Simulation of the Optimal Size of Photovoltaic System Using Heliophysical Variables

O. S. Bolaji[1,*] and A. B. Rabiu[2]
[1]*Department of Physical Sciences, Bells University of Technology, Ota, Nigeria*
[2]*Department of Physics, Federal University of Technology, Akure, Nigeria*

A method for the optimal sizing of a photovoltaic system is presented in this paper. The system studied is composed of photovoltaic array, power tracker, battery storage, inverter and load. The data used were the sunshine duration and solar radiation intensity for years 1990 to 2004 for eleven Nigerian stations: Calabar, Ibadan, Ilorin, Kaduna, Kano, Lagos, Lokoja, Maiduguri, Minna, Sokoto and Zaria obtained from the archives of the Nigeria Meteorological Agency. Appropriate programs were developed using Matlab[R] code to model the optimal size of a photovoltaic system. Input parameters, which were estimated from the obtained heliophysical variables and used in the simulation, were clearness index and total radiation on an inclined surface. The output parameters include utilizability, monthly-average fraction of the load covered by the photovoltaic system with battery storage, monthly-average fraction of the load covered by the photovoltaic system without battery storage, monthly-average of uncovered load fraction of the photovoltaic system, area of the panel, optimal area of the panel, total cost of the panel, and the optimal total cost of the panel. Maximum incident solar radiation onto the photovoltaic array is obtainable in dry season and smaller sizes of photovoltaic system are used, while minimum incident solar radiation onto the photovoltaic array were witnessed during the wet season and larger sizes of photovoltaic system are used, which all determine the optimal size of the photovoltaic system. This research also account for the cost of the optimized plant, capable of supplying 15 kW, at #809,800. A comparison of this researched optimized cost with PHCN (Power Holding Company of Nigeria) current charge indicated that after one year and six months, the user of the photovoltaic plant will become a free user of electricity. The optimized photovoltaic plant is short-term cost effective and much cheaper than the non-optimized plants.

1. Introduction

Photovoltaic field is made up of solar cells, which can either be arranged in series or parallel pattern such that a solar module contains about 20 to 40 cells. Each module may have three to five columns of cells in series in such a way that one gets the desired electrical output characteristics. For better packing densities and other preferable characteristics, squared or hexagonal shaped cells are better than circular cells [1]. The photovoltaic array comprises of arrangement of solar modules embedded on solar collector. The preferred solar collector is the flat plate collector compared to other solar concentrating collectors because it forms the heart of any solar energy collection system design for operation in the low temperature range, from ambient to 60 degree Celsius, or the medium temperature range, from ambient to 100 degree Celsius.

Hence, the size of the photovoltaic array denoted by P_o is equal to the product of the area of the solar modules in the array A_c and its conversion efficiency tested under standard irradiance of $1KWm^{-2}$ (AM-1) conditions, which correspond to solar flux density of 1070 W/m^2.

The use of maximum power point tracker (MPPT), a special converter with controlled gain DC/AC, ensures that the array is always operating at a voltage for which it produces maximum power point independent of the variation of the solar radiation intensity, ambient temperature or load. It has the ability to change the DC output voltage from the photovoltaic array to a voltage or voltages that suite to the battery or load. Modern solid-state converter uses transistors and based on high frequency chopping. The efficiencies are around 95% at full load. A MPPT has built-in control logic to keep the array voltage at or near the maximum power point. These are operated by microprocessors for sensing and collecting the array voltage and current at frequent intervals for computing and adjusting the power output.

Several types of batteries are available in the market for use in photovoltaic power systems; they are to provide a back-up power source during periods of low solar irradiance and nights by storing the excess power from the array. The

* oloriebimpjch2002@yahoo.co.uk

capacity of a battery is the total amount of electricity that can be drawn from a fully charged battery at a fixed discharge rate and electrolyte temperature until the voltage falls to a specified minimum. It is expressed in ampere-hour (Ah). The capacity of battery depends on temperature and below 25 degree Celsius it is reduced by about 0.6% per degree Celsius. The capacity also depends on the age of the battery. The depth of discharge should not exceed 80% and should not be left uncharged for long-time. Nickel-cadmium batteries though expensive are ideally more suited to photovoltaic systems than the lead-acid batteries. Ni-Cd batteries are more advantageous compare to lead-acid accumulator because they have no problem of electrolyte depletion and stratification, less sensitive to temperature, less sensitive to rate of discharge, no problem of electrolyte freezing and no damage if the battery remains fully discharged for long periods.

