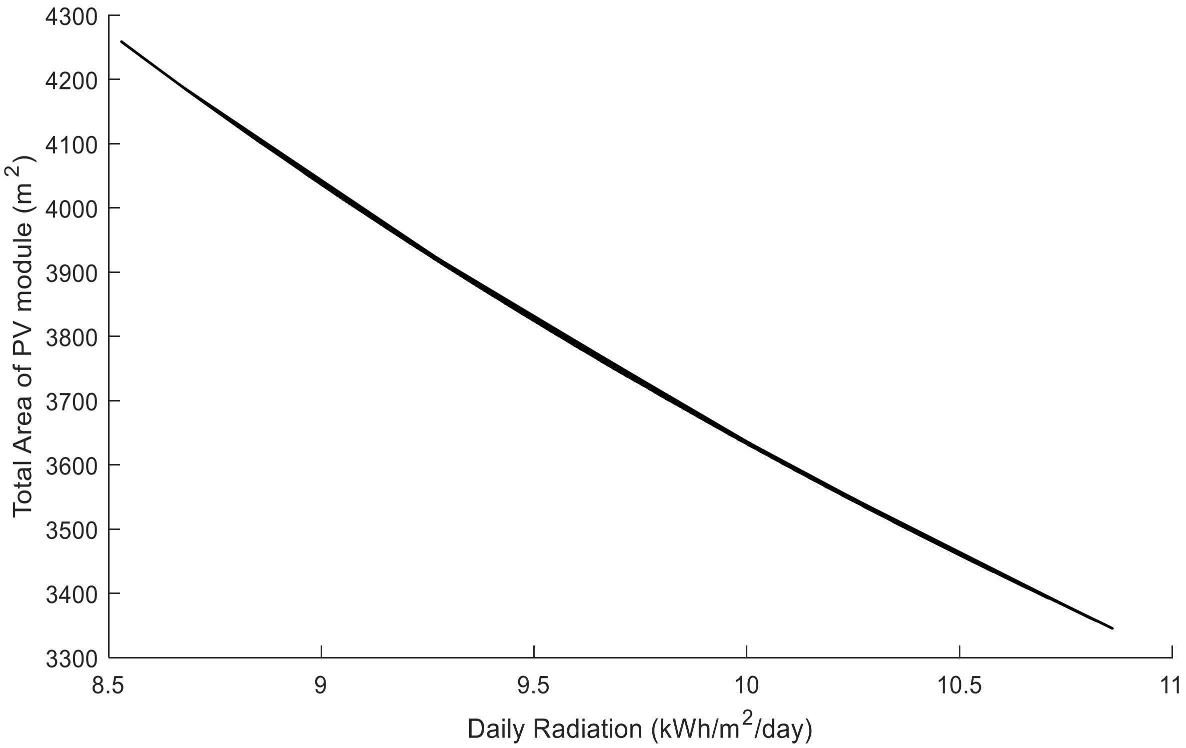

Figure 7: Effect of daily average solar radiation on the area required for PV module

Table 1 The summary of the sizing results for the off-grid photovoltaic power supply system with battery storage

S/N	Parameter Name	Parameter Value	Parameter Unit
1	Daily load demand	**2008.24**	**kWh**
2	Annual average of daily solar radiation	10.58	$kWh/m^2/day$
3	Annual average temperature	25.36	°C
4	Selected PV module	MONO SOLAR MODULE TW345MW-72 Monocrystalline solar panel	
5	PV module efficiency under standard test condition (STC)	18.3	%
6	Operating efficiency of the PV array	17.8	%
7	PV module temperature coefficient	25.36	°C
8	System bus voltage	168	Vdc
9	Area of each PV module	1.77	m^2
10	Total area of PV array	1.77	m^2
11	Total number of PV module	**763**	**PVmodules**
12	Number of PV module in series	7	**PVmodules**
13	Number of PV modules in parallel	109	**PVmodules**
14	Selected battery voltage	12	Vdc
15	Selected battery unit capacity	200	Ah
16	Depth of discharge (DoD)	50	%
17	Days of autonomy	3	days
18	The battery bank capacity	**84388.66**	**Ah**
19	Number of batteries in series	14	Batteries
20	Number of batteries in parallel	422	Batteries
21	Total number of battery	**5908**	Batteries
22	Inverter size	260	kW
23	Inverter input voltage (DC)	168	Vdc
24	Inverter output voltage (AC)	230/400	Vac
25	The charge controller rating	1068.2	A

Similarly, the effect of temperature on the performance the PV modules with solar radiation of $1000W/m^2$ are shown in Figure 8. The relationship between module temperature and module efficiency shows that an increase in the temperature of the module results in decrease in the module efficiency. Essentially, excessive heat can significantly decrease the output of a PV system.

Specifically, the results showed that there exist a linear relationship between module temperature and total area of PV module as shown in Figure 9. An increase in the module temperature result in decrease in energy yield of the PV module and hence a corresponding increase in the PV module area required for a given solar radiation and energy demand. This is a clear indication that, for a given solar radiation value, a rise in temperature means a drop in module efficiency, a rise in number of PV module and a rise in the PV module area required to satisfy a load demand.

