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Sizing a stand-alone solar photovoltaic system for remote homes at Bakassi Peninsula

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ABSTRACT

This study analyzes solar photovoltaic (SPV) module performance for sizing a stand-alone photovoltaic(PV) system for remote homes in Bakassi Peninsula, a tropical evergreen rain forest region along the African Atlantic Gulf of Guinea. The cost of a stand-alone SPV system and installation is calculated to be about ₦404,800.00. The total average ampere hour per day required is 1386Ah/d, the number of batteries required is 2 batteries of 12V- 200Ah each and the number of solar modules required is 8modules of 80W each. A stand-alone solar PV power supply system is established as a reliable and economical source of electricity in rural remote areas; especially in developing countries where the population is dispersed, with low income and lack power supply. The photovoltaic system is environmentally friendly as opposed to conventional sources of energy that cause depletion of vegetation and emit pollutants into the environment impacting it negatively.

Keywords: Photovoltaic modules, sizing, forest region, electricity, batteries, energy

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INTRODUCTION

TheSPV system converts the energy from the sun directly into direct current electricity. For remote locations, stand-alone or off-grid SPV system is used for home lighting with a bank of battery back-up for use in the night. In remote localities and water logged areas, stand-alone SPV systems are often cost-effective when compared to alternatives such as petrol generators and utility line extension [1]. The final cost of the SPV system ultimately depends on the SPV array size, the battery bank size and on the other components required for the specific applications. A stand-alone SPV power supply system is established as a reliable and economical source of electricity in rural remote areas; especially in developing countries where the population is dispersed, with low income and lack power supply due to viability and financial contrariness. Stand-alone SPV power supply systems have been studied [2-5] for other regions. Since the solar energy yield often does not coincide in time with the energy demand from the connected loads, additional storage systems (batteries) are generally used [6]. The amount of time critical loads can operate depends on the amount of power they consume and the energy stored in the battery system. A typical backup battery system may provide about 8kWh of energy storage at an 8hour discharge rate, which means that the battery will operate a 1kW load for 8 hours. A 1kW load is the average usage for a home when not running an air conditioner [7]. TheSPV system typically consists of a SPV array, a battery bank, an inverter and loads. Thepower output of a solar array deviates with weather conditions; the rewarding activity of the SPV system is therefore to find out the optimal size of a solar array and battery to meet load demand [8,9]. With rising fuel cost, concern for climate change and need to find alternative energy solutions, solar PV technology is seen as a solution toenergy supply in remote water-logged areas [10] like Bakassi Peninsula [11], Fig. 1.

Fig. 1: Areal View of Bakassi Peninsula, Gulf of Guinea

Bakassi Peninsula is along the African Atlantic Gulf of Guinea. It lies between the Cross River estuary, near the city of Calabar on the west and the Rio de Rey estuary on the east and is roughly between latitudes 4°25' and 5°10'N and longitudes 8°20' and 9°08'E [11]. It consists of a number of low-lying, largely mangrove covered islands covering an area of about 665 km² [11]. The population of Bakassi Peninsula is generally put at between 150,000 and 300,000 people. A typical home has two rooms and a parlour with an average household of about seven persons. Secondly, Bakassi Peninsula is situated at the extreme eastern end of the Gulf of Guinea, where the warm east-flowing Guinea Current (called *AyaEfiat* in Efik) meets the cold north-flowing Benguela Current (called *AyaUbenekang* in Efik). These two great ocean currents interact creating huge foamy breakers which constantly advance towards the shore and building submarine shoals very rich in fish, shrimps and wonderfully amazing variety of other marine life forms. This makes the Bakassi area a very fertile fishing ground, comparable only to Newfoundland in North America and Scandinavia in Western Europe [11]. Most of the population makes their living through fishing. The dispersed residents of this remote area use petrol generators for electricity but there is no petrol station in the Peninsula, so they transport petrol using boats from Oron and Ikang in Nigeria at high cost and risk; there is therefore a compelling need for cheaper, available and environmental friendly source of alternative energy solutions. The objective of this study is to size a stand-alone SPV system for the dispersed remote residential homes of local fishermen at Bakassi Peninsula. In this study, the first objective was to calculate the total wattage of all the electrical appliances to be used, the total average ampere hour per day required, the number of batteries of 12V-200Ah each, the number of solar photovoltaic modules (SPVMs) of 80W each, the cost of SPV system and installation, the optical tilt angle, the incident solar radiation on theSPVMs and finally results obtained were discussed.

