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Simulation of the optimal size of photovoltaic system using heliophysical variables.

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Abstract

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, this determines the optimal size of the photovoltaic system. This research also account for the cost of the optimized plant, capable of supplying 15kW, 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 plant.

Keywords
photovoltaic systems, utilizability, optimized plant, atmospheres

1.0 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

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characteristics. For better packing densities and other preferable characteristics, squared or hexagonal shaped cells are better than circular cells Wolf, [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 is 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 suited to the battery or load. Modern solid-state converters use transistors and are 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 period of low solar irradiance or in the night by storing the excess power from the array. The 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 the 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 (*Ni-Cd*) batteries though expensive are ideally more suited to photovoltaic systems than the lead-acid batteries. *Ni-Cd* batteries are more advantageous compared to lead-acid accumulator because they have no problem of electrolyte depletion and stratification. They are less sensitive to temperature, less sensitive to rate of discharge and there is 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 application 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.

Garg and Prakash [3] put conversion efficiency of solar cell at 30%. The uncovered solar load fraction Z which is 70% and the excess energy produced in a photovoltaic plant when the battery is fully charged are complicated functions of the instantaneous solar power throughout the working period 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.

The dataset used is gotten from the archive of Nigerian Meteorological Agency. In this paper, we present a method based on simplified technique, which allows one to go through the sizing procedure and cost implication by short and easy simulation.

2.0 The covered and uncovered solar load fraction

In our previous research work, Bolaji and Rabiu [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,

$$Z_m = f(K_{Tm}, I_T, d_m, A, C, \eta_{PC}, \eta_B, \eta_I, L_m, C_{om}) \qquad (2.1)$$

where, m = 1,…,12, 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 = length of the day = $\frac{(t_{ss} - t_{sr})}{24}$ (2.2)

t_{ss} = sunset time, t_{sr} = sunrise time.

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

$$X_m = \frac{A.I_{t,c}}{L_m} \qquad (2.3)$$

and

$$T_m = \frac{C.K_{Tm}.d_m}{L_m} \qquad (2.4)$$

X_m = 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,

$$I_m = \frac{X_m}{A} = \frac{I_{t,i}}{L_m} \qquad (2.5)$$

$$J_m = \frac{T_m}{C} = \frac{K_{Tm}}{L_m} \qquad (2.6)$$

I_m = minimum value of the normalized solar energy

J_m = minimum value of the normalized battery storage capacity.

K_{Tm} = clearness index

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, Barra et al [5] considered the quantity,

$$Y_m = 1 - Z_m, \qquad (2.7)$$

with the following limit conditions, when

$$X_m \to 0,\ Y_m = X_m \qquad (2.8)$$

when $X_m \rightarrow 0, Y_m = 1$ (2.9)

From equation (2.8) limit condition, for small size system, all the energy produced by the array can be transferred to the load, apart from the losses due to inefficiencies. From equation (2.9) limit condition, for very large size system, 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, $Y_m = X_m$ and $Y_m = 1$ as asymptotes (2.10)

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

$$(X_m - Y_m)(1 - Y_m) = \gamma^{-B}(T_m) \quad (2.11)$$

For this work, very large field areas is considered .The program has been run for many pairs of (X_m, Y_m) 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,

$$\delta = \alpha . \gamma^{-B} \quad (2.12)$$

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 equation (2.12) into (2.11) gives $(X_m - Y_m)(1 - Y_m) = \alpha\gamma^{-B}$ (2.13)

From equation (2.4), $T_m = J_m C;\ \gamma^{-B} = J_m^{-\beta} C^{-\beta}$ (2.14)

Substituting equation (2.14) into (2.13), gives $(X_m - Y_m)(1 - Y_m) = \alpha . J_m^{-\beta} C^{-\beta}$

$$X_m - Y_m = \frac{\alpha . J_m^{-\beta} . C^{-\beta}}{1 - Y_m} \quad (2.15)$$

But, equation (2.5) is $X_m = I_m A$, Putting this into equation (2.15) gives,

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

Substituting for *A* gives $$A = \frac{Y_m}{I_m} + \frac{\alpha . J_m^{-\beta} . C^{-\beta}}{I_m(1 - Y_m)} \quad (2.16)$$

But, $S_T = S_A . A + S_C . C$ (2.17)

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 equation (2.14) into (2.15) gives, $$S_T = S_A\left(\frac{Y_m}{I_m} + \frac{\alpha . J_m^{-\beta} . C^{-\beta}}{I_m(1 - Y_m)}\right) + S_c . C \quad 2.18)$$

