Photovoltaic Generating System Parameter Sizing for Building

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Abstract

Small to medium sized battery storage required to address the intermittency challenge of the energy of solar radiation could be achieved by appropriate sizing of the photovoltaic system parameters like photovoltaic module (PVM) number and battery capacity. This paper presents the results of evaluation of the optimum parameter values in sizing of stand-alone photovoltaic (PV) system that satisfies building energy demand, with almost zero Loss of Power Supply Probability (LPSP). A time step simulation of system performance based on energy balance for various combinations of PV numbers and battery capacities was employed. (Three seasons of operation were considered; rainy, hot and hot/dry). The rainy season result indicating high storage capacity requirement of about (2500-Ah), is of highest cost compared to other seasons. Stand-alone photovoltaic system size that will assuage the intermittency challenge; mitigate peak demand costs and provide near zero LPSP was determined.

Keywords: loss of power supply probability, photovoltaic, energy demand, parameter sizing, stand-alone

1. Introduction

"It has long been recognized that mankind must, in the near future, be faced by a shortage of power unless some means were determined of storing power from the intermittent sources of nature...a vision for small to medium sized storage and a discussion of its driving forces are appropriate in order to build up a picture of overlapping issues". (Pickard and Abbot 2012). Even though solar energy as a renewable resource is becoming more popular, the fact that time of use out-side sun hours require storage that could sometimes be quite large, militates against its wide application. Hence, the need to ensure right sizing of the parameters cannot be overemphasized.

In the service territory of Ile-Ife, Osun State, Nigeria, most buildings are connected to the electric supply grid. However, there still exist several 'off-grid' or remote locations, which, for financial and/or environmental reasons related to their distance from an existing power line, are not connected to the utility grid. Most of these residences make up for their electricity from gasoline or diesel generators. The rest derive their supply entirely from these fossil powered generators which can be noisy, unsafe and unreliable. These generators are usually only capable of supplying electricity for basic needs such as essential lighting, water pumping and a limited number of plug loads (e.g., radio, TV, computer, handset charging).

Mitigating peak demand issues in such territory can be achieved by introducing PV system into the energy mix. In which case, coincidence of need with generation is harnessed. Cooling systems cause demand to peak in the early afternoons when sun intensity is at its peak. Late afternoon peaking needs can be assuaged by storages through efficacious deployment of deep cycle batteries. Consequently PVM number and battery capacity are determined for the required load levels at peak periods.

The benefits of deploying PV system this way includes:

1. Sustainability-PV modules have very long life, very low and staggered system maintenance cost, and low pull in cost.

2. Low cost-solar energy can be competitive with diesel generator and other fossil powered systems especially considering possible future cost trends for fossil energy.

3. Storage provides load shifting functionality for late afternoon peak load. It engenders medium and long term maximum demand savings and peak period outage mitigation.

A sizing method of stand-alone PV systems has been presented by (Shrestha and Goel, 1998), it is based on energy generation simulation for various numbers of PVs and batteries using suitable models for the system devices.

(Maghraby *et al.* 2002) used Markov chain modeling for the solar radiation. In this case, the number of PVs and batteries were selected according to the desired System Performance Level (SPL) requirement, which is defined as the number of days that the load cannot be satisfied and it is expressed in probability.

It is assumed that user appliances are energy efficient and energy saving load management strategies are applied, which are common practices in renewable energy applications (Lazou, and Papatsoris, 2000). This assumption is common with most reviewed work and this leads to making use of load demand distribution of 1000W peak and near zero base values at night time. With the backdrop of the foregoing, this paper considered 3000W peak value with a base load of 400W. The parameters were determined for "wet","hot","hot/dry", season

2. Methodology

The first step in the sizing methodology consists of a simulation procedure in order to determine whether a system configuration, comprising of a certain number of devices fulfils the load power supply requirements during the year. The sizing algorithm data input is provided by a data base containing the technical characteristics of commercially available system devices. The data used are the daily solar irradiation on horizontal plane, the hourly mean values of ambient temperature and the consumer power demand for one year time period.

