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# Simulation of the performance of photovoltaic system using heliophysical variables

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***Abstract***

***A method of simulating the long-term average performance of photovoltaic systems based on the observed time series of some heliophysical variables was developed and explored in this research. The data used were the sunshine duration and solar radiation intensity for years* 1990 *to* 2004 *for eleven Nigerian stations namely Calabar, Ibadan, Ilorin, Kaduna, Kano, Lagos, Lokoja, Maiduguri, Minna, Sokoto and Zaria obtained from the archives of the Nigeria Meteorological Agency, NIMET. Appropriate programs were developed using Matlab$^R$ code to model the performance 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 and the increase in the solar load fraction due to storage. Solar load fraction with storage gotten from this work ranges between* 27.2% *and* 28.2% *conversion efficiency of solar cell. Maximum incident solar radiation onto the photovoltaic array is obtainable in dry season which lead to better performance of photovoltaic electrical output and lower values of utilizability either when the excess solar load fractions are being stored or not. Minimum incident solar radiation onto the photovoltaic array is also obtainable in wet season which lead to poor performance of photovoltaic electrical output and higher values of utilizability either when the excess solar load fractions are being stored or not.***

**Keywords:** photovoltaic systems, utilizability, performance, atmospheres

## 1.0 Introduction

Solar energy utilization has been given studious attention in developed countries (ASHRAE Standard, 1977 [1]). The success of these researches has led to broad range of potential applications of solar energy, which include the heating and cooling of buildings, water heating, water desalting by evaporation, cooking, food and drug refrigeration, high-temperature material processing, specialized solar drying, electricity generation by using photovoltaic cells etc. Many of these researches have yielded very promising results in ways such that those devices in-use have been recommended to give appreciable successful applications. But, Nigeria, a country located in the tropical region, where there is acute shortage of information, researches and technologies on alternative energy and where unreliable and unsteady of electricity is dwindling the driving forces of its economy but blessed with abundant sunshine (solar energy), needs to harnessed and maximizes its ready-made solar energy to be able to supplement conventional fuel problems in her country, hence, motivate the current research on the need to simulate the performance of photovoltaic system.

The electrical energy output produced from the photovoltaic array of a photovoltaic system is resulted from solar irradiation unto the solar cells, which generate electromotive force as a result of absorption of ionizing radiation. This electrical energy output determines the performance of photovoltaic system.

The easiest type of system to analyze is the performances of photovoltaic system without storage such that all electricity produced can be used immediately for the task at hand. The problem becomes more difficult if the photovoltaic array sometimes produces energy in excess of the load. To find the total electrical energy produced by the array, the designer must estimate how much of this electrical energy can be applied directly to the load and the electrical energy produced by the array. Depending on the system, electrical energy in excess of load may be dissipated, sold to a utility grid, or stored for a later use. For systems incorporating a dedicated battery, an additional problem arises because knowledge of the amount of energy available for storage is insufficient since some of these energies may be dissipated when the storage battery is fully charged. Hence, the useful fraction of the excess energy must also be estimated.

Evans et al (1981 [7]), 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, which addressed the aforementioned problems such that the accuracy of this method appears to be quite satisfactory. The problem outlined above shall be addressed in this research in such a way that the solar load fraction shall be determined when the photovoltaic system is incorporated with a storage battery and when such facilities is not provided.

## 2.0 Photovoltaic system performance without storage

Solar radiation utilizability $\Phi$, was originally developed as a method for predicting the long-term average performance of flat plate collectors and it is defined as the fraction of incident solar radiation that exceeds a critical value of monthly average load which can be converted to useful heat that is utilized, by a collector having $F_R(\tau\alpha)=1$ and operating at a fixed inlet to ambient temperature differences. The critical level is defined as the radiation intensity $I_{T,C}$ at which the rate of electrical energy production is equal to the load L.

With this definition, $\Phi$ represents the fraction of power production which exceeds the load. Siegel et al (1972 [11]) had applied the daily utilizability method to the analysis of photovoltaic systems. The hourly utilizability algorithm allows the method of Siegel et al (1972 [11]) to be extended to accommodate loads, which vary from hour to hour.