The minimum cost can be found by equating equation (2.18) to zero while finding the derivative of the total cost; i.e. $$0 = \frac{dS_T}{dC} = \left[\frac{-\alpha . J_m^{-\beta}}{I_m(1 - Y_m)} . ^{\beta}\ C^{(-\beta - 1)}\right] S_A + S_C$$

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

$$C^{(-\beta - 1)} = \frac{S_C}{S_A} \cdot \frac{I_m(1 - Y_m)}{\alpha J_m^{-\beta} \cdot \beta} \quad (2.19)$$

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

$$C_{opt} = \left[\frac{S_A}{S_C} \cdot \frac{\alpha J_m^{-\beta} \cdot \beta}{I_m(1-Y_m)} \right]^{\left(\frac{1}{\beta+1}\right)} \tag{2.20}$$

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

Substitute equation (2.16) for C_{opt} in equation (2.20) to get A_{opt} as

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

$$A_{opt} = \frac{Y_m}{I_m} + \left[\left(\beta \cdot J_m \cdot \frac{S_A}{S_C} \right)^{-\beta} \cdot \frac{\alpha}{I_m(1-Y_m)} \right]^{\frac{1}{1+\beta}} \tag{2.21}$$

Equations 2.18 and 2.20 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. 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,

$$S_{opt} = S_{A.}A_{opt} + S_{c.}C_{opt} \tag{2.22}$$

3.0 Results

By the current tariff of Power Holding Company Nigeria (PHCN), electrical energy is distributed and sold in *kWh* units. Hence, 1 unit costs #4/*kWh*. The load to be powered by this research is 15 *kWh*.

However, the average cost of the optimized plant is ₦809,800. It means that the optimized photovoltaic plant averagely cost ₦809,800/*kWh* throughout its useful lifetime. This gives a unit cost of ₦ $\frac{809,900}{15\ kWh}$ = ₦ $53993.33 / kWh$. In comparing this initial expensive cost of the optimized photovoltaic plant with the billing of the PHCN so as to be able to decide when the total cost of photovoltaic plant can match the ₦4/k*Wh*, then

Time (Years) $\frac{53993.33}{35040} = 1.540906$ years.

Table 3.1: Monthly-average total cost of the Photovoltaic plant (S_t) in Billion Naira

	CAL	IBAD	LRN	KAD	KANO	LAG	LKJ	MAD	MNA	SOK	ZAR
JAN	3.88	3.88	3.88	3.88	3.88	3.88	3.88	3.88	3.88	3.88	3.88
FEB	3.88	3.88	3.88	3.88	3.88	3.88	3.88	3.88	3.88	3.88	3.88
MAR	3.88	3.88	3.88	3.88	3.88	3.88	3.88	3.88	3.88	3.88	3.88
APR	3.88	3.88	3.88	3.88	3.88	3.88	3.88	3.88	3.88	3.88	3.88
MAY	3.88	3.88	3.88	3.88	3.88	3.88	3.88	3.88	3.88	3.88	3.88
JUN	3.88	3.88	3.88	3.88	3.88	3.88	3.88	3.88	3.88	3.88	3.88
JUL	3.88	3.88	3.88	3.88	3.88	3.88	3.88	3.88	3.88	3.88	3.88
AUG	3.88	3.88	3.88	3.88	3.88	3.88	3.88	3.88	3.88	3.88	3.88
SEP	3.88	3.88	3.88	3.88	3.88	3.88	3.88	3.88	3.88	3.88	3.88
OCT	3.88	3.88	3.88	3.88	3.88	3.88	3.88	3.88	3.88	3.88	3.88
NOV	3.88	3.88	3.88	3.88	3.88	3.88	3.88	3.88	3.88	3.88	3.88
DEC	3.88	3.88	3.88	3.88	3.88	3.88	3.88	3.88	3.88	3.88	3.88

Table 3.2: Monthly-average total cost of the optimized area of the Photovoltaic plant (S_{opt}) in Million Naira