MATERIALS AND METHODS

This study was carried out focusing on sizing aSPV system so that the number of PV modules, capacity of storage battery, capacity of inverter and PV array tilt angle were optimally selected as already stated by other scholars [12-15]. The following materials were used for this study: 80W photovoltaic modules, 12V-10Acharge controller, 12V-200Ah solar batteries, 1000VADC/AC inverter, solarimeter, multimeter, 2.5mm connecting copper wires and other accessories [8, 16], theset up was as shown in Fig. 2.

For the practical purpose of designing a solar PV system, the solar irradiation at the optimal tilt angle in July was estimated using a linear approximation to calculate the optimal tilt angle [17-20]:

$$\beta_{opt} = 3.7 + 0.69|\emptyset| \quad (1)$$

where$\beta_{opt}$is the optimal tilt angle (deg) and $\emptyset$ is the latitude of the site (deg);

$$\emptyset = 23.45 \sin\left(300 \frac{284 + d_n}{365}\right) \quad (2)$$

A polynomial approximation for the solar irradiation at the optimal tilt angle is given as:

$$G(\beta_{opt}) = \frac{G(0)}{1 - 4.46 \times 10^{-4} \times \beta_{opt} - 1.19 \times 10^{-4} \times \beta_{opt}^2} \quad (3)$$

where$G(\beta_{opt})$ is the solar irradiation on a surface at the optimal tilt angle (Whm^{-2}), $G(0)$is the solar irradiation on the horizontal plane (Whm^{-2}) and

βopt is the optimal tilt angle (deg).
After calculating the optical tilt angle and the solar irradiation at the optimal tilt angle, five general accepted steps were taking into consideration in sizing the stand-alone SPV system for remote homes in Bakassi Peninsula. The five steps (a-e) are viz: Determination of power consumption demands, Optimization of power system demands, Sizing the battery bank, Determination of the sun hours available per day and Sizing the PV array [21].

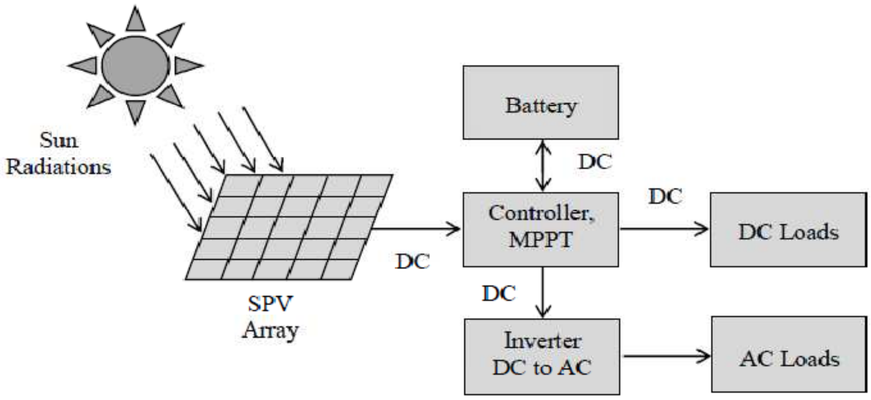

Fig. 2: Stand-alone SPV Power Supply System

a. Determination of Power Consumption Demands

In determining the power consumption demands [21], a list of the appliances/loads to be run from the SPV system was made for a typical house of about three rooms. The power each device consumes while operating for about 6hours (from 4:00pm to 10:00pm) was found out by using the labels at the back and specification sheets which list the wattage, as shown in Table 1.