An inverter is a device for converting DC from the array or battery to single- or multiphase AC suitable for AC loads. The output must meet the necessary requirements of the electricity authority in terms of voltage, frequency and harmonic purity of the waveform for the grid interactive systems. Additional transformer and special filtering respectively do these. But this may lead to additional losses and increase in cost. An inverter for photovoltaic systems should have the following in-built protective features: automatic switch off if the array output voltage is too high or low; automatic restart when the array output voltage is within the desired range; and protection against short circuit and overloading.

The load represents systems to be powered by the photovoltaic system depending on its application, which varies from industrial applications to consumer applications. The systems to be powered can be specific single load such as light (resistive load), electromechanical load, coupled to DC motors and electrolysis load.

Evans and Klein [2] developed both computational and graphical design methods for determining the average electrical output of a photovoltaic array taking into account the temperature dependence of photocell efficiency. The problem becomes more difficult if the photovoltaic array sometimes produces energy in excess of the load. The continuous discouraging effort of photovoltaic array's inability to produce energies at its maximum 100% as a result of generalized conversion efficiency of solar cell, put at 30% by [3], makes the uncovered solar load fraction Z a very complicated function of the instantaneous solar power throughout the working period and of all the properties of the photovoltaic system.

Therefore, simulating the photovoltaic plant behaviour characterized by photovoltaic system configuration, the efficiencies, the battery storage capacity, the covered and the uncovered solar load fraction, the climatic condition of the site and the load by a computer over a period of at least one year will determine the size of the photovoltaic system. Repeating the simulation with several values of unknown quantities: field area A and the total cost S_t such that (A , S_t) pairs satisfying the required conditions shall be determined by the optimization procedure.

Heliophysical variables from Nigerian Meteorological Agency shall be employed to solve these aforementioned proposed possibilities in an attempt to provide and enlighten the tropical users and designers of photovoltaic system with adequate knowledge in order to maximize its available efficiency and at the same time challenging the existing hydroelectric power system (HEP) in terms of effectiveness, reliability and cost.

2. The covered and uncovered solar load fraction

In our previous research work [4], we have dealt with the solar load fraction with storage Y_m , which is the covered solar load fraction and applied it to simulate the performances of photovoltaic system in the tropics using heliophysical variables.

Barra et al. [5] showed that the uncovered load fraction is considered to be a function of the averaged values of the efficiency of the system components and of the daily values of climatic data, that is,

$$Z_m = f(K_{TM}, I_T, d_m, A, C, \eta_{PC}, \eta_B, \eta_I, L_m, C_{om}) \tag{1}$$

Where, $m = (1...............12)$ and C_{om} is the energy stored in the battery at the beginning of the given month, which is inconvenient for quick calculations.

$I_{t,i}$ = monthly-average hourly radiation incident on the array

$$d_m = \text{length of the day} = \frac{(t_{ss} - t_{sr})}{24} \tag{2}$$

t_{ss} = sunset time

t_{sr} = sunrise time

To determine the functional f, we introduce the following dimensionless quantities:

$$X_m = \frac{A.I_{t,c}}{L_m} \qquad (3)$$

$$T_m = \frac{C.K_{TM}.d_m}{L_m} \qquad (4)$$

Where, X_m is the amount of electrical energy the photovoltaic array can deliver to the load directly without storage and T_m is the battery storage capacity normalized to the load L_m.

But,

$$I_m = \frac{X_m}{A} = \frac{I_{t,i}}{L_m} \qquad (5)$$

$$J_m = \frac{T_m}{C} = \frac{K_{TM}}{L_m} \qquad (6)$$

Where, I_m is the minimum value of the normalized solar energy and J_m is the minimum value of the normalized battery storage capacity.

For the relation between the solar load fraction met by the photovoltaic system with storage, Y_m, the uncovered load fraction Z_m and the solar load fraction met without storage X_m [5], consider the quantity:

$$Y_m = 1 - Z_{m,} \qquad (7)$$

with the following limiting conditions:

$$X_m \longrightarrow 0, \qquad Y_m = X_m \qquad (8)$$

$$X_m \longrightarrow 0, \qquad Y_m = 1 \qquad (9)$$

From Eqn. 8, the limiting condition, which is small in area size system, all the energy produced by the array can be transferred to the load, apart from the losses due to inefficiencies. The limit condition, Eqn. 9, which is very large field areas, the energy produced by the cell is able to satisfy the load and charge the battery storage completely.