	CAL	IBAD	LRN	KAD	KANO	LAG	LKJ	MAD	MNA	SOK	ZAR
JAN	0.825	0.823	0.817	0.815	0.813	0.826	0.819	0.819	0.812	0.813	0.816
FEB	0.845	0.838	0.832	0.832	0.831	0.843	0.835	0.834	0.833	0.831	0.833
MAR	0.877	0.866	1.242	1.241	0.860	0.871	1.243	1.243	0.865	0.858	1.243
APR	0.909	0.911	0.892	0.890	0.895	0.910	0.893	0.893	0.899	0.891	0.890
MAY	0.893	0.917	0.915	0.911	0.834	0.920	0.914	0.913	0.895	0.913	0.910
JUN	0.952	0.931	0.928	0.924	0.931	0.938	0.928	0.927	0.940	0.923	0.922
JUL	0.958	0.939	0.932	0.926	0.932	0.945	0.928	0.933	0.940	0.928	0.925
AUG	0.942	0.924	0.919	0.910	0.917	0.933	0.917	0.917	0.929	0.915	0.910
SEP	0.905	0.892	0.888	0.879	0.883	0.901	0.885	0.887	0.891	0.882	0.878
OCT	0.929	0.913	0.908	0.903	0.910	0.917	0.907	0.909	0.915	0.904	0.903
NOV	0.830	0.826	0.820	0.820	0.819	0.831	0.820	0.824	0.820	0.821	0.821
DEC	0.816	0.817	0.811	0.810	0.811	0.821	0.813	0.814	0.809	0.810	0.812

Table 3.1 and Table 3.2 present the summaries of results obtained from the application of equations (2.18) and (2.22) respectively. It is evident from this research that maximum total cost S_T calculated across the stations are the same and fixed (Table 3.1), 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 S_{opt}, the sizes of the photovoltaic plant increases but the cost reduces from Billion Naira to the ranges of ₦809,800 to ₦1,243,700 and has an overall average of ₦893,844 (Table 3.2). This means that at least, the minimum average cost of setting

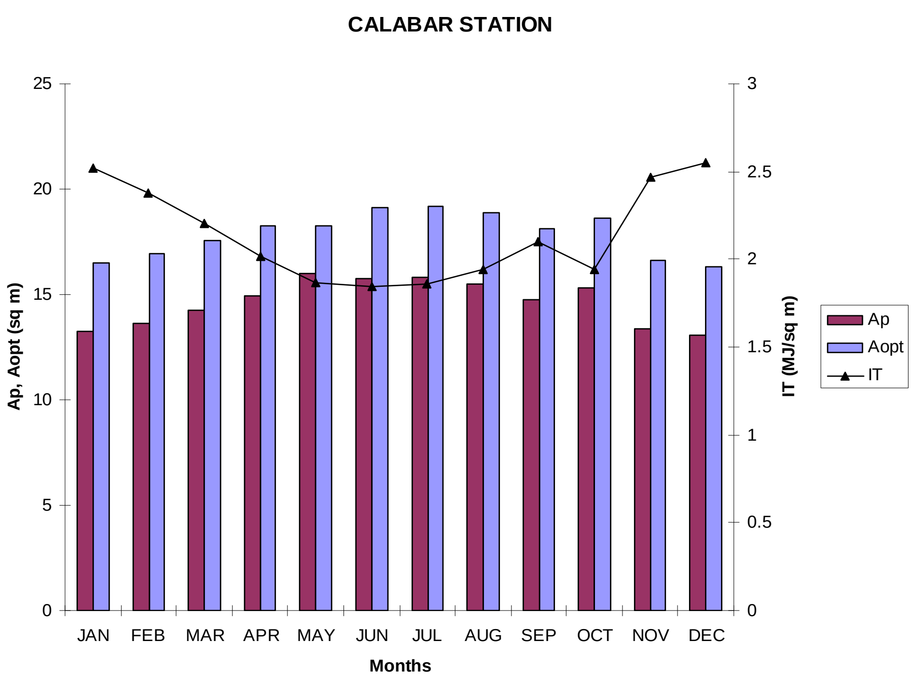

Figure 3.1: Monthly variation of area of the panel A_p, optimal area of the panel A_{opt} and the impinging solar radiation onto the photovoltaic array I_T at Calabar station.

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 results also show that it takes 1.540906 years for the total cost of photovoltaic plant to match the PHCN ₦4/*kWh*.

