# Sizing Of Stand-Alone Solar Power For A Smart Street Light System With Vandalisation Monitoring And Tracking Mechanism

**Archibong, Ekaette Ifiok**[1]
*Department of Physics*
*University of Uyo*

**Ozuomba, Simeon**[2]
*Department of Electrical/Electronic and Computer Engineering*
*University of Uyo*
*simeonozuomba@uniuyo.edu.ng*

**Etinamabasiyaka Edet Ekott**[3]
*Department of Physics*
*University of Uyo*

***Abstract—*** ***Stand-alone photovoltaic (PV) system is a system that converts solar energy directly into electricity using photovoltaic principle and it is increasingly finding applications as environmentally friendly means of generating electricity. In this paper, sizing of stand-alone solar power for a smart street light system with vandalisation monitoring and tracking mechanism is presented with Uyo Metropolis in Akwa Ibom State as the case study site. First, the daily electric load demand of the micro-controller-based street light was estimated based on Watt-hour energy demand of the different components that make up the circuitry of the system. The estimated daily load demand is 44.5 Wh/day. Then, the relevant meteorological data for Uyo were obtained from NASA portal. The annual average of daily solar irradiation for the case study location (Uyo) is 4.71kW/m2/day and the least monthly average of daily solar irradiation (of 3.77kW/m2/day) occurred in the month of August. The least monthly average of daily solar irradiation of August was considered for the system sizing in order for the stand-alone PV system to keep the battery fully charged in the worst month of the average year. Next, the sizing of the system components was done using requisite analytical expressions presented in the paper. The sizing processes considered the least monthly average of daily solar global solar irradiation incident on the horizontal plane for the geographical location of Uyo, Akwa Ibom State, the annual average temperature, the temperature de-rating factor for the PV module output, the efficiency of the system components and the system bus voltage. With 3 days of autonomy (days of low insolation or cloudy days), and the resultant load demand, along with the meteorological data, the sizing results showed that the system requires 20 W, 18 V solar PV modules and 19.8 Ah battery capacity which amounts to one (1) unit of the selected PV panel and 9 units of the selected battery.***

***Keywords—Stand-Alone Power, Electrical Load Demand, Solar Irradiation, Photovoltaic System (PV), Daily Load Profile, Micro-Controller-Based System, Sizing Of Solar Power, Vandalisation Monitoring, Vandalisation, Tracking Mechanism***

## I. INTRODUCTION

The concept of renewable energy is an indispensable tool for the development and growth of any country [1,2, 3,4,5]. Accordingly, today, solar energy therefore, being a form of renewable energy is significant in the delivery of energy [6,7,8,9]. Due to the abundance of solar energy, in one hour, the earth receives enough energy from the sun to meet its energy need for nearly a year [10,11,12,13]. Photovoltaic (PV) effect is the direct conversion of solar energy into electricity using the photovoltaic (PV) system and is considered as one of the important alternatives to the constant fluctuation in fossil fuel prices and its pollution risk to the preservation of the ecological cycle of the bio-systems on the earth [14,15,16,17]. Stand-alone PV systems use photovoltaic technology only and are not connected to a utility grid. They use the DC output of the PV modules to power DC loads, while a bank of battery is used to store energy for use when the need arises. Off-grid street lighting systems have an edge over traditional grid-connected street lights for a number of reasons amongst which is majorly, the availability of solar energy and the fact that it is clean energy. The initial cost of installation of solar PV systems may be on the high side, but in the long run, they are more economical [18,19,20]. In this paper, the focus is on the sizing of solar PV module, sizing of the power storage system (battery bank), as well as sizing of the solar charge controller for microcontroller based stand-alone solar PV street light for Uyo metropolis, Akwa Ibom state of Nigeria.

## II. METHODOLOGY

First, the meteorological data of the case study site (Uyo) is obtained from NASA website. Next, the daily load demand of the stand-alone solar street light is determined. Finally, the sizing of the various components of the stand-alone solar street light (PV module array, battery bank and solar charge controller)was done.