This method utilizes a simulated system operation for one year with a time step of one hour. The power produced by the PV is assumed to be constant in that 1hr time step. Therefore the energy produced is compared with the load demand during that time step.

The current–voltage and power–voltage characteristics of a PV array consists of ζ PV panels having ζP modules connected in parallel, and ζS modules connected in series, as depicted in Figure1. The running temperature TC can be calculated from the Nominal Operating Cell Temperature NOCT and air temperature using (Emery, 2003),

$$T_C = T_{amb} + \left(NOCT - 20^0 C\right)\frac{G_i}{800}, \qquad (1)$$

Where T_{amb} , is ambient temperature °C, G_i is the global incident irradiance W/m^2, T_C is cell temperature, °C.

The maximum output power of the PV array on day i and at hour t_i , is calculated using the specifications of the PV module under Standard Test Conditions (STC, cell temperature = 25°C and solar irradiance = 1000W/m^2), provided by the manufacturer, as well as the ambient temperature and irradiation conditions, according to equation (2):

$$P_{PV}(t) = \zeta_S \times \zeta_P \times V_{OC}(t) \times I_{SC}(t) \times FF \qquad (2)$$

Where,

ζ_P is modules connected in parallel, ζ_S is modules connected in series, V_{OC} is the open-circuit voltage (V), $I_{SC}(t)$ is short-circuit current (A) of the PV module, and FF is fill factor.

$$V_{OC}(t) = V_{OC,STC} - K_V \times T_C(t) \qquad (3)$$

$$I_{SC} = GG(P_{GC}, t, i) \times \left(I_{SC,STC} + K_I \times \left(T_C(t) - 25\right)\right) \times 10^{-3} \qquad (4)$$

$$T_C = T_A(P_{TC}, t, i) + GG(P_{GC}, t, i) \times \frac{(NOCT - 20)}{800} \qquad (5)$$

where $I_{SC}(t)$ is short-circuit current (A) of the PV module, $I_{SC,STC}$ is the short-circuit current under STC (A), $GG(P_{GC}, t, i)$ is the global irradiance (W/m^2) incident on the PVM placed at the optimum tilt angle, K_I is the short-circuit current temperature coefficient (A/°C), V_{OC} is the open-circuit voltage (V), $V_{OC,STC}$ is the open-circuit voltage under STC (V), K_V is the open-circuit voltage temperature coefficient (V/°C), $T_A(P_{TC}, t, i)$ is the ambient temperature (°C), NOCT is the Nominal Operating Cell Temperature (°C), provided by the manufacturer, $T_C(t)$ is the cell working temperature (°C), and FF is the fill factor. The value of $GG(P_{GC}, t, i)$ is calculated from the daily solar irradiation on the horizontal plane. (Kaldellis et al., 2004). The PV modules tilt angle has been selected to be constant at the latitude of the site for optimum result. The number of PV modules connected in series in the PV array, depends on the battery charger maximum input voltage, V_{BCH} and the PV modules open-circuit voltage level, V_{OC}

$$\zeta_S = \frac{V_{BCH}}{V_{OC}} \quad (6)$$

A maximum power point tracker (MPPT) is a high efficiency DC to DC converter which functions as an optimal electrical load for a photovoltaic (PV) cell, commonly used for a solar panel or array, and converts the power to a voltage or current level which is more suitable to whatever load the system is designed to drive (Cherguil and Bourahla., 2009). PV cells have a single operating point where the values of the current and Voltage of the cell result in a maximum power output. A PV cell has an exponential relationship between current and voltage, and the maximum power point (MPP) occurs at the knee of the curve, where the resistance is equal to the negative of the differential resistance ($\Delta R = -\Delta V/\Delta I$). MPP trackers utilize some type of control circuit or logic to search for this point and thus allow the converter circuit extract the maximum power available from a cell (CRC Press LLC, 1999).