For the ith hour of the day, the average electrical/useful output $Q_u$ of the array is;

$$Q_u = A_c F_R I_T (\tau\alpha)\Phi_i \tag{2.1}$$

Monthly-average hourly electrical energy in excess of the load $D_{o,i}$ is expressed by Clark et al (1983 [3]) as:

$$D_{o,i} = Q_u \Phi_i \tag{2.2}$$

and the maximum amount of energy which the cell can deliver to the load is

$$Q_{u,L} = Q_u(1-\Phi_i) \tag{2.3}$$

Monthly-average daily results are obtained by summing hourly quantities over all hours of the day:

$$\bar{D}_o = \frac{1}{24}\sum_i D_{o,i} \tag{2.4}$$

and

$$\bar{Q}_u = \frac{1}{24}\sum_i Q_{u,L} \tag{2.5}$$

The monthly-average fraction of the load supplied by the system without storage is:

$$X_m = \frac{\bar{Q}_u}{\bar{L}} \tag{2.6}$$

$L$ is equal to 15$kWh$ which is the load to be power by the photovoltaic plant.

## 2.1 Photovoltaic system performance with storage

Further investigation by Clark et al (1984 [4]) shows that $\overline{D}_0$ is the excess energy which cannot be sent directly to the load, it must be dissipated, sold or stored. In this section, a correlation is developed for

estimating $\Delta W_m$, defined as the increase in the solar load fraction due to the addition of storage as,

$$\Delta W_m = Y_m - X_m \tag{2.7}$$

$Y_m$ is the solar load fraction covered by the system with storage.

If $\overline{D}_0$ could be stored, the resulting values of $\Delta W_m$ would be:

$$\frac{\bar{D}_o \eta_b}{\bar{L}} \text{ Usually denoted by } d_o \tag{2.8}$$

Where $\eta_b$ is the battery storage efficiency. Physical constraints that limit the possible values of $\Delta W_m$ are:

(i) If $d_o$ is much less than, the ratio of the storage capacity due to the average load, then the battery will not be filled, and energy dissipation from the system with storage is zero. Regardless of the storage capacity, this limiting case occurs as $d_o$ approaches zero.

$$\lim_{d \to 0} \Delta W_m = 0 \tag{2.9}$$

(ii) A quantity $\Delta W_m$ can be defined for a very large value of $d_o$ where the energy available for storage becomes very large relative to the load.

$$\Delta W_{\max} = \lim_{d \to 0} \Delta W_m \tag{2.10}$$

$\Delta W_m$ cannot exceed $1-X_m$ since the load fraction supplied by the system cannot exceed unity.

$$Lim \Delta W_m \leq 1 - X_m \tag{2.11}$$

Therefore, for conveniently large $d_o$, all the daytime portion of the load will be satisfied directly from the photovoltaic array. The battery will then be discharged only at night. $\Delta W_m$ may also be limited by the effective daily storage capacity of the battery relative to the load

$$\lim_{d_0 \to \infty} \Delta W_m \leq \frac{B_c}{\overline{L}} \tag{2.12}$$

The limiting value of $\Delta W_m$ as $d_o$ become very large can be explicitly expressed by combining equations (2.10) and (2.12) such that:

$$\Delta W_{\max} = \text{Min } (1-X_m, \frac{B_c}{\overline{L}} \tag{2.13}$$

Hence, the equation for $W_m$ which satisfies the constraints estimated above for both very large and very small values of $d_o$ is:

$$\Delta W_m = \frac{1}{2A} \{ d_o + \Delta W_{\max} - [( d_o + \Delta W_{\max} )^2 - 4A\, d_o\, \Delta W_{\max}]^{1/2} \} \tag{2.14}$$

A, the only parameter with free degree of freedom can be used to vary the rate at which $\Delta W_m$ approaches $\Delta W_{\max}$ as $d_o$ increases. By adjusting the value of A, equation (3.8) is good for all battery sizes as well as for all values of $d_o$.

Clark et al (1984 [4]) based on 73 yrs of hourly simulations, using 15 diurnal load profiles in Seattle, Madison and Albuquerque climates, the following empirical correlation for the parameter A was developed for battery storage capacities ranging from 0 to 2 $\bar{L}$ .

$$A = 1.315 - 0.1059 \frac{X_m \bar{L}}{B_c} - \frac{0.1847}{\overline{K_T}} \tag{2.15}$$

where $\bar{K}_T$ is the monthly-average clearness index which is defined as the ratio of monthly radiation on the horizontal surface to the extraterrestrial radiation.