### *A. Meteorological Data*

The city of Uyo, Akwa Ibom State lies between 5.02° latitude and 7.9° longitude. The 22 years annual averages of the daily meteorological data were retrieved from the NASA website. Specifically, the parameters considered here are: global solar radiation on the horizontal plane (KW-h/m$^2$/day), wind speed and the earth's ambient temperature. The requisite meteorological data for the case study site as retrieved from the NASA website is hereby given in Table 1 [21]. The bar chart showing the global solar irradiation on the horizontal plane and the monthly averages is given in Figure 1 while the bar chart for the monthly and annual average temperature is given in Figure 2.

Table 1. Monthly and annual average values of meteorological data for Uyo Metropolis Akwa Ibom State

| Months | Temperature (°C) | Wind Speed (m/s) | Global Solar Radiation On The Horizontal Plane (kW-hr/m^2/day) |
|---|---|---|---|
| JAN | 24.71 | 2.01 | 5.53 |
| FEB | 25.94 | 2.07 | 5.59 |
| MAR | 26.46 | 2.2 | 5.32 |
| APR | 26.38 | 2.28 | 5.09 |
| MAY | 26.02 | 2.23 | 4.72 |
| JUN | 25.13 | 2.5 | 4.31 |
| JUL | 24.46 | 2.78 | 3.85 |
| AUG | 24.41 | 2.87 | 3.77 |
| SEP | 24.69 | 2.54 | 3.94 |
| OCT | 25.03 | 2.12 | 4.27 |
| NOV | 25.44 | 1.67 | 4.84 |
| DEC | 24.7 | 1.76 | 5.29 |
| ANNUAL AVERAGE | 25.28 | 2.25 | 4.71 |

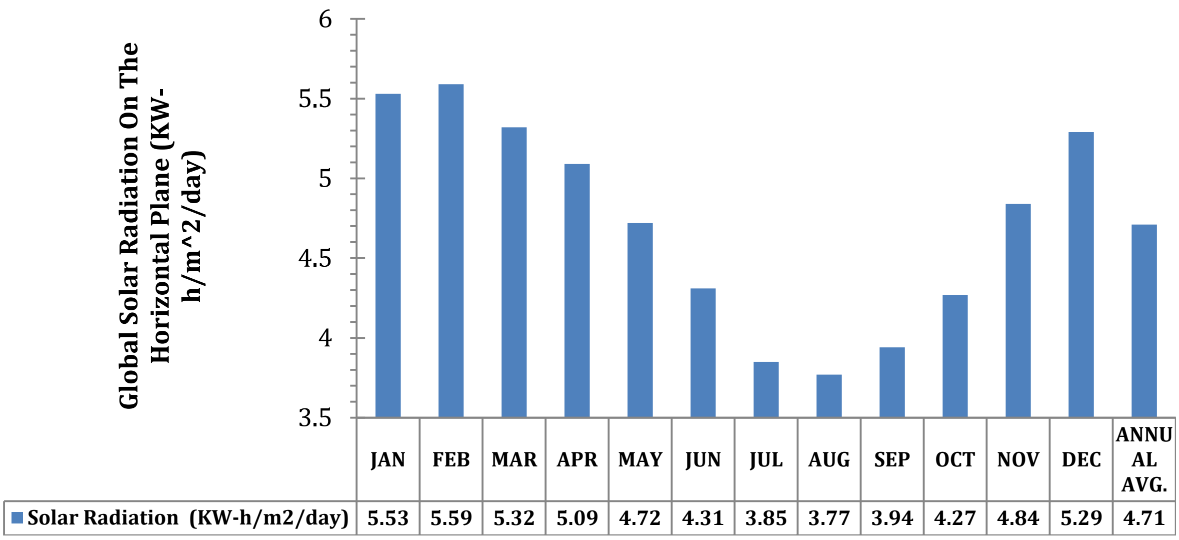


Figure 1. Global solar radiation on the horizontal plane (KW-h/$m^2$/day).