The PV power actually transferred to the battery bank on day i is related to the maximum output power of the PV array, $P_M(t)$ by the battery charger conversion factor, qch defined by equation (7).

$$qch = \frac{P_{PV}(t)}{P_M(t)} = \eta_1 \times \eta_2 \quad (7)$$

where η_1 is the battery charger subassembly efficiency, specified by the manufacturer and η_2 is a conversion factor, which depends on the battery charging algorithm. It gives an indication of PV power generated deviation from the corresponding maximum power (Koutroulis *et al*., 2006). With MPPT embedded battery charger η_2 is set at value1approximately. It makes good economic sense to use very-high-efficiency low-power MPPTs in order to scale down the PV array and batteries, culminating in a lower cost system (Eslin, *et al.,* 1997).

3. Battery state of charge model

There are two voltage thresholds or activation set points, at which the controller will take action to protect the battery. Each threshold has a complementary action set point. For instance, the array disconnect voltage is set near 14 volts for a nominal 12-volt battery. When the array is disconnected, the battery voltage will drop immediately to about 13 volts. The array re-connect voltage is usually set near 12.8 volts. Similarly, when the voltage reaches about 11.5 the load is disconnected and not re-connected until the voltage reaches about 12.4 volts. The battery bank total nominal capacity B_{MC} (Ah), is permitted to discharge up to the maximum permissible depth of discharge DOD percent, which is specified by:

$$B_{MN} = DOD \times B_{MC} \quad (8)$$

where B_{MIN} is the minimum permissible battery capacity (Ah), during discharging. Depending on the PV energy profile and the load power requirements, the battery state of charge is accumulated during the simulation period as follows:

$$B_{SOC}(t) = B_{SOC}(t-1) + \eta_B \times \frac{P_E(t)}{V_{BUS}} \Delta t \quad (9)$$

Where $B_{SOC}(t)$, $B_{SOC}(t-1)$ is the available battery capacity (Ah) at hour t and (t-1), respectively, of day i, η_B = 80% is the battery efficiency during charging and η_B = 100% during discharging. V_{BUS} is the DC bus voltage (V), P_E (t), is the battery input/output power (which is less than zero during discharging and greater than zero during charging), and t, is the simulation time step, set to Δt = 1 h

The number of batteries connected in series, is given by:

$$N_{BS} = \frac{V_{BUS}}{V_{BAT}} \quad (10)$$

where, V_{BUS} is the DC bus voltage, V_{BAT} (V) is the nominal voltage of each individual battery

4. Inverter model

The inverter input power, P_{inv} (t), is calculated using the corresponding load power requirements, as follows:

$$P_{inv} = \frac{P_D(t)}{\eta_{inv}} \quad (11)$$

Where P_D (t) is the power consumed by the load at hour t, η_{inv} is the inverter efficiency. During this operation of the PV three different scenarios are considered:

a) the total power generated by the PV generators is greater than the inverter in- put power, P_{inv} **.** In this case, the energy surplus is stored in the batteries and the new storage capacity is calculated using equation (9), until the full capacity is obtained.

b) the total PV generators power is less than the power needed by the load, P_{inv}, the energy deficit is covered by the storage and a new battery capacity is calculated using equation (9).

c) in case of inverter input and total power equality, the storage capacity remain unchanged.

In case (a) when the battery capacity reaches a maximum value, B_{MC}, the control system stops the charging process.

5. Autonomy model

After the integration of energy balance analysis, a (ζ- B_{MC}) curve is predicted under a given reliability level "R" restriction, specifically,

$$R = 1 - \frac{h}{8760} \quad (12)$$

Where h is the total number of hours the load is not satisfied during the period.

It should be noted that for every pair of (ζ- B_{MC}) examined, the predicted stand-alone photovoltaic system is energy autonomous for the period investigated (1 month, 2 months, 6 months, or 1 year, as the case may be), excluding a small period of "h" hours per annum. For full system autonomy, h takes on the value zero.