Table 1: Estimated Ratings of Appliances and Costs

Appliance	Quantity	Power (W)	Hours per week (hr/wk)	Watt-hours per week (Wh/wk)	Cost (₦)
21″Colour Flat screen TV	1	75	6 x 7=42	75 x 42=3150	42,000.00
CD Player	1	35	42	1470	6,000.00
Satellite Dish	1	30	42	1260	15,000.00
Table Fan	2	12.5	42	1050	12,000.00
Lights – 20W Fluorescent	3	22 x 3=66	42	2772	3 x 1000.00 = 3,000.00
Total		**231**		**9702**	**78,000.00**

The following calculations were carried out:

-Direct current (DC) watt hours per week: Wh/wk x Correction for inverter losses = $\frac{Wh}{wk} x\ 1.2$

-Inverter DC input voltage: 12 or 24 volts.

-Total amp hours per week used by alternating current (AC) loads

$= \frac{Correction of inverter losses}{Inverter DC input voltage}\ (in\ Ah/wk)$

- Total average amp hours per day = $\frac{(Ah/wk)}{7 days}\ (in\ Ah/d)$

b. Optimization of Power System Demands

The optimization of power system demands [21] was carried out as follows:

- Examination of power consumption and reduction of power needs as much as possible, (the cost savings can be substantial).
- Identification of large loads such as outdoor lights.
- Replacement of incandescent fixtures with fluorescent lights wherever possible. (Fluorescent lamps provide the same level of illumination at lower wattage levels).
- Being creative and innovative in solar PV system sizing.
- Revising the Load Sizing Worksheet with optimized results for amendments.

c. Sizing the Battery Bank

The battery bank was sized by determining how much storage the battery bank should provide [21] as follows:

- Choose days of autonomy (DOA) i.e. the number of days the system is expected to provide power without receiving an input charge from the solar array.
- Daily amp-hour requirement: 1386Ah/d
- Number of days of autonomy: 1day of consecutive cloudy weather expected in the area.
- Amount of amp-hours needed for storage = $Dailyamp/hourrequirement$ $xnumberofdays\ (in\ Ah)$

- Depth of discharge (DOD) for the battery: Discharge limit is 20%
- Amp-hours of storage needed /depth of discharge limit = $\frac{Ah}{0.2}\ (in\ Ah)$
- Ambient Temperature Multiplier for wintertime: 80^{o}F, 26.7^{o}C is 1.00
- Capacity to overcome cold weather effects = $\frac{Ah}{0.2} xAmbienttemperaturemultiplier.$
- Number of batteries connected in parallel =$\frac{Total\ battery\ capacity}{Battery\ amp-hour}$
- Number of batteries connected in series = $\frac{Nominalsystemvoltage\ (12V or\ 24V)}{Batteryvoltage}$
- Number of batteries required = $\frac{Numberofbatteriesinparallel}{Numberofbatteriesinseries}$

d. Determination of the Sun Hours Available per Day

The sun hours available per day show how much sun power the modules are exposed to [21], this depends on the following:

- Location and angle of SPV array: Solar arrays power generation capacity is dependent on the angle of the rays as they hit the modules and insolation.
- Peak power occurs when the rays are at right angles or perpendicular to the modules.
- Depending on the application, sun tracking mounts can be used to enhance the power output by automatically positioning the array.
- The average daily hours of sunshine for an array at latitude tilt is about 5hours for the tropical rain forest region of Bakassi, Cameroon and Nigeria.

e. Sizing the Array

The PV array was sized by considering the following [21]:

- Compensation for losses from battery charge/discharge
 $= Totalaverageamp/hoursperdayx\ 1.2$
- Total solar array amps required = $\frac{(Compensationforlossesfrombatterycharge/discharge)}{Averagesunhoursperdayinthearea}$
- Total number of solar modules in parallel required = $\frac{Totalsolararrayampsrequired}{Optimumorpeakampsofsolarmoduleused}$ (i.e.)
$\frac{Module's\ wattage}{Peakpowerpointvoltage,usually\ 17.5V}$
- Number of modules needed to provide DC battery voltage:

Total number of solar modules required = $\frac{Totalnumberofsolarmodulesinparallelrequired}{Numberofmodulesineachseriesstring}$

Mismatch Power Loss:

$$P_{\max\ (mismatch\ loses)} = \left(P_{\max\ (module\ 1)} + P_{\max\ (module\ 2)}\right) - P_{\max\ (array)}$$

Utilization Factor: $UF_{(array)} = \frac{P_{\max\,(array)}}{P_{max\,(module\,1)} + P_{\max\,(module\,2)}}$

i.e. loss of power due to series and parallel connections

RESULTS AND DISCUSSION

The prices of the components of the SPV system were obtained from the local markets close to Bakassi Peninsula. The cost of materials and transporting by boat to the mangroves was calculated as shown in Table 2.