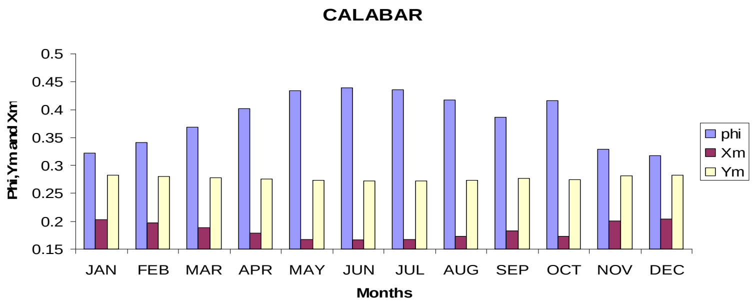


**Figure 2.1**: Calabar station

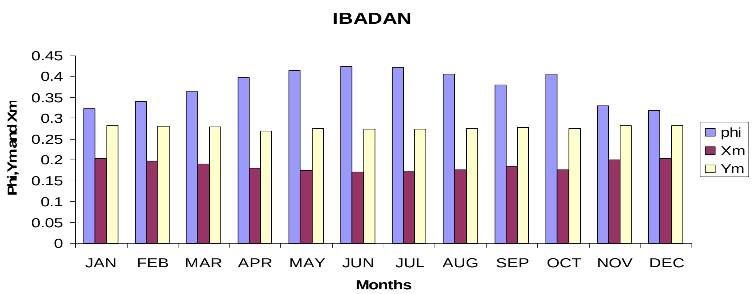


**Figure 2.2:** Ibadan station

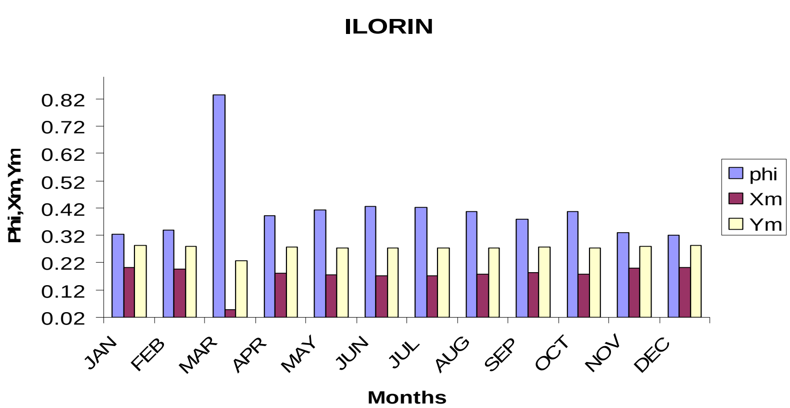


**Figure 2.3**: Ilorin station

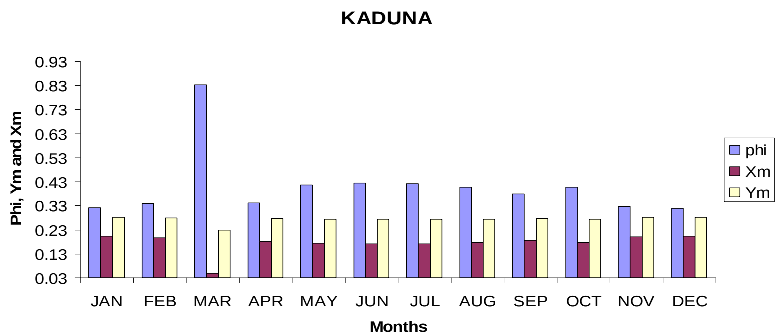


**Figure 2.4**: Kaduna station

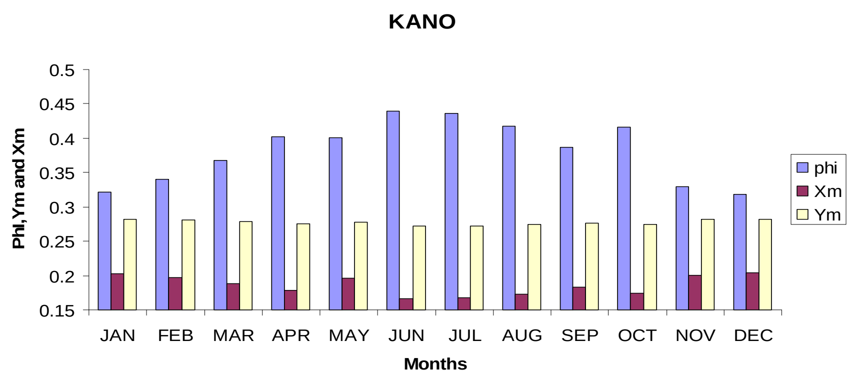


**Figure 2.5**: Kano station

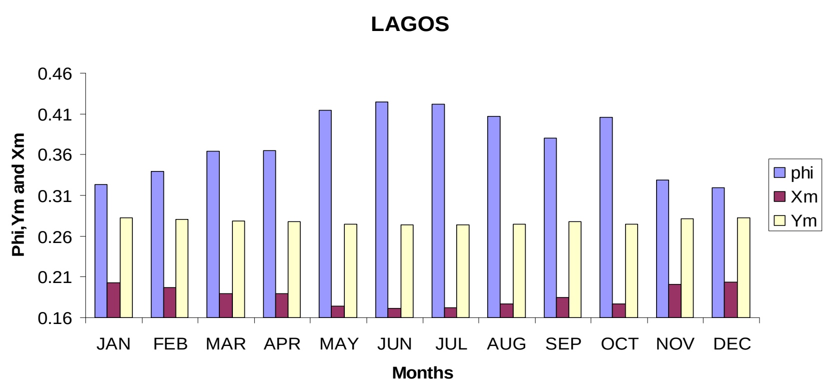


**Figure 2.6**: Lagos station

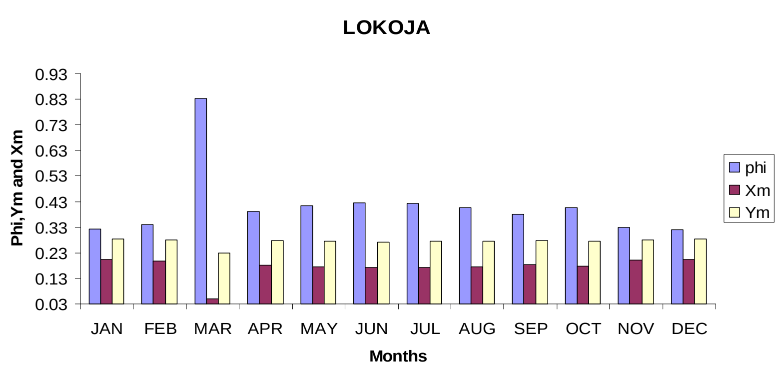

**Figure 2.7**: Lokoja station

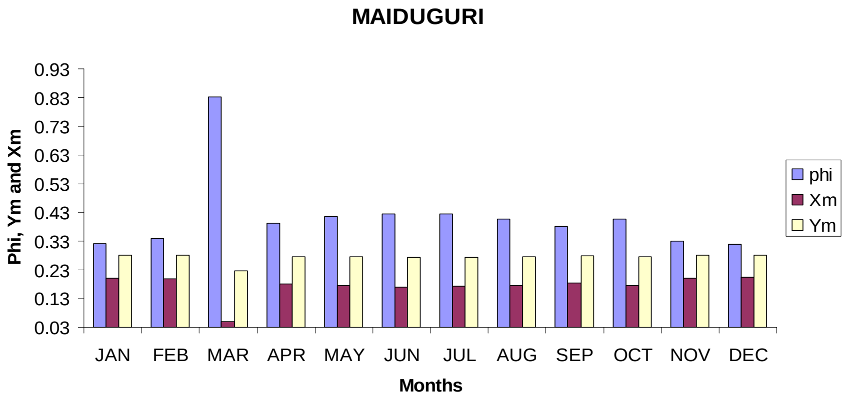


**Figure 2.8**: Maiduguri station





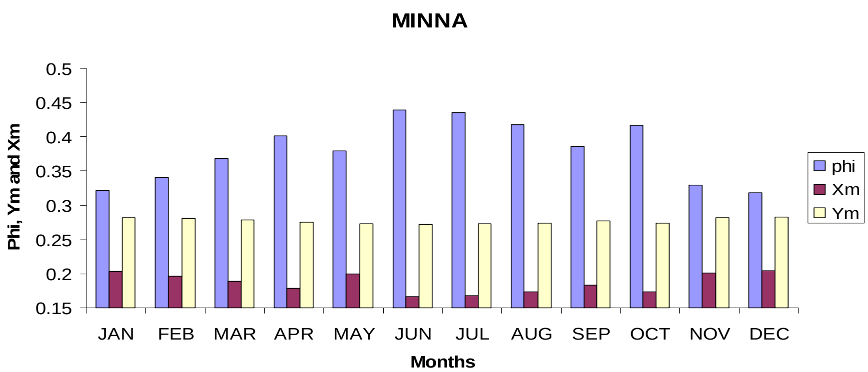