6. Optimal parameters

Photovoltaic (PV) power sources are widely used in order to supply power to consumers in remote and grid deprived areas. The block diagram of a stand-alone PV system is shown in Figure 2. Depending on the battery charger technology, the maximum available power can be extracted from the PV power sources. The battery bank, which is usually of lead-acid, deep cycle type, is used to store the energy surplus and to supply the load in case of low irradiation conditions.

A DC/AC converter is used to interface the DC battery voltage to the consumer load AC requirements. The outputs of all battery chargers, the battery bank and the DC/AC converter input terminals are connected in parallel. The energy produced from each PV is transferred to the consumer load through the battery charger and the DC/AC inverter, while the energy surplus is used to charge the battery bank.

The system operation is simulated for various combinations of PV array and battery sizes and the Loss of Power Supply Probability (LPSP) is calculated for each combination. Then, for the desired LPSP, the PV array versus battery size is plotted and the optimal solution, which minimizes the total system cost, is defined as the point on the sizing curve where:

$$\frac{d\zeta}{d(B_{MC})} = -\frac{C_\zeta}{C_{BMC}}, \quad (13)$$

where ζ , B_{MC} , are the number of PV modules and batteries while C_ζ , C_{BMC} are the unit costs of PV module and battery respectively.

7. Test results and analysis

The load profile of 400W (base load) and a peak of 3000W was considered for use in the energy balance simulation algorithm.

Obafemi Awolowo University (OAU), Ile-Ife is located between longitude 4°40′and latitude 7°30′. The topography of the campus is fairly plain with some gentle slopes and low mountains with remarkable vegetation. The area possesses high solar potential as shown in Figure 5. The dry season lasts from about late October and ending in March. The rainy season begins in the month of April and ends about the end of October. The rainfall is heavy reaching an average of between 45 and 60 inches. The Months of July and August have the most remarkable rainfall. It is possible to observe three different segments in the solar energy profile for "hot/dry", "hot", "wet", corresponding to November/December, February/March, and July/August, in that order as depicted in Figure 3. Using the "photoveff" algorithm developed for PV module performance, comparison can be made between the three regions

7.1 Parameter analysis

The computational algorithm "optiphotov" III developed for the simulation of various combinations of PV number and battery capacity was used to estimate the PV system configuration for the selected 3 segments "hot", "wet", and "dry" of the year as shown in figure 3. The optimum parameter configuration is realised at the transition of PV number to a higher figure, while the battery selection transits the opposite way, leading to the quotient of the change, equaling the negative of the battery- PV costs ratio. These transitions are clearly evident in figures 4, 5 and 6. There is a remarkable difference between the proposed solutions (photovoltaic system size), for the 3 representative segments examined. There is a disparity between the best solar potential segment, "hot" and the worst, "wet". An almost 16% photovoltaic panel number increase, as it reflects in Table 5, is required to ensure the system energy autonomy for the worst solar potential segment, "wet" (July/August) , in contrast to the "hot". The quality of the solar potential directly influences the battery size, and the "wet" almost triples the figure for "hot/dry". The PV number for the "hot" turns out to be less than that of the "dry".

It can be conveniently stated that the selected time period strongly influences the system size when predicting photovoltaic system parameter. It is also noteworthy that base load value and its distribution as well as the peak load and its duration affect the value of the PV system parameter. It is important to note that where the consumer can afford DC appliances and reduce base load, the initial cost can be considerably low. More specifically, a favorable paradigm shift is emerging, incorporating energy efficient AC and DC appliances and even intelligent appliances, ready for demand response integration. In effect good energy management practice is complementary to harnessing the full benefit of the PV system.