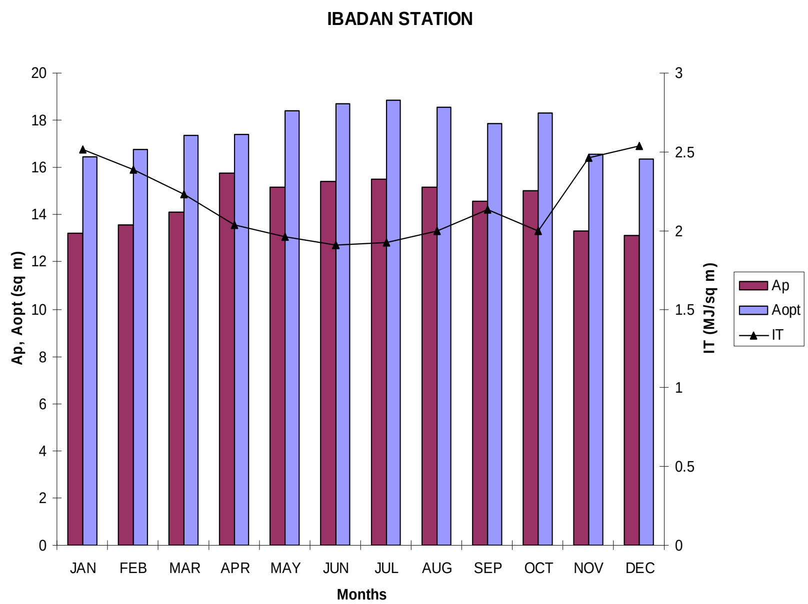

Figure 3.2: Monthly variation of area of the panel A_p, optimal area of the panel A_{opt} and the impinging solar radiation onto the photovoltaic array I_T at Ibadan station.

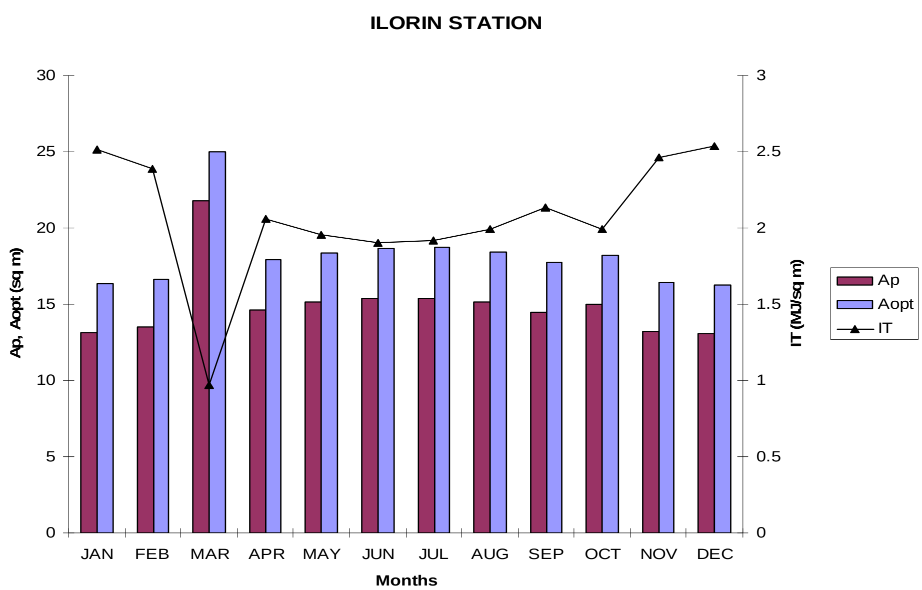

Figure 3.3: Monthly variation of area of the panel A_p, optimal area of the panel A_{opt} and the impinging solar radiation onto the photovoltaic array I_T at Ilorin station.

Also, the graphical results of the monthly-average of impinging solar radiation I_T, monthly-average area of the photovoltaic plant A_p and monthly-average optimal area of the photovoltaic plant A_{opt}, are presented in figures 3.1 to 3.11.

At Calabar, Kano and Minna stations, minimum values of I_T occurs in the month of June with value of 1.8452 MJ/m^2 each and the optimal size of the photovoltaic plant at these stations is 19.1068 m^2 at Calabar station; 18.689 m^2 at Kano; and 18.8664 m^2 at Minna.