The simplest curve satisfying the above limit condition is the hyperbola curve with the straight lines,

$$Y_m = X_m \text{ and } Y_m = 1 \qquad (10)$$

as asymptotes. We can then make the hypothesis that it is possible to write,

$$(X_m - Y_m)(1 - Y_m) = \gamma^{\beta}(T_m) \qquad (11)$$

For this work, very large field areas are considered. The program has been run for many pair of $(X_{m,}Y_m)$ values using solar data of the meteorology station of the "Aereonautica Militare Italiana". The results of the simulation show that the equation is a good fit, and also allow us to determine the parameter. Let us write,

$$\delta = \alpha\gamma^{\beta} \qquad (12)$$

Parameter α and β values are determined from a best fit to the result of the simulation.

2.1 Optimization procedure

For the determination of the optimal size of the panel area A and the battery storage capacity C values which satisfy the condition required for the photovoltaic system, putting Eqn. 12 into Eqn. 11, gives

$$(X_m - Y_m)(1 - Y_m) = \alpha\gamma^{\beta} \qquad (13)$$

From Eqn. 4,

$$T_m = J_m C \text{ and } \gamma^{\beta} = J_m^{-\beta} C^{-\beta} \qquad (14)$$

Substituting Eqn. 14 into Eqn. 13,

$$(X_m - Y_m)(1 - Y_m) = \alpha J_m^{-\beta} C^{-\beta}$$

$$X_m - Y_m = \frac{\alpha.J_m^{-\beta}.C^{-\beta}}{1 - Y_m} \qquad (15)$$

But, Eqn.5 is $X_m = I_m A$, putting this into Eqn. 15 gives

$$I_m A - Y_m = \frac{\alpha.J_m^{-\beta}.C^{-\beta}}{1 - Y_m}$$

$$I_m A = Y_m + \frac{\alpha.J_m^{-\beta}.C^{-\beta}}{1 - Y_m}$$

Substituting for A,

$$A = \frac{Y_m}{I_m} + \frac{\alpha . J_m{}^{-\beta} . C^{-\beta}}{I_m (1 - Y_m)} \qquad (16)$$

But,

$$S_T = S_A A + S_c C \qquad (17)$$

Where: $S_T =$ Total cost of the PV plant
$S_A =$ The panel cost (S / m^2)
$S_C =$ The storage battery cost (S / Kwh)

Putting Eqn. 14 into Eqn. 15 gives

$$S_T = S_A \left(\frac{Y_m}{I_m} + \frac{\alpha . J_m{}^{-\beta} . C^{-\beta}}{I_m (1 - Y_m)} \right) + S_c . C \qquad (18)$$

The minimum cost can be found by setting Eqn. 18 to zero, while finding the derivative of the total cost, i.e.,

$$0 = \frac{dS_T}{dC} = \left[\frac{-\alpha . J_m{}^{-\beta}}{I_m (1 - Y_m)} . \beta \; C^{(-\beta - 1)} \right] S_A + S_C$$

$$-S_C = \left[\frac{-\alpha . J_m{}^{-\beta}}{I_m (1 - Y_m)} . \beta \; C^{(-\beta - 1)} \right] S_A$$

$$C^{(-\beta - 1)} = \frac{S_C}{S_A} \cdot \frac{I_m (1 - Y_m)}{\alpha J_m{}^{-\beta} \cdot \beta} \qquad (19)$$

$$C^{-(\beta + 1)} = \frac{1}{C^{(\beta + 1)}} = \frac{S_C}{S_A} \cdot \frac{I_m (1 - Y_m)}{\alpha J_m{}^{-\beta} \cdot \beta}$$

$$\therefore C^{(\beta + 1)} = \frac{S_A}{S_C} \cdot \frac{\alpha J_m{}^{-\beta} \cdot \beta}{I_m (1 - Y_m)}$$

$$C_{opt} = \left[\frac{S_A}{S_C} \cdot \frac{\alpha J_m{}^{-\beta} \cdot \beta}{I_m (1 - Y_m)} \right]^{\left(\frac{1}{\beta + 1} \right)} \qquad (20)$$

C_{opt} = the optimal value of the storage capacity.

