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Optimal Sizing of a Stand-Alone Photovoltaic Power Plant and Cost Comparison with Grid and Diesel Generator for a Remote Farm

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ABSTRACT

Electric power from the grid is inadequate and unreliable in Nigeria, thus making it mandatory for operators of remote farming settlements to rely on private power generation equipment and usually in the form of a diesel engine generator. Concern for environmental pollution coupled with falling trends in the price of solar photovoltaic module, a major component in the standalone solar photovoltaic power plant, has considerably lowered the overall cost for the standalone solar power plant to the level of cost of power generation which is at parity with Power Holding Company of Nigeria (PHCN) private residential tariff and lower than the cost of power generation using diesel engine generator. A balancing parameter M, which characterizes the relative size of the battery storage in relation to the Photovoltaic power is defined and optimized for a minimum cost of power generation subject to an acceptable level of loss of load probability.

Key Words: *Stand-Alone PV Power Plant; Cost Of Electricity; Diesel Engine Generator, Grid Supply; Optimal Sizing Of SAP; Loss Of Load Probability*

1. INTRODUCTION

It is common knowledge that the nonrenewable sources of energy such as oil, coal, gas and uranium are being depleted. As a result, the renewable sources of energy such as hydro, wind, biomass, geothermal, oceanic and photovoltaic have become increasingly more important [1]. Energy experts believe that renewable energy sources can meet the energy need of every man on earth so many times over. Dominant among the renewable energies is solar energy. There are two forms of solar radiation conversion which result in useable energy. The two forms are thermal and photovoltaic; thermal solar application which has been in use much longer is mainly for heating of water and drying of agricultural produce. The other conversion process-photovoltaic, involves the generation of electricity in the form of direct current which occurs whenever the PN junction of a semiconductor material is exposed to solar radiation. A single solar cell is incapable of generating an appreciable power because the current is no more than a few amps while the voltage is no more than 0.6V hence the cells usually come in modules consisting of between 33 to 36 series connected cells for a module of 12V nominal voltage. Two or more modules may then be connected in series to form a string of the desired voltage and several strings may be connected in parallel to obtain the desired current. Fig. 1 shows a schematic of the major components of a typical stand-alone solar photovoltaic power plant

2. INSOLATION AND SITING

To properly locate a suitable site for a fixed solar array facing due south with a tilt angle of 20^0 (this is approximately the latitude angle of 10.5°N for Kaduna plus 10° to prevent accumulation of solid materials collecting on the modules so that water falling on it could potentially sweep off the dirt which could otherwise degrade the module output through partial shading). An open area will generally be required for the array. An area can be considered open if the angular of elevation of neighboring trees, tall buildings, etc within an azimuth angle $\pm$60°due south (for those in the northern hemisphere or 60°due North (for those in the southern hemisphere) satisfy the relationship in equation (1)[3].

$$e \leq 56^O - \gamma \qquad \dots (1)$$

Where e = elevation angle above the horizon,

γ= latitude angle for the PV installation site (10.5°for Kaduna).

Thus for the latitude location of the farm, e must be less than 45.5^0 as per the requirement of equation (1). The measured angular elevation of the tallest nearby tree is 32^0 which is less than elevation that could possibly cast a shadow on the solar array. Next, we compute the area required by the solar PV modules. Due to the differences in the apparent position of the sun with respect to different locations on earth and also due to atmospheric constituents such as cloud cover, gas particles etc., there is a corresponding clearness index $K_H$for each location (defined by its latitude and longitude).The clearness index is defined as the ratio of solar radiation on a horizontal surface to the extraterrestrial radiation. It varies from one location to the other and also varies with time in any given location. The extraterrestrial solar radiation is more or less constant for all locations on the earth with a value of 1370W/m^2.Average clearness index for each month for some selected Nigerian towns can be found in Table1. For locations not covered in the table, it is possible to obtain their clearness indices by adopting the clearness index of a nearby location (latitude) that has a similar whether condition [3]. Using the computed value of the clearness index, the average daily insolation along with the standard deviation is obtained from Table 2 [3], and for the purpose of estimating the required cleared area for the solar farm, the minimum average monthly daily insolation value is used for the purpose of cleared area requirement. The required cleared area is given in equation (2) as follows:

$$A = \frac{L\left[\cos(\alpha) + \frac{\sin(\alpha)}{\tan(66.5-\beta)}\right]}{\eta I} \quad \dots (2)$$