Table 2: Cost of SPV System and Installation at Bakassi

Material	Quantity	Cost (₦)
Solar Battery (200Ah-12V)	2	2x45,000.00 = 90,000.00
SPV Module (80W) (Polycrystalline)	8	8x25,000.00 = 200,000.00
Charge Controller (20A-12V)	1	15,000.00
DC/AC Inverter (1000VA)	1	35,000.00
Accessories (meter, cables, …)		10,000.00
Transportation		18,000.00
Installation Cost (10% of Total Cost)		10% of 368,000.00 = 36,800.00
Total		**404,800.00**

Table 2 shows the basic materials required for a stand-alone SPV system, the quantities, transportation and the total cost of about ₦404,800.00 which is affordable for an average fisherman in the creeks per year but realizable over months. However, the drawback ofSPV system is the initial high capital cost compared to conventional energy sources [12], government assistance is therefore required to offset the initial high capital cost for the low income dwellers of the Peninsula.In this study, the SPV modules used, SOL MODEL: SPA80 had the following parameters based on Standard Test Conditions (STC): an irradiance of 1,000 Wm^{-2}, the standard reference spectral irradiance with Air Mass 1.5 and a cell temperature of 25ºC; the parameters are given in Table 3.

Table 3: SPV Module Parameters

Parameter	Quantity/Unit
Peak Power, P_{max}	80.08W
Voltage, V_{mp}	17.96V
Current, I_{mp}	4.46A
Open Circuit Voltage, V_{oc}	22.915V
Short Circuit Current, I_{sc}	5.01A
Maximum Series Fuse	8A
Tolerance	±5%

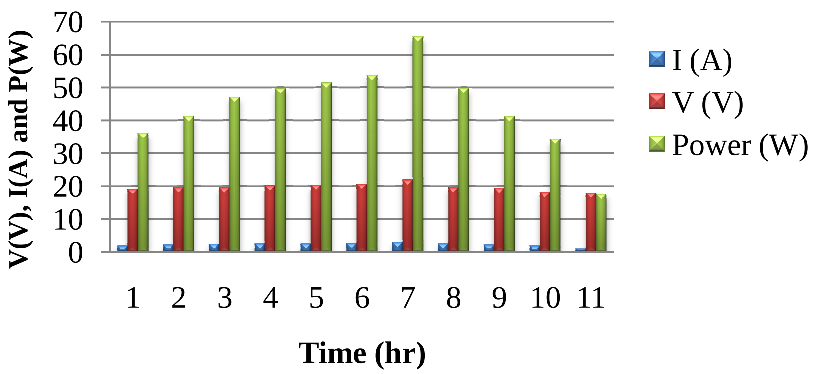

Fig. 3: Power Output from 80W SPVM per day

The values of the parameters in Table 3 are based on standard laboratory test conditions which are not applicable in field locations such as Bakassi Peninsula especially during the raining season months of July, August and September. Thus, the power output from an 80W SPV module is below the maximum quoted due to the weather conditions of the tropical rain forest region in the month of July. The results V(V), I(A) and P(W) output are shown in Fig. 3.

From Fig. 3, the power output from the 80W SPVM per day increased from about 37W at 8:00am to a maximum of about 66W at 2:00pm and then decreased to about 19W at 6:00pm; it was a sunny day.For this experimental day, the averageinstantaneous power output per module of about 41W is a fair approximation for the month of July but not an accurate representation of the month.In this study, two solar PV modules (SPVM) of 80W each were tested outdoor in series and parallel connections under tropical evergreen rain forest environment in July; the result is shown inTable 4. The readings were taken on hourly basis from 8:00am (1hr) to 6:00pm (11hrs) local time.