**Figure 2.9:** Minna station

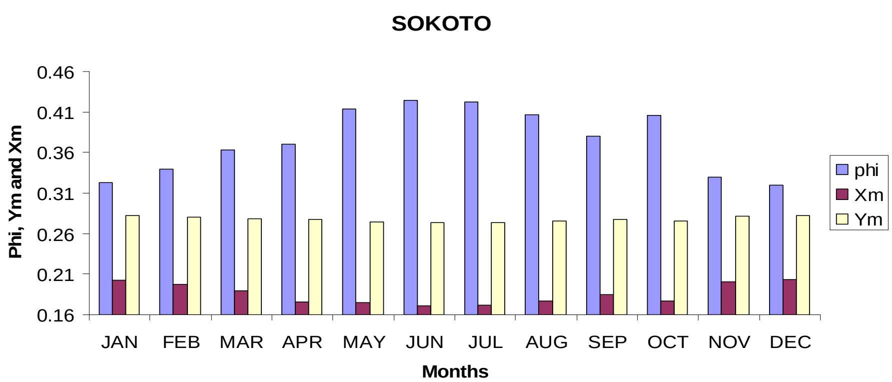


**Figure 2.10**: Sokoto station

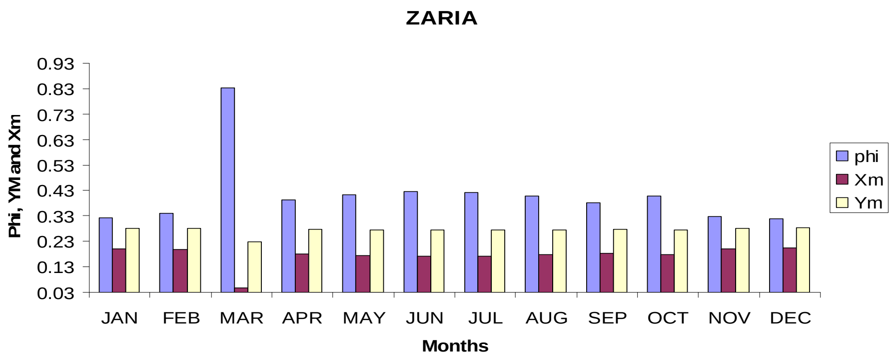


**Figure 2.11**: Zaria station

## 3.0 Results

The annual means of $Y_m$ falls within the range 0.275 ± 0.02 across the stations, which implies that $Y_m$ is almost uniform with low deviations across the stations considered. The annual means of $X_m$ fall within the range 0.174 – 0.186 across the stations, which implies that $X_m$ is almost uniform with low deviations across the stations considered. The annual means of $\phi$ fall within the range 0.374 – 0.416 across the stations, which implies that, $\phi$ is almost uniform with low deviations across the stations considered. This may be due to receiving solar radiation almost at the same value ranges over the country (Nigeria) as a result of two equinoxes

Monthly variations exist in $\phi$, $Y_m$, and $X_m$ across the stations. The results clearly showed that high values of utilizability are associated with low fractions of useful electrical output with or without storage across the stations. The increase and decrease in utilizability as a function of solar load fraction are attributed to the seasonal variation pattern in the tropical Nigeria, namely: dry and wet season.