Where A is the required area for the solar array in m^2, L is the daily energy demand in Watt-hours, α is the solar array tilt angle in degrees, β is the latitude angle of the location in degrees but in some cases the tilt angle could be set higher than the latitude angle in a situation where the need could arise to get rid of dust or debris that could otherwise reduce the PV power output via shading. $\eta_{abi}$is a composite cascade conversion efficiency of the solar array, battery and inverter as expressed in equation (3).

$$\eta_{abi} = \eta_a \eta_b \eta_i \quad \dots (3)$$

Whereη_a= array efficiency

η_b= battery efficiency

η_i = inverter efficiency

The composite efficiency may be assumed to be 0.9[2].‘I’ is the monthly average daily insolation in kWh/m^2 per day. To estimate the required solar array area for the installation site in Kaduna, the month with the worst clearness index is selected. From Table1, the least clearness index occurs in August with a value of 0.449.Tables 2 and 3 [1] show the average monthly daily insolation and the corresponding average standard deviation (σ) for clearness indices of 0.3 and 0.5 respectively. Since the clearness index of the chosen location ranges between 0.3 and 0.5, then the average monthly daily insolation for the location is obtainable by a linear interpolation as given by equation (4) and thus the estimated average daily insolation is obtained to be 4.650 kWh/m^2 and substituting this value of ‘I’ in equation (2) the required area is determined to be A= 17.50 m^2. Thus, this should give a rough estimate of the required area to be cleared for the installation. The load requirement for the orchard unit of the farm consists of a 2 horse power pump which is run for 4 hours daily, 4 x 50Wceiling fans and 6 x 20W energy saving tubes. While the poultry unit consists of 12 x 20W light bulbs powered for 12 hours every day .The load curve for combined load of the farm is as presented in Fig. 2.

$$K_{HM} = M_1 + \frac{L_M - L_{M1}}{L_M + L_{M1}} \quad \dots (4)$$

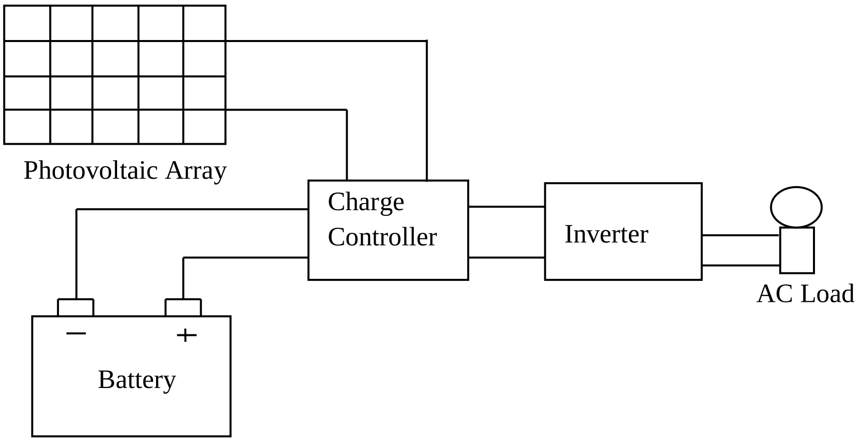

Figure 1: Block Diagram of a Stand-alone Solar Photovoltaic Power Plant

Table 1: Clearness indices for various locations in Nigeria (Each value must be divided by 1000)