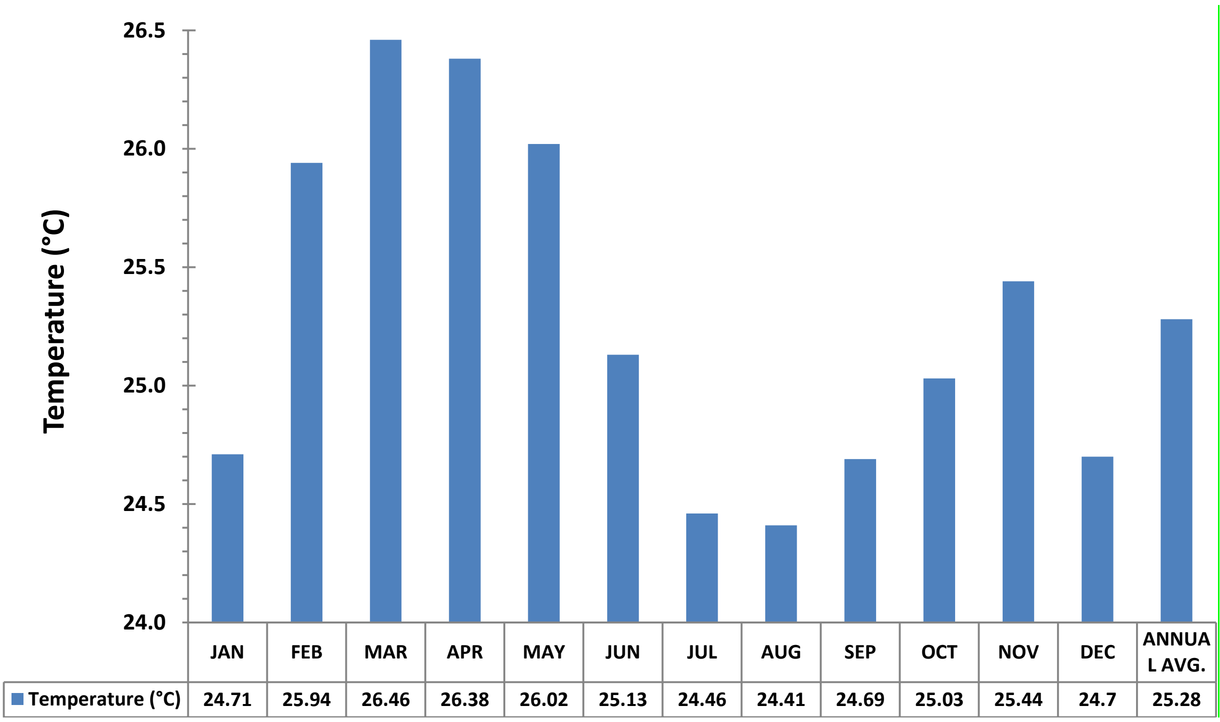


Figure 2. The monthly and annual average **Temperature (°C)**

### *B. Daily Load Profile of the System*

The daily load profile for the system is determined by calculating the power demand in watts-hour per day (Wh/day) for all load types to be powered by the stand-alone solar street light system. This is the total power consumption of the LED array and the other parts that will need to be powered by the solar system, such as the Arduino Wi-Fi module, the infrared module, the light dependent resistor and the buzzer. The daily load profile is calculated by profiling these different loads with their respective power ratings and average operation hours within twenty-four hours. The result of this analysis is used to determine the components sizes of the proposed stand-alone photo voltaic system. In this study, the ESP2866MOD Wi-Fi module being used has an operating voltage of range 3.0 to 3.6V, with an average operating current of 80mA. The power consumption of the module can therefore be calculated from the power law equation as follows [22]:

$$P = IV \qquad (1)$$

Where V = 3.6V and I = 80mA,

P = 80 x 3.6 = 288mW.