Table 4: Power Output from two 80W SPVM Connected in Series and Parallel

Time (hrs)	Power Output in Series Connection (W)	Power Output in Parallel Connection (W)	Solar Radiation (Wm^{-2})	Ambient Temperature (°C)	Weather Conditions
1	39.94	56.55	98.08	26	Clear
2	49.88	75.17	228.24	27	Sunny
3	87.31	100.48	344.96	28	Sunny
4	92.12	108.03	397.48	28.5	Sunny
5	93.96	121.3	465.74	29	Sunny
6	115.6	129.3	476.89	30	Sunny
7	122.52	150	564.09	30.5	Sunny
8	96.74	123.03	429.98	29	Sunny
9	69.94	108.45	385.76	28	Sunny
10	62.72	82.86	187.85	27	Sunny
11	48.39	60.01	68.09	26	Dull
Total	**879.12**	**1,115.18**			

From Table 4, the solar radiation for the day varied from about 98.08Wm^{-2} at 8:00am in the morning to about 564.09Wm^{-2} at 2:00pm in the afternoon and then to about 68.09Wm^{-2} at 6:00pm in the evening. The ambient temperature increased from 26.0°C at 8:00am to a maximum of 30.5°C at 2:00pm and then decreased to about 26.0°C at 6:00pm. Table 4 also shows the results of two SPV modules power output connected in series and parallel for the experimental day in the month of July. The month of July was chosen because in the mangroves of the Bakassi Peninsula, the months of July, August and September more often experience the heaviest cloud cover in the year due to heavy and continuous rainfall. The total hourly SPV power output for the parallel connection (i.e. ₦1,115.18W) was higher than for the series connection (i.e. ₦879.12W) for the experimental day in July because there is more voltage gain in parallel connection and more current gain in series connection [22].So generally, SPV modules connected in parallel give greater power output than those connected in series, although a good combination of parallel and series connection is required for the best and desired output.The summary of vital results for the sizing of a stand-alone solar PV system for remote homes at Bakassi Peninsula is shown in Table 5.

Table 5 gives a quick review of the major calculations and measurements carried out in the study. This summary of SPV system results for remote homes gives a quick view of what it takes to install SPVM and the expected power output at Bakassi Peninsula. Generally, 1kW load is the average usage of 8hrs for a home when not running an air conditioner [6], therefore a typical backup battery system should provide about 8kWh of energy storage at an 8hour discharge rate, which means that the battery will operate a 1kW load for 8 hours. The power output from two 80W SPVM in series and parallel connections is shown in Fig. 4.

Table 5: Summary of SPV System Results for Remote Homes at Bakassi

S/N	Item	Quantity/Unit
1	Costs of Appliances	₦ 78,000.00
2	Watt-hours per week	9702 (Wh/wk)
3	Cost of SPV System and Installation	₦ 404,800.00
4	Hourly Power Output in Series Connection	879.12 W
5	Hourly Power Output in Parallel Connection	1,115.18 W
6	Total average amp hours per day	1386 Ah/d
7	Number of 200Ah-12V batteries required	2 batteries
8	Average daily hour of sunshine	5 hours
9	Number of 80W SPV modules required	8 modules
10	Mismatch power loss	183.26W
11	Utilization factor	0.436
12	$P_{max\ (module)}$	81.07W
13	Latitude of the site, ϕ	14.11°
14	Optical tilt angle, β_{opt}	13.43°
15	Solar irradiation at horizontal plane, $G(0)$	331.56kWm^{-2}
16	Solar irradiation at optical tilt angle, $G(\beta_{opt})$	340.88kWm^{-2}