For A_{opt}, substitute Eqn. 16 for C_{opt} in Eqn. 20

$$A_{opt} = \frac{Y_m}{I_m} + \frac{\alpha \cdot J_m{}^{-\beta}}{I_m (1 - Y_m)}{}^{-\beta}$$

$$\cdot \left\{ \left[J_m{}^{-\beta} \cdot \frac{S_A}{S_C} \cdot \frac{\alpha}{I_m (1 - Y_m)} \cdot \beta \right]^{\left(\frac{1}{1+\beta} \right)} \right\}$$

$$= \frac{Y_m}{I_m} + \left[\frac{\alpha}{I_m (1 - Y_m)} \right]^{\frac{1}{1+\beta}} \cdot J_m{}^{-\frac{\beta}{1+\beta}} \left(\frac{S_A}{S_C} \cdot \beta \right)^{-\frac{\beta}{1+\beta}}$$

$$A_{opt} = \frac{Y_m}{I_m} + \left[\left(\beta \cdot J_m \cdot \frac{S_A}{S_C} \right)^{-\beta} \cdot \frac{\alpha}{I_m (1 - Y_m)} \right]^{\frac{1}{1+\beta}} \qquad (21)$$

Eqns. 18 and 20 provide the total cost of the PV plant and the optimal value of the storage capacity, respectively.

The sizing of the photovoltaic system is determined by the minimum incident solar radiation I_m onto the surface of the photovoltaic array, the reason for using minimum I_m is that these lower values of solar radiation usually occur during the wet season characterized by larger dust particles, water vapour and cloudiness and will require bigger size of photovoltaic plant to be able to meet the required load for the month, but if the impinging solar radiation is maximum, that is, during the dry season, it will require smaller size of photovoltaic plant compare to meet the same require load for the month. Using the month having minimum value of impinging solar radiation I_m at a particular station shall surely size any photovoltaic system.

Hence, the minimum total cost of the photovoltaic plant is,

$$S_{opt} = S_{A.} A_{opt} + S_{c.} C_{opt} \qquad (22)$$

3. Results

It is evident from this research that maximum total cost across the stations are the same and fixed, having the value of #3,880,000,000 when the area of the photovoltaic plant is not optimized but when the area of the photovoltaic plant is optimized, the sizes of the photovoltaic plant increases and the cost reduces from Billion Naira to the ranges of #809,800 to #1,243,700, and has an overall average of #893,844. This means that at least, the minimum average cost of setting up photovoltaic plant is #809, 800 throughout its lifetime, which give a unit cost of #53993.33/kWh in respect to Power holding company of Nigeria of #4/kWh. The result also show that it take 1.540906 year for the total cost of photovoltaic plant to match the PHCN #4/kWh.

Also, the graphical results of the monthly-average of impinging solar radiation I_m, monthly-average area of the photovoltaic plant A_p and monthly-average optimal area of the photovoltaic plant A_{opt} are presented in Figs. 1 to 11. These results reveal that maximum I_m occurs during the dry season and as a result of this, smaller optimal sizes of the photovoltaic plant are required to meet the monthly average solar load fraction either with or without storage. This dry season spreads across these stations in these months; September, October, November, December, January, February and March. However, minimum I_m is experienced in the wet season which, results in bigger optimal sizes of the photovoltaic plant required to meet the monthly average solar load fraction with or without storage. The wet season of the aforementioned stations occurs in these months; April, May, June, July and August.

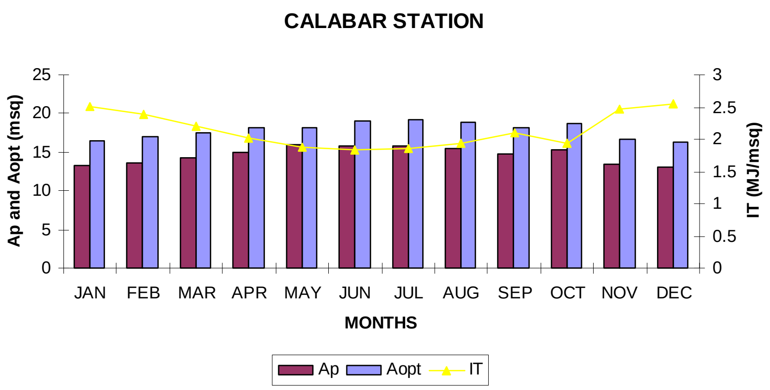

Fig.1: Calabar Station.