Station	Latitude	Longitude	Elevation	January	February	March	April	May	June	July	August	September	October	November	December
Minna	9.5oN	6.5oE	260	585	577	562	571	569	478	411	407	492	563	644	627
Kaduna	10.5oN	7.5oE	646	627	628	596	579	560	546	488	449	500	562	635	644
Enugu	6.5oN	7.5oE	137	501	508	462	494	496	567	400	378	419	453	516	518
Kano	12.0oN	8.5oE	476	628	613	589	589	578	573	561	514	570	618	624	622
Sokoto	13.5oN	5.3oE	252	651	632	603	600	575	602	526	513	571	623	642	642
Jos	10.0oN	9.0oE	1286	639	630	581	558	531	530	482	463	499	568	648	655
Port-Harcout	5.0oN	7.0oE	20	452	452	437	440	422	386	347	359	362	390	420	485

Table 2: Average Monthly Daily Insolation and Corresponding Standard Deviation for August at $K_H = 0.3$

	Tilt = Latitude			Latitude = Latitude + 10°		
Latitude	0°	15°	30°	0°	15°	30°
Mean I	2.923	3.039	2.949	2.838	2.899	2.770
σ	0.492	0.480	0.492	0.474	0.468	0.485

Table 3: Average Monthly Daily Insolation and Corresponding Standard Deviation for August at $K_H = 0.5$

	Tilt = Latitude			Latitude = Latitude + 10°		
Latitude	0°	15°	30°	0°	15°	30°
Mean I	4.865	4.987	4.887	4.632	4.705	4.561
σ	0.312	0.302	0.312	0.299	0.294	0.307

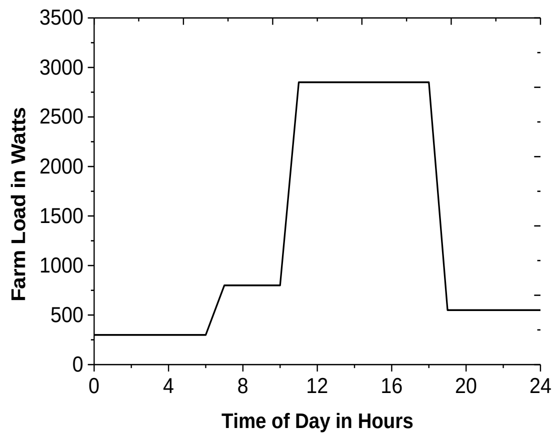

Figure 2: Daily Load Curve of the

The farm's daily energy demand (E_d) is the area under the load curve or may be calculated using equation (5).

$$E_d = \sum_{i=1}^{4} p_i * H_i \qquad \ldots (5)$$

Where $p_i = i^{th}$ load

$H_i = i^{th}$ load duration in hours

The daily energy need of the farm is computed to be 10,940Wh/day; while the peak power on the system is 2850W. Design of the power rating of the inverter is possible by adding a margin factor of 1.25 on the peak demand of the load curve [4].Consequently, a 3.5 kVA, (48V/220V) single phase Sukam inverter is considered appropriate for the application. Design of the other power handling components of the stand-alone PV power plant is not yet possible since an optimal configuration of the PV power generation and energy storage components yet to be determined and will therefore be explored in the next section.

3. OPTIMAL DESIGN OF THE PV POWER PLANT

A major problem with the design of stand-alone power plant (SAP) is to assume the manufacturer's rating for the modules, which is usually based on Standard Test Condition (STC). Furthermore, the choice of an arbitrary number of days of autonomy could often result in an overly expensive installation and grossly underutilized power generation or storage component in the SAP [3]. When power storage is too large, the battery may most of the time be undercharged leading to 'sulfation' and truncated battery life. On the other hand an oversized power generation will result in an underutilized PV and a tendency for damage to storage due to overcharging. An optimal design of the SAP therefore entails the sizing of the generation in relation to the storage which will guarantee the supply of power to the load up to an acceptable probability of loss of power (PLOP) given the average monthly daily solar insolation and a standard deviation representing the stochastic nature of the solar insolation. This is the main thrust of this paper. PLOP may be defined as in equation (6).

$$\mathrm{PLOP} = \frac{\text{Period for Demand not Supplied}}{\text{Total Demand Period}} \qquad \dots (6)$$