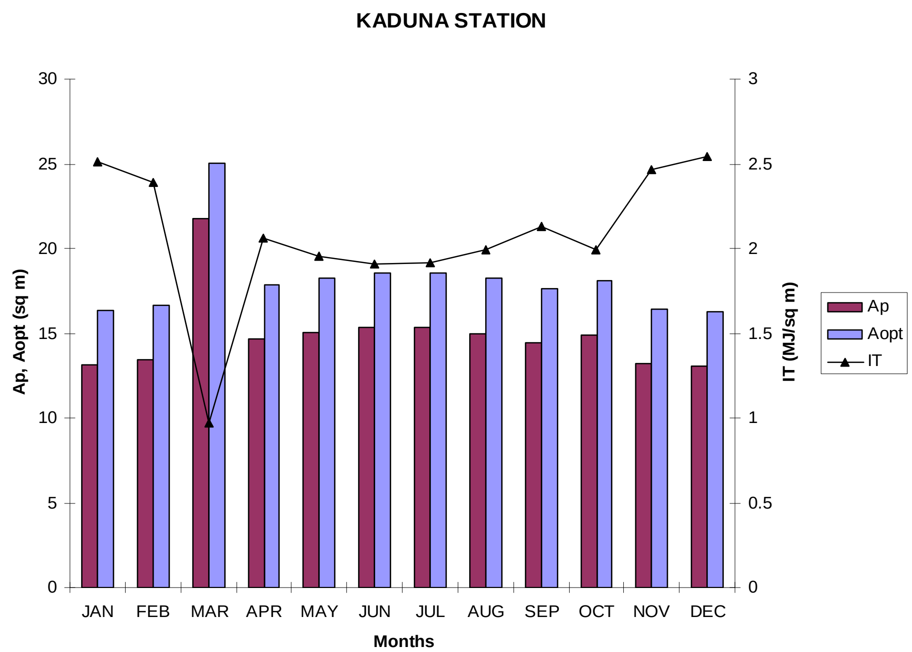

Figure 3.4: Monthly variation of area of the panel A_p, optimal area of the panel A_{opt} and the impinging solar radiation onto the photovoltaic array I_T at Kaduna station.

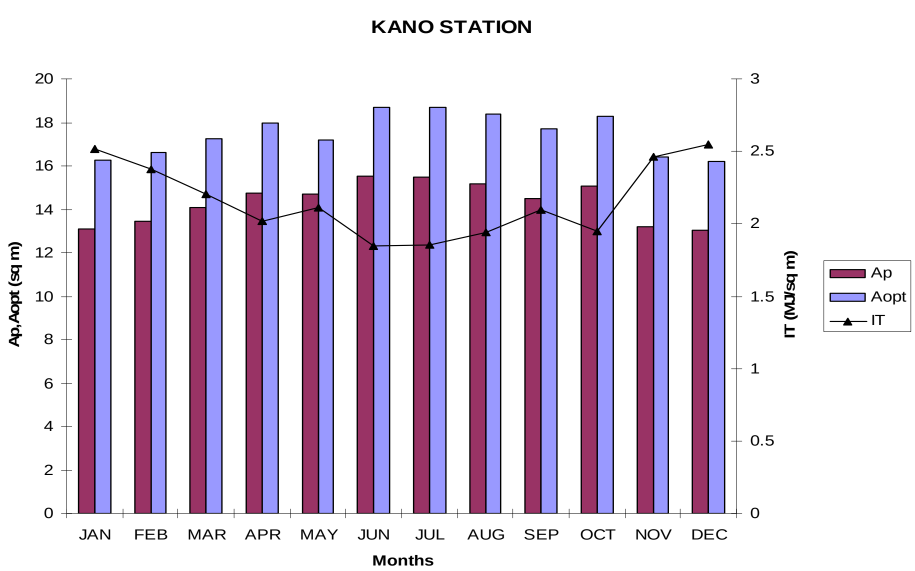

Figure 3.5: Monthly variation of area of the panel A_p, optimal area of the panel A_{opt} and the impinging solar radiation onto the photovoltaic array I_T at Kano station.

Ibadan, Lagos and Sokoto stations also experience minimum I_T in the month of June as well with value of 1.9093 MJ/m^2 for these stations. The optimal area of the Photovoltaic plant at Ibadan is 18.6858m^2; 18.8146m^2 at Lagos; 18.529m^2 at Sokoto.

The minimum I_T is having the lowest regular value of 0.9722 MJ/m^2 in the month of March at Ilorin, Kaduna, Lokoja, Zaria and Maiduguri stations. The reason for this could be as a result of sun-earth distance variation causing earth's axis tilt of $23.5°$ that result to earlier start of the wet season in the month of March. Hence, the optimal size of the photovoltaic plant is equal to 25.0299m^2 at Ilorin; 25.0058m^2 at Kaduna; 25.0576m^2 at Lokoja; 25.0536m^2 at Zaria; and 25.0520m^2 at Maiduguri. Hence, this minimum I_T having the lowest value of 0.9722 MJ/m^2 in the month of March at Ilorin, Kaduna, Lokoja, Zaria and Maiduguri stations with average optimal area of 25.0576m^2 is therefore recommended as the least size for designer and user of photovoltaic plant in Nigeria so as to be able to meet the required load for all the months.