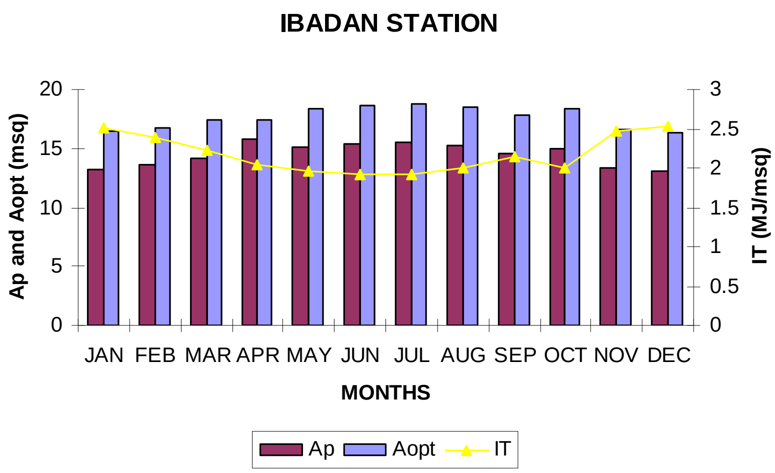

Fig.2: Ibadan Station.

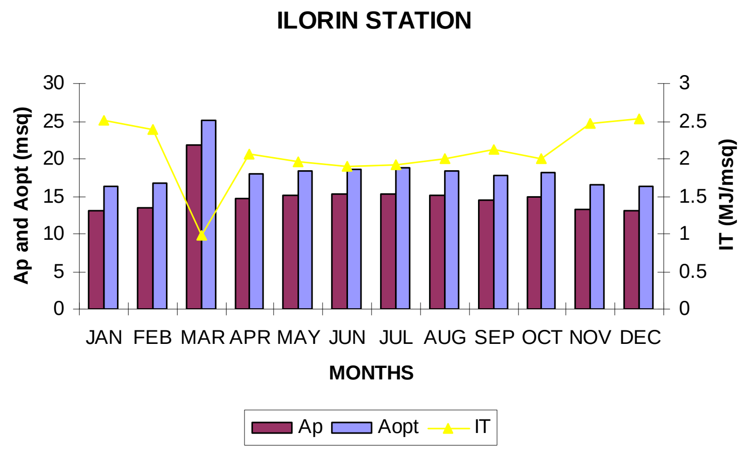

Fig.3: Ilorin Station.

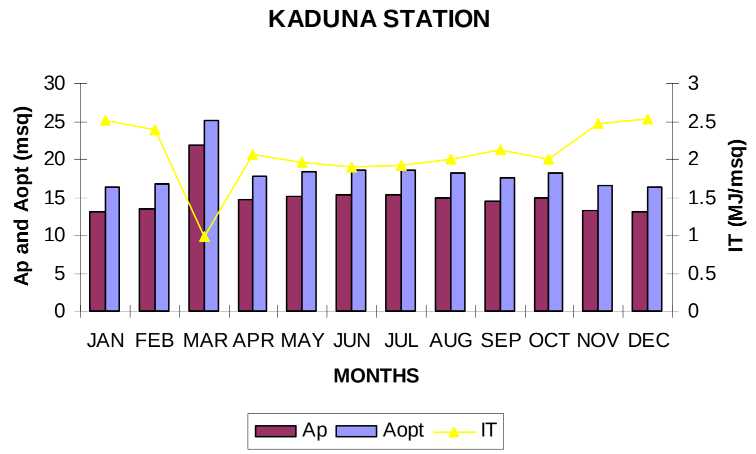

Fig.4: Kaduna Station.