The trend that can be observed in the change in parameter size as the peak load moves from 1 to 3 kW is positive. The solar intensity for the "hot" segment is the best of the three load levels. The panel number is consequently the least for the energy peak loads used. The charging current provided by these will however not give the best battery sizes, in fact the battery capacities corresponding to the "hot" are sub-optimal and are a practical nuisance. In the "wet" season, solar intensity is poor; hence large numbers of panels are required along with large battery capacity. Coming in between the two segments in term of size is the panel size for "hot/dry". This is true for the three peak loads used and the battery capacity is best for this segment.

8. Conclusion

In this paper the sizing for stand-alone photovoltaic generator system was proposed. The simulated results verify the ability of the PV system to overcome peak demands, this shows that peak period failures and outages will be mitigated by the proposed system. Also, the capability provided by the storage system provides demand shifting functionality, wherein late afternoon peak demand could be shaved, which implies stability for contiguous utility network resource. The battery energy storage system can be used to reduce this peak demand and thus reducing building's electricity bill by discharging a stored energy during load peaks. The economic benefit of the peak shaving application is directly measurable by comparing power demand load taxes for large customers with realistic installation and maintenance costs of PV system.

So many savings is expected from financial losses due to outages and failures from the utility grid. The proposed system being controlled by intelligent inverter will provide seamless transition between sources. The results obtained for the parameter size of the photovoltaic system may be applied to a typical West African sub-Saharan, semi-arid region. They are based on one year long experimental measurements and the manufacturer's operational characteristics.

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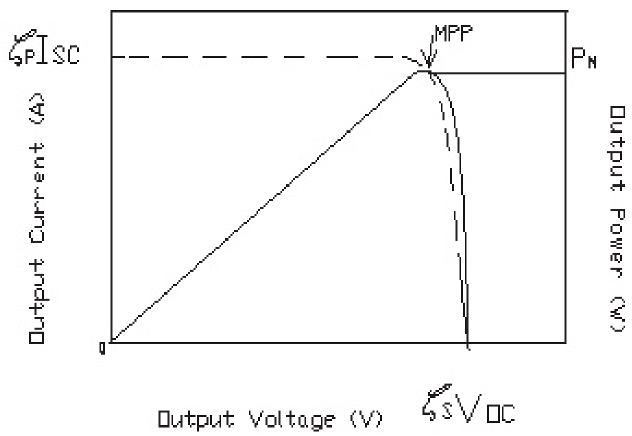

Figure: 1 PV module current-voltage and power-voltage characteristics.