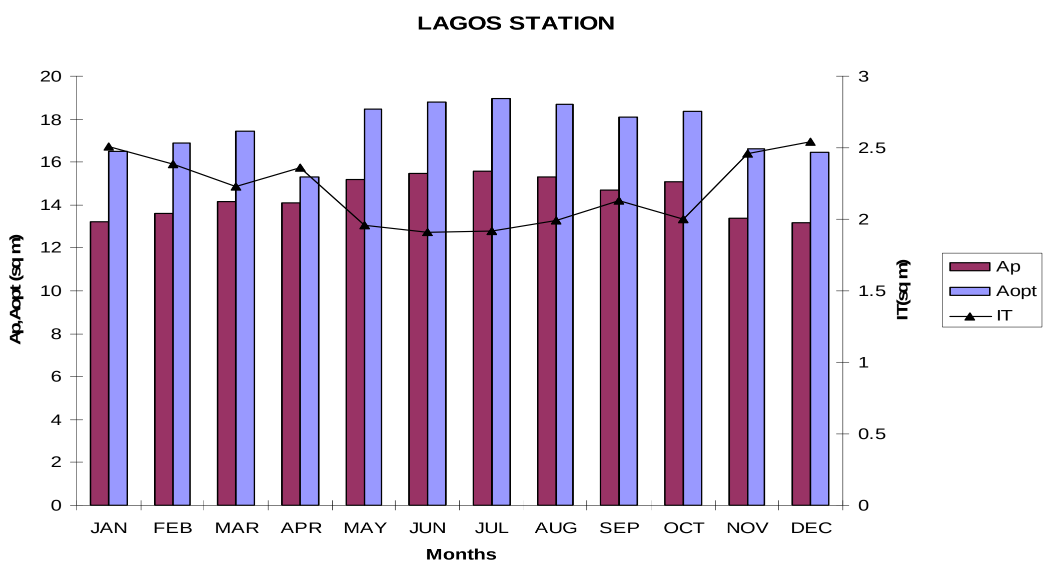

Figure 3.6: Monthly variation of area of the panel A_p, optimal area of the panel A_{opt} and the impinging solar radiation onto the photovoltaic array I_T at Lagos station.

LOKOJA STATION

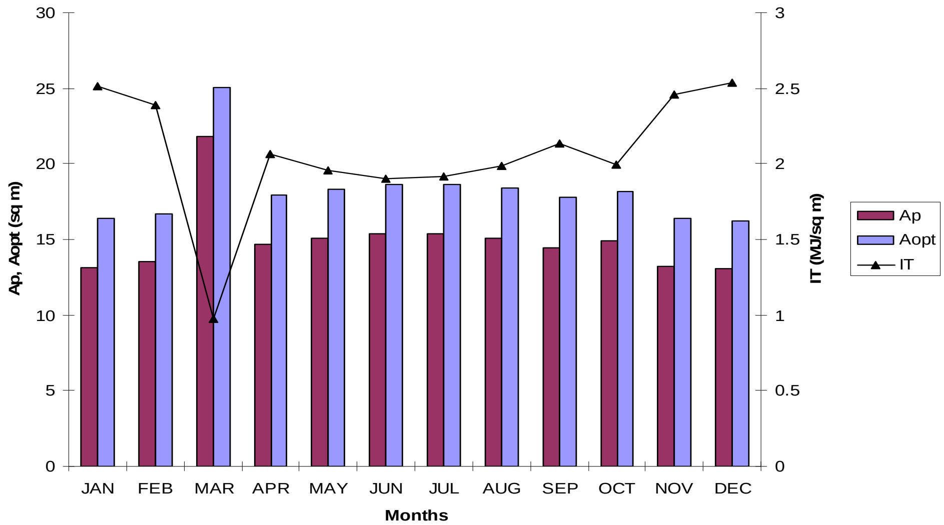

Figure 3.7: Monthly variation of area of the panel A_p, optimal area of the panel A_{opt} and the impinging solar radiation onto the photovoltaic array I_T at Lokoja station.