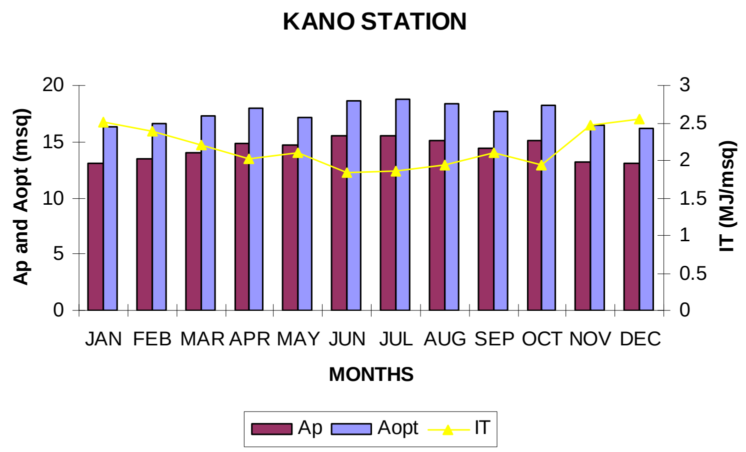

Fig.5: Kano Station.

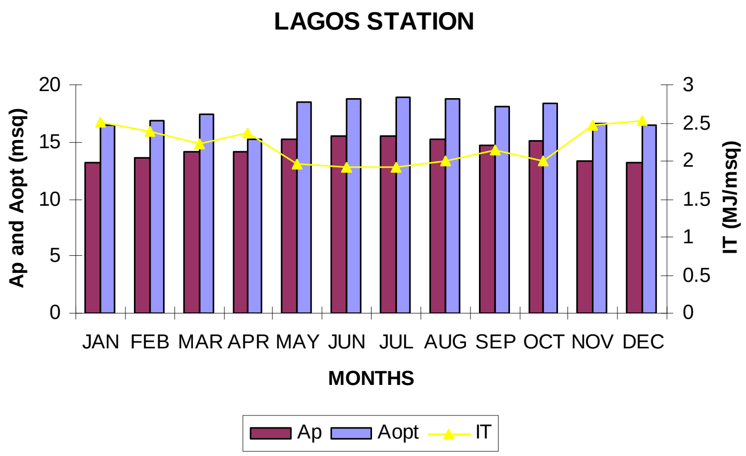

Fig.6: Lagos Station.

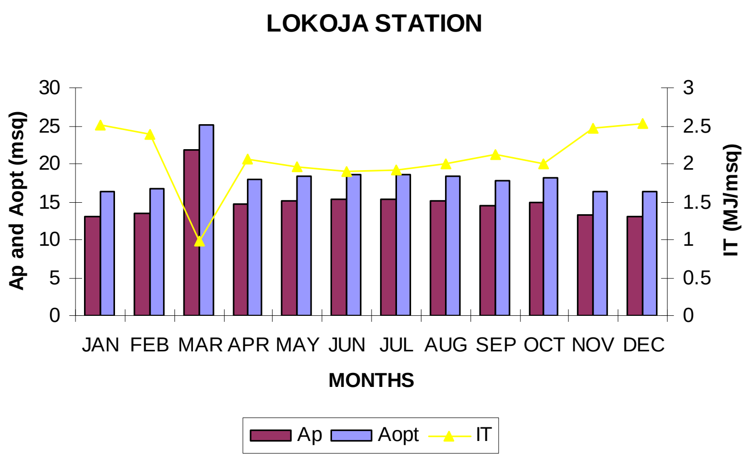

Fig.7: Lokoja Station.

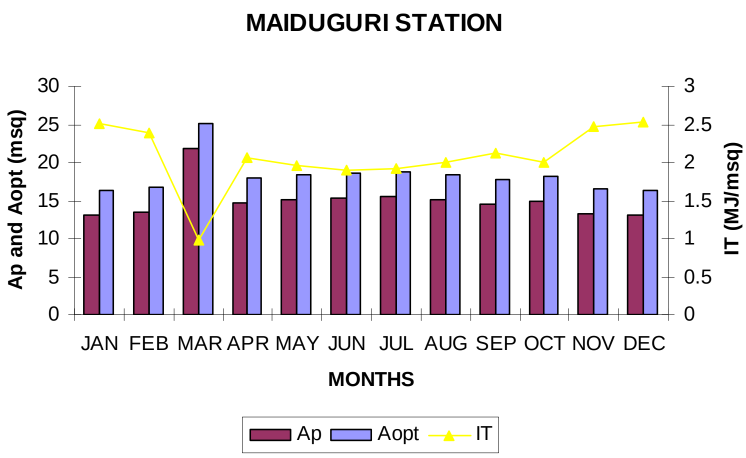

Fig.8: Maiduguri Station.