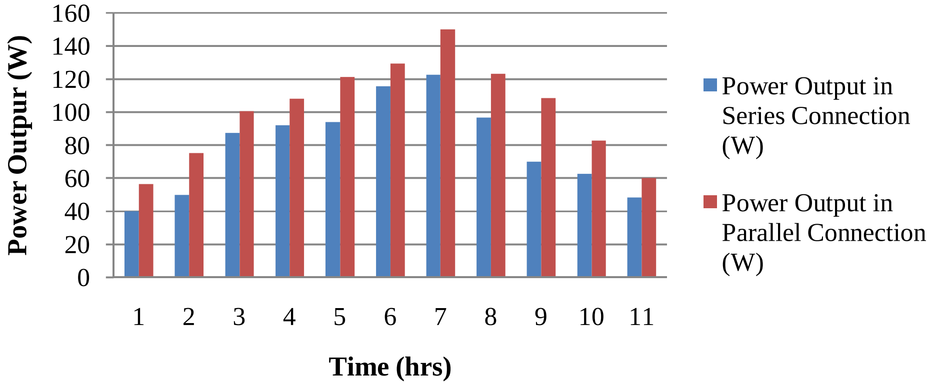

Fig. 4: Power Output from two 80W SPVM Connected in Series and Parallel

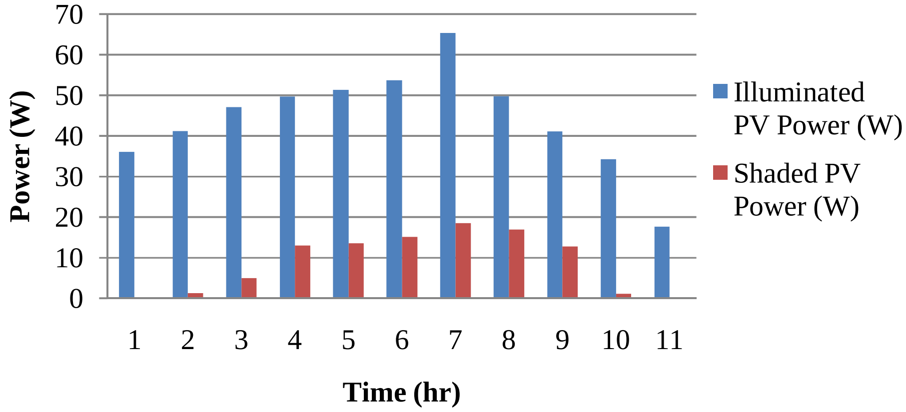

Fig. 5: Power Output from Illuminated and 70%Shaded 80W SPVM

From Fig. 4, the maximum power output for series and parallel connections for two SPVMs occurred at 2:00pm which were about 122W and 150W respectively. The maximum power output of the total SPV array is always less than the sum of the maximum power output of the individual modules [22]. This difference is as a result of slight inconsistencies in performance from one module to the next and is called module mismatch and amounts to at least 2% loss in system power [7]. In the tropical rain forest region, there are always tall evergreen trees that often cast shadows of their leaves on the SPVMs causing partial or total shading [22-24]. The result of 70% shading of one SPVM was compared with that of one SPVM fully illuminated as presented in Fig. 5.

Fig. 5 shows a significant difference in power output from the illuminated and the 70% shaded SPVM, which at maximum power output were about 65W and 18W respectively. The power output decreases with increasing shading of the solar cells andsolar panels could be damaged by shading due to heat buildup [22]. Solar panels in parallel are less affected by shading as compared withsolar panels in series connection. Shading of SPVM is never a good idea and couldlead to damaged panels before their natural lifetime which could bein decades. Mounting SPVMs away from natural obstacles like trees or man-made obstacleslike chimneys and taller buildings should be a must for proper and efficient operation.Generally, sizing a stand-alone SPV system as discussed [25, 26] is essential in order to optimize SPV, the battery bank, the charge controller, the inverter and the optical tilt of the PV modules especially at the remote water-logged tropical rain forest region of Bakassi Peninsula in the Gulf of Guinea.

CONCLUSION

The sizing of a stand-alone SPV power supply system as a reliable and economical source of electricity in tropical rural remote rain forest region of Bakassi Peninsula weather conditionshas been studied.A stand-alone solar PV power supply system is established as suitable for developing countries where the population is dispersed with low income and lack power supply especially water-logged remote forest region of Bakassi Peninsula. The photovoltaic system is environmentally friendly as opposed to conventional sources of energy such as petrol generator used by fishermen at Bakassithat causes global warming, depletion of vegetation and emit pollutants into the environment impacting it negatively.

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