An acceptable PLOP, and upon which the design in this work is based is 1% i.e. the probability that the load is not served for 3 days and 16 hours in a year.
By interpolation the average monthly daily insolation and the corresponding standard deviation are 4.55kWh/m^{2}and 0.698 kWh/m^2, respectively.
A dimensionless design parameter M is defined as:

$$\mathrm{M} = (\mathrm{I} - \mathrm{E_d})/\sigma \qquad \dots (7)$$

Where 'I' is the monthly average daily insolation, $E_d$is the daily energy and σ is the standard deviation of the insolation. The formula for the PV array area which accounts for the month's variation as embedded in the standard deviation is given by equation (8) as follows [4]:

$$\mathrm{A} = \frac{\mathrm{E_d}}{[\eta_{abi}(\mathrm{I} - \mathrm{M}\sigma)]} \qquad \dots (8)$$

Another dimensionless ratio is defined by equation (9) as:

$$\mathrm{R} = \sigma/\mathrm{I} \qquad \dots (9)$$

Substituting equation (9) into equation (8) results in equation (10) as follows:

$$\mathrm{A} = \frac{\mathrm{E_d}}{\eta_{abi}\,\mathrm{I}(1 - \mathrm{MR})} \qquad \dots (10)$$

NASA [3] published a set of design curves which help provide the storage size of the SAP in terms of the number of days of autonomy as a function of M as defined in equation (7) and R as input parameter. It can be seen from Fig. 3 that the curve of R=1 will require the most storage even for modest values of M >0.5; and for each R curve, the storage requirement C generally reduces with increasing M. The general shape of the curves which is exponential decay suggests an equation of the form given by equation (11):

$$\mathrm{C} = \frac{\mathrm{C_1}}{\mathrm{M}} + \mathrm{C_2} \qquad \dots (11)$$

Where $C_1$and $C_2$are functions of R. The R value for the design location σ/I or 0.153corresponding to R =0.1 and R =0.3 where fed into Origin Lab for curve fitting and it returned the following equations for R = 0.1 and 0.3 respectively:

$$\mathrm{C} = \frac{0.7}{\mathrm{M}} - 0.93 \qquad \dots (12)$$

$$\mathrm{C} = \frac{1.17}{\mathrm{M}} - 0.67 \qquad \dots (13)$$

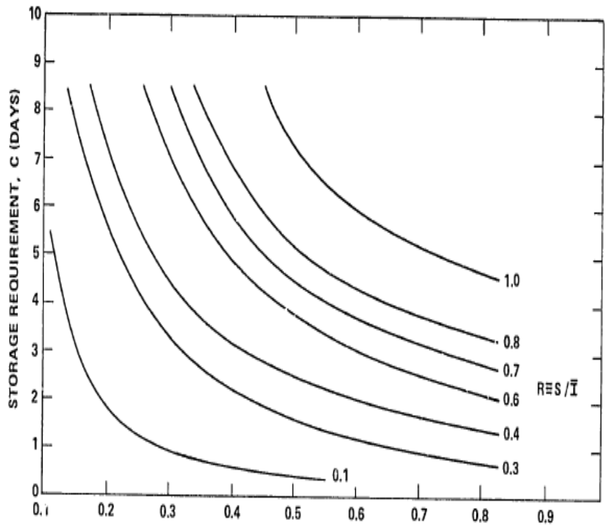

Figure 3: Curves for Days of Storage versus M with R Parameters

For any intermediate value of R, such as the R= 0.153 for the location in this work the parameters C_1 and C_2 , the parameters of the equation representing the storage C can be obtained by a linear interpolation as the type shown in equation (4). Hence for the site location, we use equation (14) as:

$$\mathrm{C_1(R)} = 2.41\mathrm{R} + 0.47 \qquad \dots (14)$$

From which we obtain equation (15) as:

$$\mathrm{C_2(R)} = 1.4 - 1.08 \qquad \dots (15)$$

Now to obtain the expression for the cost of PV generation, the expression for the PV array area (A) in equation (8) is multiplied by the unit cost of PV (AC/m^2).Similarly to obtain the cost of storage, the expression for C in equation (11) is multiplied with unit cost of battery storage (BC/kWh). The major cost of the SAP (C_{major}) is the sum of PV generation and storage component costs as expressed in equation (16).