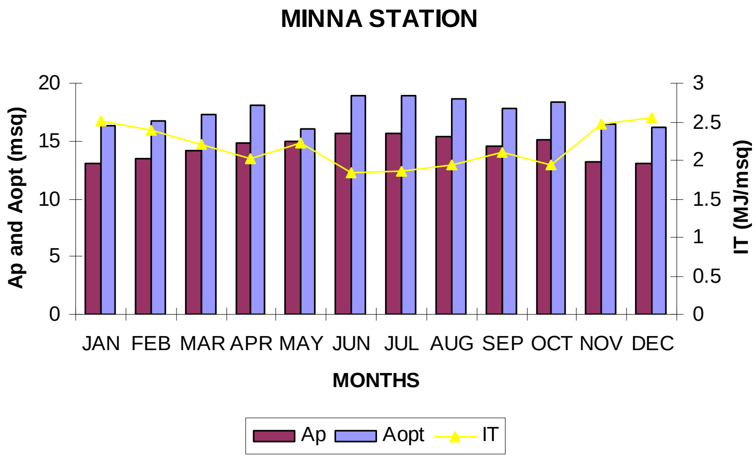

Fig.9: Minna Station.

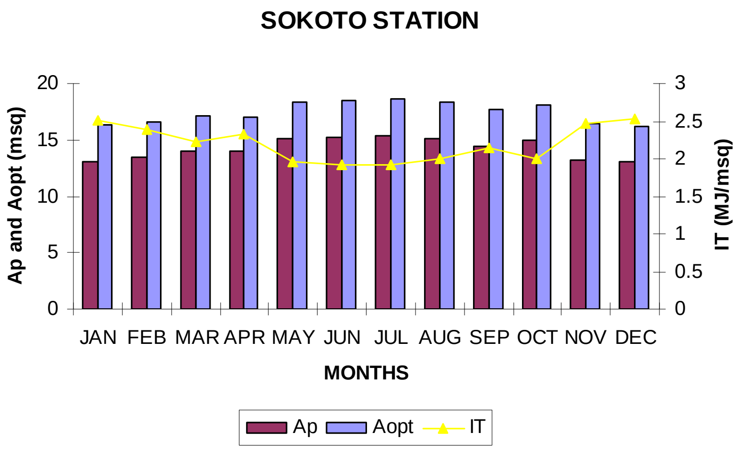

Fig.10: Sokoto Station.

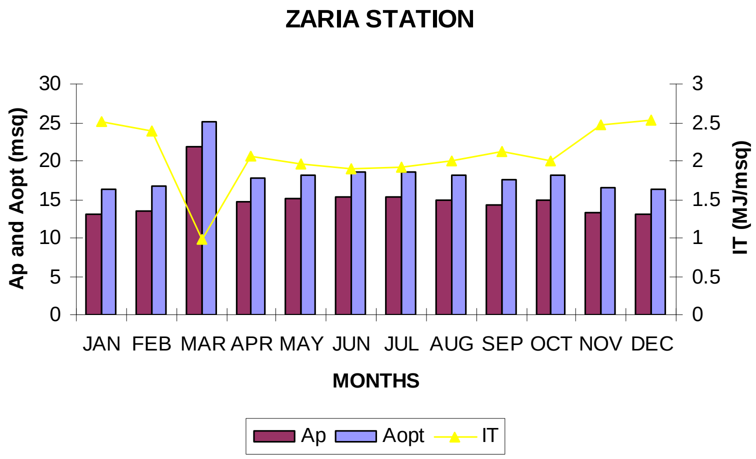

Fig.11: Zaria Station.

4. Conclusion

Over 70% of uncovered solar load fraction with storage is accounted for in this work using the relations provided by [5] in equation 2.1. This, over 70% of uncovered solar load fraction, is more prevalent during the wet season than in the dry season. The average cost of the optimized plant, capable of supplying 15 kW, is #809, 800. A comparison of the optimized cost with PHCN current charge indicated that after one year and six months, the user of the plant will become a free user of electricity. The optimized photovoltaic plant is short term cost effective and much cheaper than the non-optimized plant. Meanwhile, the photovoltaic plant has longer useful life of at least 20 years characterized with low operation and maintenance costs advantages over the conventional hydro-electric power system having expensive operation and maintenance costs, which is increasing day by day and therefore it is economical and reliable to use photovoltaic plant over many years than the PHCN electrical supply.

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