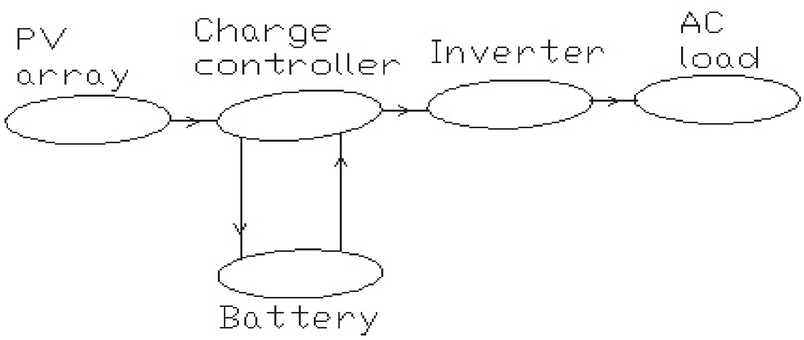

Figure 2: Block diagram of stand-alone PV system

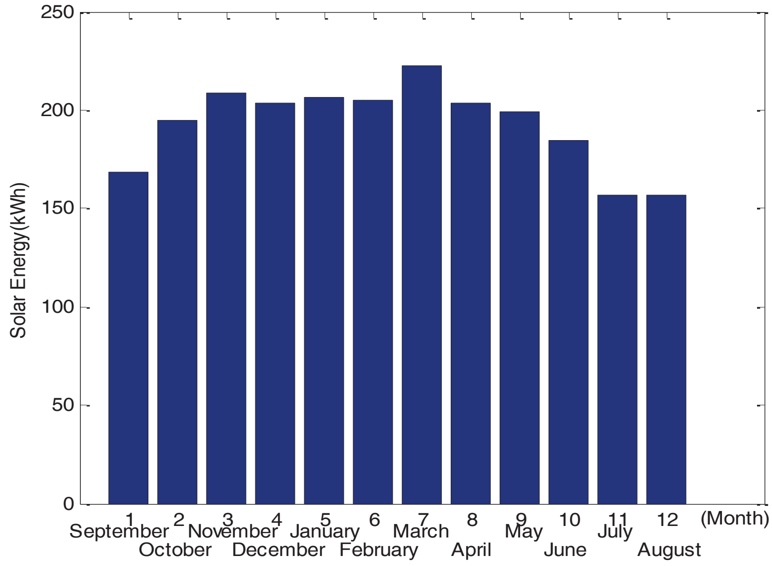

Figure 3: Measured Solar Potential Values for OAU Campus Ile-Ife

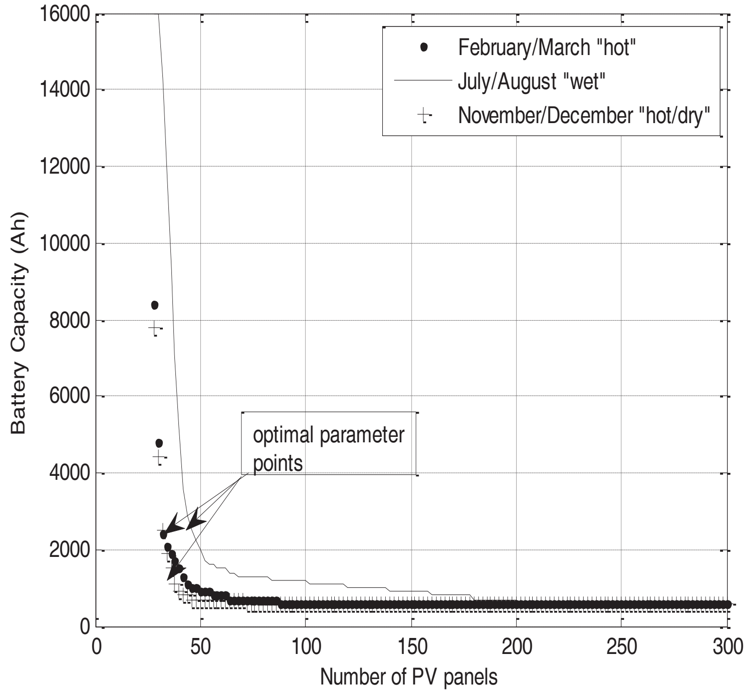

Figure4: Comparison of optimum parameters for representative solar potential segments (1kW peak load)

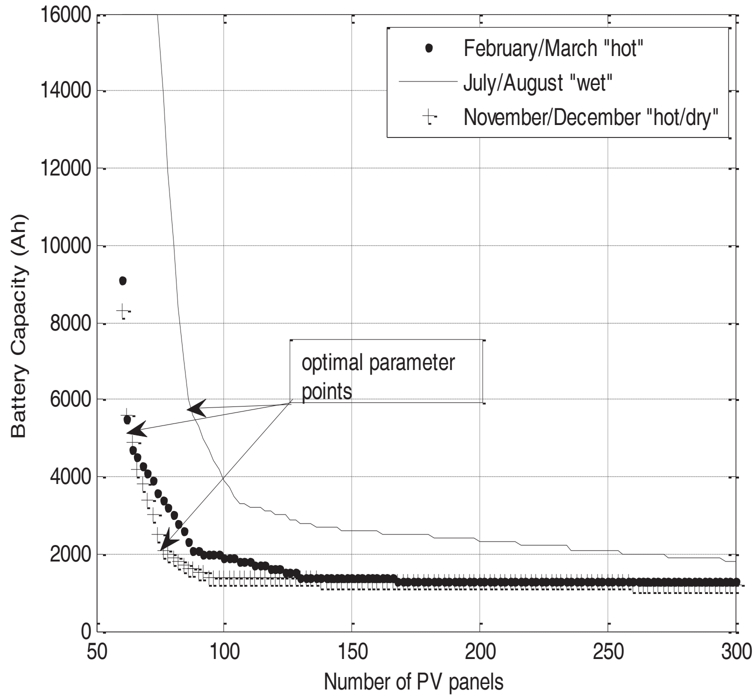

Figure 5: Comparison of optimum parameters for representative solar potential seasons. (2kW peak load distrib ution)