$$\mathrm{C_{major}} = \frac{(\mathrm{AC})\mathrm{E_d}}{\eta_{abi}\,\mathrm{I}(1 - \mathrm{MR})} + \mathrm{BC}\,[\mathrm{C_1}/\mathrm{M} + \mathrm{C_2}]\mathrm{E_d} \qquad \dots (16)$$

Assuming I and E_d are constant, the problem is to minimize the expression for C_{major}; and this is done by differentiating equation (16) with respect to M and setting the numerator of the result to zero as expressed in equation (17).

$$E_d \left[\frac{(AC)R}{\eta_{abi}\, I(1-MR)^2} - \frac{(BC)C_1}{M^2}\right] = 0 \qquad \ldots (17)$$

Further simplification of equation (17) leads to equations (18) and (19) as follows:

$$\frac{(AC)RM^2-(BC)C_1\eta_{abi}I(1-MR)^2}{\eta_{abi}IM^2(1-MR)^2} = 0 \qquad \ldots (18)$$

$$(AC)RM^2 - (BC)C_1\eta_{abi}I(1-MR)^2 = 0 \qquad \ldots (19)$$

Equation (19) is a second order equation with respect to M and the optimal M value (M_{opt}) in equation (20)is the root of the equation.

$$M_{opt} = \frac{-b+(a^2+4bC)^{1/2}}{2C} \qquad \ldots (20)$$

Where $a = (AC)R - BC * C_1\eta_{abi}IR^2$

$b = 2(BC)C_1\eta_{abi}IR$

$c = BC * C_1\eta_{abi}IR$

Substituting for I and R for the location, we obtain M_{opt}= 0.38 and using equations (12), (14) and (15), the optimum storage in number of days is 0.87days corresponding to 0.87*E_d or 9.51 kWh. Substituting $M_{opt}$and the known values of I and R in equation (10), the optimum PV area is obtained as 23.4 m^2.

3.1 Modeling of PV Power when Powering a Nonlinear Load

The model used in evaluating the power available from a PV array generally assumes a linear load (i.e. a load which obeys ohm's law), but where a nonlinear load is involved such as a stand-alone solar powered power plant which contains storage batteries, assuming a linear load for such a standalone PV power plant could lead to an over optimistic design, i.e. the PV cannot deliver as much power to the load as it could have driven into a linear load. A simple experimental setup can easily be used to model the PV array when charging a battery and obtain its I-V characteristic. The modeling should include reading of solar irradiance but without taking temperature into account. To obtain the I-V characteristic for each irradiance level, the duty cycle of the converter pulse width modulation is varied from 0 - 100% and the Origin software is then used for curve fitting on the obtained I-V data.

4. COST ESTIMATE OF THE STAND-ALONE POWER PLANT, DISEL GENERATOR AND GRID SUPPLY

The required array area can be covered using 24 pieces of 130W modules each with an area of 1.005m2. The array structure consists of 6 parallel strings with each string containing 4 series connected modules to give an PV array with an output voltage of 48 V. The total cost of the 24 PV modules at twenty five thousand naira (₦25,000.00) per module is six hundred thousand naira (₦600,000.00). The expected life of these modules is 25 years [5].

The cost of the PV array support structure is considered to be 12% of the total cost of modules [4], which turns out to be seventy two thousand naira (₦72,000.00). The support structure also has an expected life of 25 years [5]. The current rating of the required charge controller is 1.1x maximum current in a string and therefore a 60 Amps, 48 V Charge controller, is considered adequate and its cost is eighty two thousand naira ((₦82,000.00). The cost of the required 3.5 kVA, 48 V inverter is two hundred and thirty thousand naira ((₦230,000.00) and has an expected life of 10 years. The cost for a maximum power point tracking controller is sixty thousand naira ((₦60,000.00) and also has an expected life of 10 years. Finally, the cost of 9.51 kWh battery storage at twenty thousand eight hundred naira per kWh ((₦20,800.00/kWh) is one hundred and ninety eight thousand naira (₦198,000.00). Typical solar batteries are known to have an expected life of 5 years.