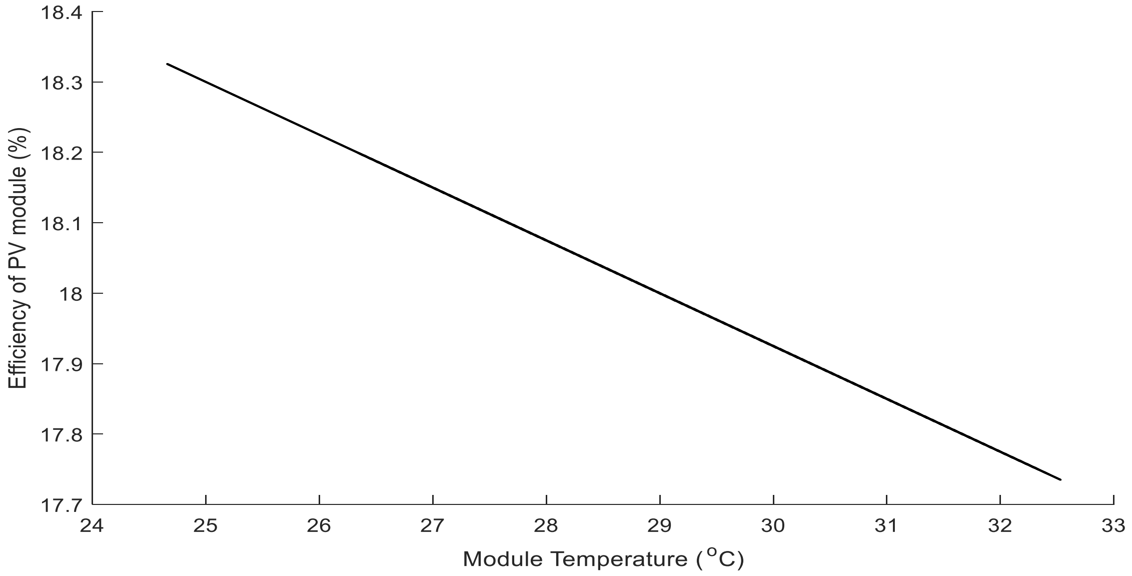

Figure 8: Effect of temperature on the efficiency of the PV module

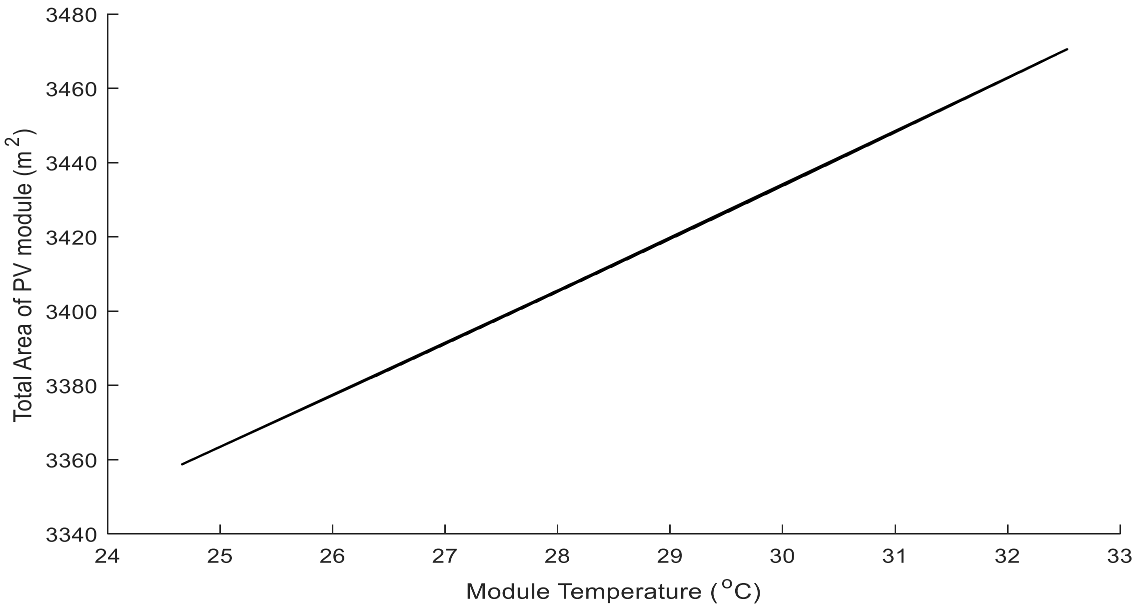

Figure 9: Effect of temperature on the area required for PV module

4. Conclusion

The sizing computations for a standalone solar power system is presented and along with the parametric analysis of the effect of some of the meteorological parameters on the PV components sizes. The computations were based on the load demand and meteorological data obtained from a case study site which is located within University of Uyo main campus. The results show how the PV module efficiency drops with increase in cell temperature. Also, the results showed that more PV modules will be required to satisfy a given load demand if the cell temperature is increased.

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