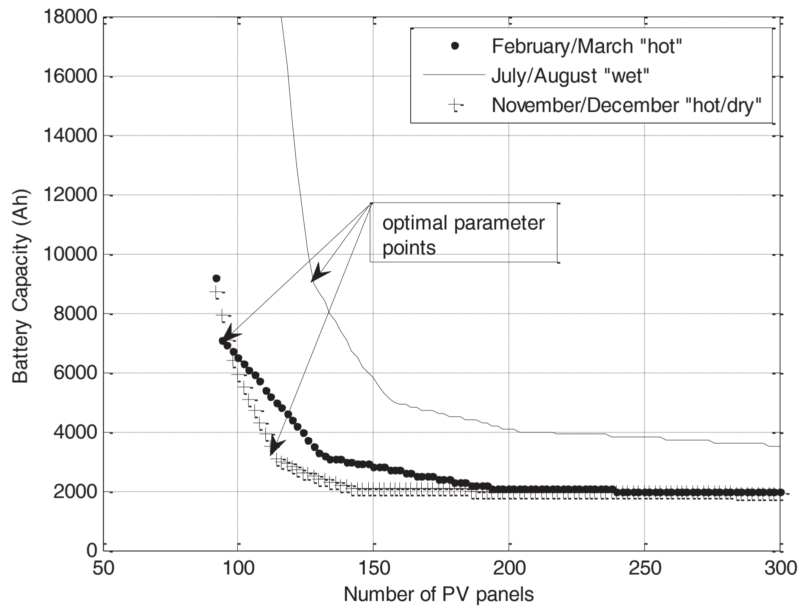

Figure 6: Comparison of optimum parameters for representative solar potential segments (3kW peak load)

Table 1: PV module specifications

Voc (V)	Isc (A)	Vmax (V)	Imax (A)	Pmax (W)	NCOT (°C)	Capital cost (₦)
21	10.22	17.3	10.10	125	43	29732

Table 2: Battery specifications

Nominal Capacity (Ah)	Voltage (V)	DOD (%)	Capital cost (₦)
200	12	80	47520

Table 3: DC/AC inverter specifications

Efficiency (%)	Power rating (W)	Capital cost (₦)
80	3000	259000

Table 4: PV battery charger specifications

$\eta 1$ (%)	$\eta 2$ (%)	Power rating (W)	Capital cost (₦)
95	100	300	3600

Table 5: Optimum parameter values for a stand-alone photovoltaic system (1kW peak load)

Solar Potential Level	(ζ) PV Panel Number	Battery Maximum Capacity BMC (Ah)	cost (₦´000)
"hot"	32	2400	2912
“wet”	46	2500	3789
“hot/dry”	38	1100	2771

Table 6: Optimum parameter values for a stand-alone photovoltaic system (2kW peak load)

Solar Potential Level	(ζ) PV Panel Number	Battery Maximum Capacity BMC (Ah)	cost (₦´000)
"hot"	64	4700	5656
“wet”	88	5600	7406
“hot/dry”	76	2100	5440

Table 7: Optimum parameter values for a stand-alone photovoltaic system (3kW peak load)

Solar Potential Level	(ζ) PV Panel Number	Battery Maximum Capacity BMC(Ah)	cost(₦´000)
"hot "	95	7000	8299
"wet"	129	8800	10934
"hot/dry"	114	3100	8101