Maximum I_T also occur in the month of December across the station with the same value of 2.548 MJ/m^2 at Calabar, Kano and Minna; 2.537 MJ/m^2 at Ibadan, Lagos and Sokoto; 2.538 MJ/m^2 at Ilorin, Kaduna, Lokoja and Maiduguri and 2.533 MJ/m^2 at Zaria.

MAIDUGURI STATION

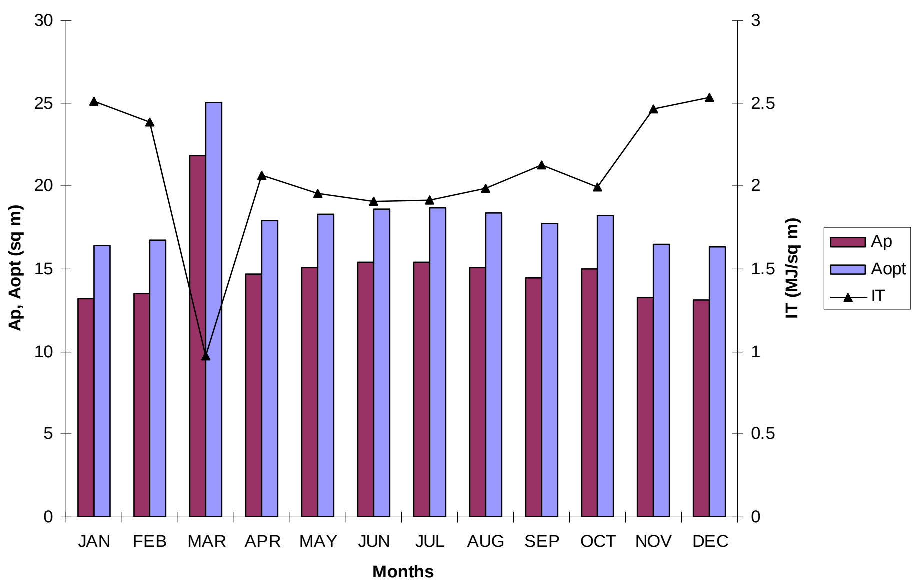

Figure 3.8: Monthly variation of area of the panel A_p, optimal area of the panel A_{opt} and the impinging solar radiation onto the photovoltaic array I_T at Maiduguri station.

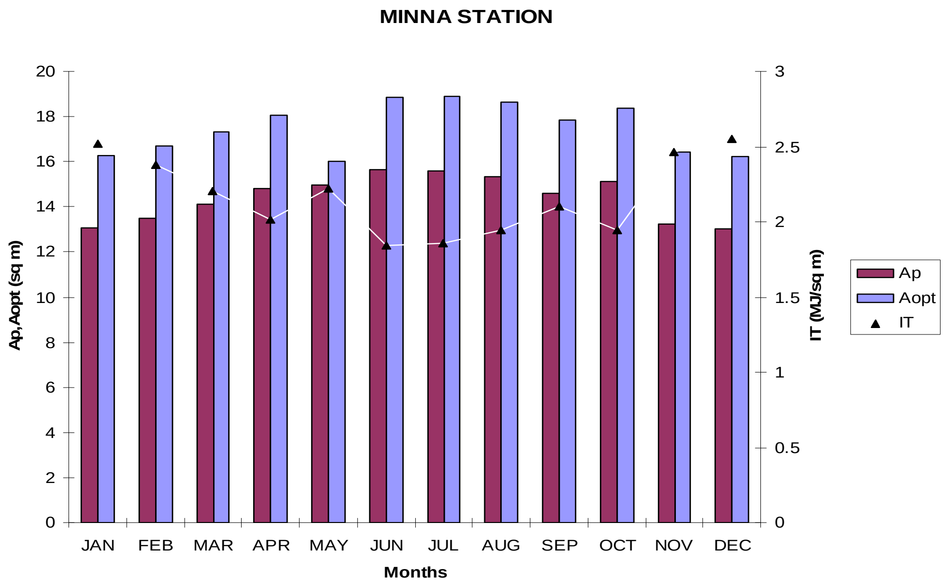

Figure 3.9: Monthly variation of area of the panel A_p, optimal area of the panel A_{opt} and the impinging solar radiation onto the photovoltaic array I_T at Minna station.