However, it is assumed most vandalisations take place during the late hours of the night, so the Wi-Fi module is in sleep mode and standby mode most hours of the day unless a fault is detected in the system and it is required to send signals to the control station. Taking this into consideration, along with the manufacturer's data specification for the Wi-Fi module, the power consumption of the Wi-Fi module is halved to arrive at 144mW per day.

The IR sensor module chosen for this work has an operating voltage of 3.3 to 5V DC, and a 20mA supply current [23]. Considering 5V and applying P = IV therefore, the power consumption is 20 X 5 = 100mW.

Theoretically, the resistance of the LDR in the presence of light is 1kΩ or lower, while its resistance in the dark is about 1MΩ. The operating voltage of the LDR is 3.6V. Therefore, applying Ohms law (V=IR) [24], and the power law equation (P=IV), the power consumption of the LDR can be calculated as follows:

Let $R_1$ = resistance of LDR (1KΩ in light state and 1 MΩ in dark state)

$R_2$ = fixed resistance, 10KΩ

Since the resistors are connected in series, we find the sum thus:

$$R\ (dark) = R_1 + R_2 \qquad (2)$$

$= 1.01 \times 10^6 \Omega$

Since V = 3.6V

V (dark) = I (dark) x R (dark)

Where V (dark) = voltage generated in the dark state, R (dark) = resistance of the LDR in the dark state and I (dark) = current produced in the dark state

$I\ (dark) = \frac{3.6}{1.01\ X\ 10^6} = 3.56 \times 10^{-6}$A

Accordingly, I (light) is calculated to give, I (light) = $3.27 \times 10^{-4}$A, Where I (light) = current produced in the bright state.

Applying (1), P (light) = 1.2mW and P (dark) = 13µW.

The calculations show that the power consumption of the LDR is very minute, almost negligible. However, the power consumption during the day time will be considered here since the power consumption in the night is almost insignificant. The LED array has a power rating of 3.2W as specified by the manufacturer. The buzzer has an operating voltage of 6 V DC and rated current of ≤30mA as specified in the datasheet found in the appendix. Considering its maximum voltage, 8V, and applying (1) thus:

P = IV

P = 6 x 30 = 180mW.

Therefore, the power rating of the buzzer is 180mW. The electrical load demand for the stand-alone street light is given in Table 2.

Table 2. Daily load profile of the stand-alone street light system

| S/N | Components | Quantity | Power Rating (mW) | Hourly Use | Total power (mW) | Energy (mWh/day) |
|---|---|---|---|---|---|---|
| 1 | LED array | 1 | $3.2 \times 10^3$ | 12 | $3.2 \times 10^3$ | $38.4 \times 10^3$ |
| 2 | Wi-Fi module | 1 | 144 | 24 | 144 | 3456 |
| 3 | LDR | 1 | 1.2 | 12 | 1.2 | 14.4 |
| 4 | IR sensor | 2 | 100 | 7 | 200 | 1400 |
| 5 | Buzzer | 1 | 180 | 7 | 180 | 1260 |
| | Total | | 3,725 | | 44,530 | |

### *C. Sizing of the PV Array*

The output power of required PV array is determined as follows [12]:

$$P_{pv} = \frac{E_{ld}}{\eta_{b.o}\ x\ K_{loss}\ x\ I_s}\ x\ PSI \qquad (3)$$

Where $E_{ld}$= average daily load energy (Wh/day) which is 44.5Wh/day from calculations

$I_s$ = average solar irradiance on the horizontal plane (KWh/m$^2$/day) which is 3.77KWh/m$^2$/day. The bar chart in Figure 1 clearly shows the month with the lowest solar radiation of 3.77KWh/m$^2$/day. This value was chosen for our calculations in this study in order to cover for the worst weather conditions.

PSI = peak solar intensity at the earth's surface (1KW/m$^2$) [12]. $\eta_{b.o}$ = efficiency of balance of system [12].