The reason for this is that lower values of incident solar radiation was being impinging onto the solar photovoltaic array which results in higher values of utilizability which cannot be converted to useful electrical energy to meet the monthly average load of the photovoltaic plant [9], and the end result is lower values of fraction of useful electrical output. Also, high values of incident solar radiation will result in low values of utilizability and the end result is high values of fraction of useful electrical output.

At Calabar, Ibadan, Kano, Lagos, Minna, and Sokoto stations high values of utilizability are witnessed in the months of April, May, June, July, August, and September; the corresponding results of the fraction of the useful electrical output with and without storage are lesser in these stations. These lesser values of useful electrical output reveal that wet season is predominant at these months which are characterized by increased cloud cover and precipitate water, poor sky condition caused by atmospheric controls as the atmosphere is partly cloudy and has lower values of clearness index [8].

In the month of October to March, lesser values of utilizability associated with higher values of fraction of useful electrical outputs with or without storage are experienced in the dry season characterized with clear skies, lower precipitate water and higher values of clearness index are responsible for the appreciable values of solar load fraction either when stored or not.

The utilizability value is more pronounced, with regular value of 0.8338 MJ/$m^2$, at Ilorin, Kaduna, Lokoja, Maiduguri and Zaria in the month of March. The corresponding fraction of the useful electrical output without storage across these stations in the month of March is 0.1973 and the fraction of the useful electrical output with storage this same month is 0.2808. These values of $X_m$ and $Y_m$ at Ilorin, Kaduna, Lokoja, Maiduguri and Zaria in the month of March are smaller than other months. The reason for this higher value of utilizability in this month of March which is expected to be lower because it falls within the month of dry season according to the seasonal pattern in the tropics, and is expected to yield higher values of useful electrical outputs 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, meanwhile the wet season is expected to start in the month of April proper in the tropics. For this reason, pronounced values of utilizability occur in this month as a result of low solar irradiation. Other months in these stations experience the same seasonal variation pattern as Calabar, Ibadan, Kano, Lagos, Minna and Sokoto station.

Figures 2.1 to 2.11 explain generally that those highest values of fraction of useful electrical output with or without storage are witnessed in the month of December across the stations which also show that the month of December has corresponding least values of utilizability. December falls within dry season in Nigeria (Rabiu et al; 2005) and is equally within the December solstice when the sunlight hours are more over the country.

In addition, it is clear from Figures 2.1 to 2.11 that the load fractions of the useful electrical output with storage ($Y_m$ ) at all stations are greater than the load fractions of the useful electrical output without storage ($X_m$) in every month. The reason for this is that ($Y_m$ ) has a battery as back up that stores most of the excess useful electrical output of the photovoltaic system such that, this excess is much less than the ratio of the battery capacity to the average load. The consequence of this is that the battery will be able to accommodate more solar load fraction and dissipation of excess useful electrical output will never happen. Photovoltaic system ($X_m$) has no back up (battery), that is, without storage. The result of this is that the excess fraction of the useful electrical output are wasted, hence there will be lesser output of solar load fraction that will be met by the system ($X_m$) compare to ($Y_m$ ).

## 4.0 Conclusion

The results of this work show that the solar load fraction with storage range between 27.2% and 28.2% conversion efficiency of solar cell. Garg and Prakash (1997) reveals that the conversion efficiency of solar cell is 30%, this value is very low and accounted for over 70% loss of useful electrical energy output which cannot be stored or useable for any task (utilizability). This research also reveals that the utilizability is much higher compared to the covered load fraction throughout all the stations which is as a result of obsolete equipments used in collection of solar radiation. Hence, more work is needed to develop real time solar radiation measurements and to do more research on the efficiency of the solar cell thin-film fabrication and technology in order to improve its efficiency to at least 50% in order to give better covered solar load fraction and lesser utilizability for better performance of photovoltaic system in future.

Finally, this research also shows that maximum incident solar radiation $I_T$ onto the photovoltaic array is obtainable in dry season which leads to better performance of photovoltaic electrical output compared to wet season either when the excess solar load fractions are being stored or not.

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