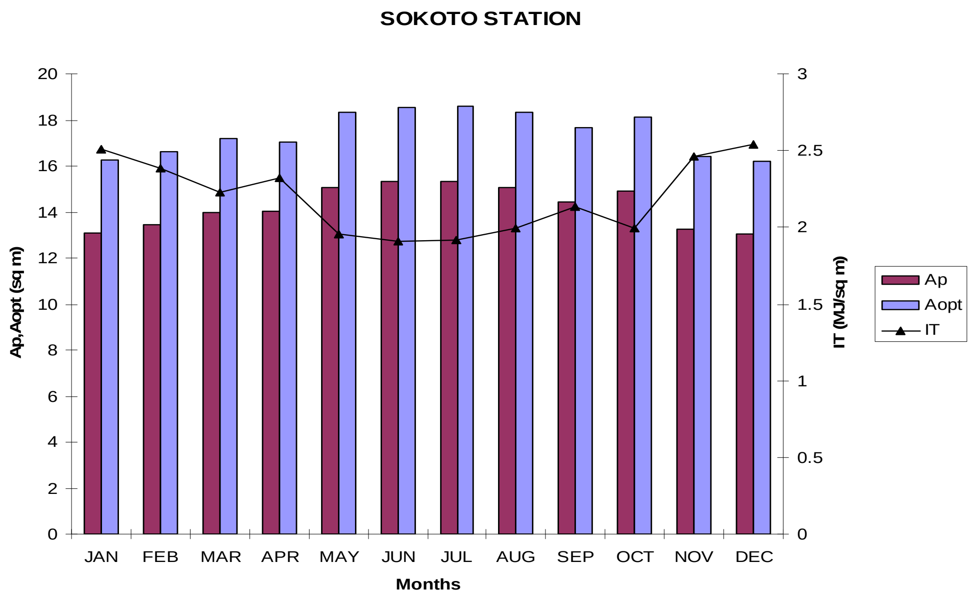

Figure 3.10: Monthly variation of area of the panel A_p, optimal area of the panel A_{opt} and the impinging solar radiation onto the photovoltaic array I_T at Sokoto station

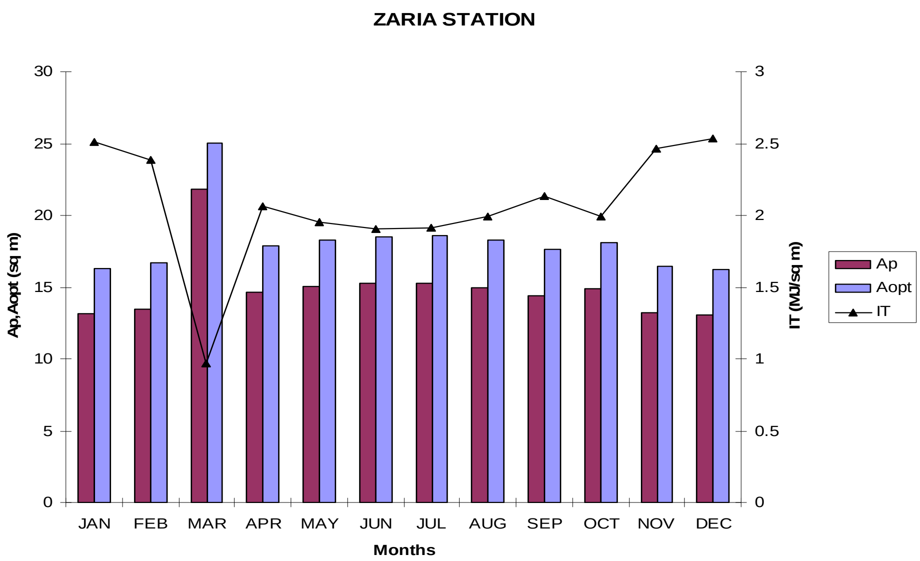

Figure 3.11: Monthly variation of area of the panel A_p, optimal area of the panel A_{opt} and the impinging solar radiation onto the photovoltaic array I_T at Zaria station.

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 mostly 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 mostly in these months; April, May, June, July and August.

4.0 Conclusion

Over 70% of uncovered solar load fraction with storage is accounted for in this work using the relations provided by Barra et al (1984) [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. Experimental and theoretical studies on life-cycle and cost-benefit of a photovoltaic plant conducted by Wong (1977) [6], showed that the optimized photovoltaic plant is short term cost effective and much cheaper than the non – optimized plant. Also, 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, therefore it is economical and reliable to use photovoltaic plant over many years than the PHCN electrical supply.

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