$= \eta_{inverter\ loss}\ x\ \eta_{wiring\ loss}$

In this design, the inverter loss is not taken into consideration since there are no inverters used. However, the suggested wiring loss for most systems is 2% and connection losses are valued at 0.5% [25]. Hence a generic loss value of 3% is adopted for most PV systems therefore the wiring loss efficiency is valued at 97% [25]. So $\eta_{b.o}$ = 97%.

$$K_{loss} = f_{man}\ x\ f_{temp} x\ f_{dirt} \quad (4)$$

Where $f_{man}$= manufacturer's tolerance given as 97%
$f_{temp}$ = temperature de-rating factor
$f_{dirt}$ = de-rating due to dust. The acceptable de-rating due to dirt is 5%, hence the dirt de-rating efficiency is 95% [12].
$F_{temp}$ is given by Nwabuokei*et al.* [12] as:

$$1 - [\gamma(T_{cell.eff} - T_{stc})] \quad (5)$$

Where γ = power temperature coefficient (°C)
$T_{stc}$= cell temperature at standard test conditions (°C), given as 25°C [12].
$T_{cell.eff}$ = the average daily effective cell temperature (°C) [12]; $= T_{a.day} + 25$
Where $T_{a.day}$ = daytime average ambient temperature (°C)
The daytime average ambient temperature can be seen in table 3.4 to be 25.28°C. Therefore, $T_{cell.eff}$ = 25.28 + 25 = 50.28°C. γ, according to the manufacturer's specifications is 0.48%/°C. Therefore,

$$f_{temp} = 1 - \left\{\frac{0.48}{100}(50.34 - 25)\right\} = 1 - 0.1 = 0.88°C$$

Substituting these values into Equation 3.4, $K_{loss}$ gives 0.81.
Substituting these values in Equation 3.3 gives:

$$P_{pv} = \frac{44.5}{0.97\ x\ 0.81x\ 3.77\ x\ 1000}\ x\ 1000 = 15.02W.$$

In rounding up, a suitable PV module for this solar energy system would be rated at 20W. Therefore only one PV module rated 18V, 20W will suffice for this design. Therefore, the SARODA SP09-05 model polycrystalline module rated 18V, 20W was chosen for this design

### D. Sizing of the Battery Bank Capacity

In designing the capacity for the storage bank, it is pertinent to consider some important factors as this will ensure the availability of power at all times and proper functioning of the batteries. These factors include: the days of autonomy (these are assumed days where there is little or no solar irradiation on cloudy days based on a typical rainy season in Akwa Ibom State), allowable Depth of Discharge (DOD), possible battery loss, nominal system voltage of selected battery and estimated load energy in Watt-hour. The storage capacity can be calculated as follows [12]:

$$C_B = \frac{E_{ld}\ x\ N_a}{DOD\ x\ V_{system}\ x\ \eta_{bat}} \quad (6)$$

Where, $C_B$ = required minimum battery capacity
$N_a$ = number of days of autonomy (3 days)
DOD = depth of discharge (80%)
$E_{ld}$ = average daily load energy in Wh/day (44.5Wh/day)
$V_{system}$ = system voltage (12V)
$\eta_{bat}$= battery efficiency (85%)
In this design, the days of autonomy are taken as 3 days and $V_{system}$is 12V. The battery selected for this work is the 18650 3.7V, 2200mAh cylindrical lithium ion battery. Generally, lithium batteries have a DOD of 80% and energy efficiency ($\eta_{bat}$) of 85%. Hence,

$$C_B = \frac{44.5\ x\ 3}{0.80\ x\ 12\ x\ 0.85} = 16.36Ah$$

$C_B$ gives 16.4Ah. In this work however, 19.8Ah is chosen for ease of battery equalisation and balancing, therefore $C_B$ = 19.8Ah. In order to calculate the number of battery units required for the system, the following equation is used [12]:

$$N_{req} = \frac{C_B}{C_{sel}} \quad (7)$$

Where $C_{sel}$ = 2.2Ah, 3.7V and $C_B$ = 19.8Ah, $N_{req}$ = 9

Therefore, this design needs nine (9) lithium batteries rated at 2.2Ah, 3.7V each. Since the system voltage is 12V, a number of batteries need to be connected in series to achieve this voltage requirement. Hence, the number of batteries to be connected in series is calculated as follows [12]:

$$N_{bs} = \frac{V_{system}}{V_{battery}} \quad (8)$$

$$N_{bs} = \frac{12}{3.7} = 3.24$$

Hence, the number of batteries to be connected in series is three (3). Also, to achieve the required capacity, the number of batteries to be connected in parallel to arrive at the required amperage is calculated as follows [17]:

$$N_{bp} = \frac{N_{req}}{N_{bs}} \quad (9)$$

$$N_{bp} = \frac{9}{3} = 3$$

Hence, the number of batteries to be connected in parallel is 3.The total number of batteries required in the system is calculated as follows [17]:

$$N_{BR} = N_{bs}\ x\ N_{bp} \quad (10)$$

$$N_{BR} = 3\ x\ 3 = 9$$

Hence the battery arrangement is a 3S3P combination.

### E. Sizing of the Solar Charge Controller

The charge controller regulates the flow of electricity from the solar modules to the battery bank [12]. It feeds all the electricity from the PV array to the battery when the battery is low, and stops the supply when the battery is fully charged. This prevents overcharging, which could lead to reduction of the battery life and can even cause explosions.
Charge controllers are generally selected by their size or ability to control a given amount of current and by their operating voltage [12]. The rated maximum current of the charge controller is obtained by multiplying the short circuit current, $I_{SC}$ of the modules connected in parallel by a safety factor, $f_{safety}$ to allow for short periods of high irradiance produced by momentary cloud enhancement and is given by the expression that follows [12]:

$$I_{max} = N_{mp}\ x\ I_{sc}\ x\ f_{safety} \quad (11)$$

Where $F_{safety}$ is considered to be 1.25 for most solar PV systems [17].
$I_{sc}$ for the selected PV module is 1320mA (1.32A) and it has $V_{oc}$of 21.6V. Since there is only one PV module for each stand-alone street light, $N_{mp}$= 1. Hence,
$I_{max}$ = 1 x 1.32 x 1.25 = 1.65 ≈ 2A.
Therefore, a 2A solar charge controller is suitable for this design.

## III. RESULTS

The sizing calculation results are presented in Table 3. The calculations show that the daily load demand of the microcontroller based, stand-alone solar street light is 44.5Wh per day. This load demand will be satisfied by using one (1) unit of PV module rated at 1V, 20W. The system is designed to supply power for at least three days, considering the days of worst weather condition in the case study site. With three days of autonomy, the required battery capacity is 16.36Ah. However, 19.8Ah was selected for this design for ease of battery combination. For the selected battery, 2200mAh, 3.7V 18650 cylindrical lithium-ion battery, a total of 9 units of the battery is required; 3 in series and 3 in parallel. Also, the required capacity of solar charge controller is 2A and one (1) unit will suffice.

Table 3:Results Obtained from Equipment sizing for the microcontroller based, stand-alone solar street light.

| Component | Description of Component | Result |
|---|---|---|
| Load estimate | Daily load requirement per day | 44.5 Wh/day |
| PV array | PV module capacity | 18 V, 20 W |
| | Total number of modules required | 1 |
| Battery bank | Battery bank capacity | 19.8 Ah |
| | Number of batteries in series | 3 |
| | Number of batteries in parallel | 3 |
| | Total number of batteries required | 9 |
| Solar charge controller | Capacity of charge controller | 2 A |
| | Number of charge controller | 1 |

## IV. CONCLUSION

This study evaluated the sizing of a photovoltaic stand-alone system for a microcontroller based stand-alone street light system in Uyo, Akwa Ibom State. The case study site lies between 5.02° latitude and 7.9° longitude. The 22 years annual averages of the daily meteorological data were retrieved from the NASA website. The average solar irradiation for the case study is 4.71kW/m$^2$/day and the least which usually occurs in the month of August is 3.77kW/m$^2$/day was considered for the system design in order for the stand-alone PV system design to keep the battery fully charged in the worst month of the average year.

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