The PV cost of electricity (COE_{PV}) is the present worth of the capital and maintenance costs of generating electricity over the entire useful life of the plant as expressed in equation (21)

$$COE_{PV} = \frac{\text{Total Capital Cost+Maintenance Cost}}{\text{Total Energy Generation over the Useful Life}} \qquad \ldots (21)$$

Annual maintenance cost of the power plant is assumed to be 2% of the capital cost. It is important to note that the cost of items that have truncated life, e.g. batteries which have an expected life of 5 years, may have to be replaced 5 times

Hence the capital life cost is computed to be two million three hundred and eighty seven thousand naira (₦2,387,000.00) and total operation and maintenance cost is found to be one million one

Annual maintenance cost of the power plant is assumed to be 2% of the capital cost. It is important to note that the cost of items that have truncated life, e.g. batteries which have an expected life of 5 years, may have to be replaced 5 times over the plant's lifespan. Similarly a charge controller may be replaced 2.5 times during the useful life of the plant, etc.

Thus, the total life capital cost of the PV plant is $\sum_{i=1}^{n} C_i R_i$

Where C_i= cost of i^{th} component in the SAP

R_i= number of replacement of the i^{th} component

Hence the capital life cost is computed to be two million three hundred and eighty seven thousand naira (₦2,387,000.00) and total operation and maintenance cost is found to be one million one hundred and ninety three thousand five hundred naira (₦1,193,500.00).Thus the total cost of capital, operation and maintenance stands at three million five hundred and eighty thousand five hundred naira (₦3,580,500.00). The total energy generated over the entire life assuming a PLOP of 1% is E_d *0.99*8750 *25 or 2.369 GWh. Hence, the cost of PV generated electricity (COE_{PV}) as per equation (21) is one naira fifty kobo per kWh ₦1.5/kWh).

The cost of a 5 kVA diesel engine generator is two hundred and fifty thousand naira (₦250,000.00) with a life expectancy of 4 years. The annual costs of fueling and maintenance are five hundred and forty seven thousand naira (₦547,500.00) and fifty four thousand naira (₦54,000.00) respectively. Thus the cost of electricity of the diesel generator (COE_{diesel}) using equation (21) is six naira ninety three kobo per kWh (₦6.93/kWh)

Cost of grid electricity for class R1 residential category is four naira per kWh (₦4.00/kWh) in Kaduna district of PHCN as at July 2014.

5. CONCLUSION

An analytical method for optimizing the sizes of the major components of a stand-alone power plant (SAP), which is based on optimized cost of electricity (COE) generation to meet the power demand of a remote orchard and poultry farm in Kaduna, Nigeria was demonstrated. The cost of electricity generated from the optimized PV power plant was determined to be ₦1.5/kWh. Power generation using diesel engine generator is ₦6.93/kWh while the cost of grid power for RI class of residential category is ₦4.00/kWh. It is clear that power generation using the stand-alone PV power plant (SAP) is quiet economical and affordable in the long term. A SAP with the above design configuration was installed and its operation was monitored for one calendar year. It was observed from the records of voltage and current readings on the charge controller that in the whole year, except in August, the storage battery will be fully charged with a reduced output from the PV for trickle charging and support of non-pumping load. During the month of august when clouds shade the PV array for most of the time, the batteries were not fully charged throughout most of the days in the month. The SAP, however, never failed to supply the non-pumping load because the month of August also records the highest rainfall which naturally waters the orchard part of the farm and there was therefore no need to provide electrical power to the pump load during this period. On occasions of poor solar insolation when the system voltage falls below 42 V, the plant was observed to be incapable of powering the load.

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