Estimation of Mean Monthly Solar Radiation Components and Clearness Index

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Abstract: Estimation of the component of solar radiation was carried out to ascertain the feasibility of solar energy utilization in sudan and fresh water swamp vegetation zones, Nigeria. The results showed that the variation of direct and diffuse component of solar radiation is a function of the atmospheric conditions and elevation. A seasonal range of 0.477 – 0.664 and 0.377 – 0.567 for sudan and fresh water swamp respectively, were obtained. Also, correlation coefficient of more than 99% between the direct and diffuse component with clearness index, was obtained for all the zones.

Keywords: Direct solar radiation, diffuse solar radiation, Clearness index, vegetation zone, solar radiation.

I. INTRODUCTION

Common meteorological data such as temperature and relative humidity are usually easier to access than solar radiation data or its components. However, the need for solar radiation data bank for any particular region of interest has necessitated the development of different types of models to enable the estimation and application of such a vital parameter.

As radiant energy passes through the earth’s atmosphere, due to attenuation, part of it is absorbed (the reason for some atmospheric heating), reflected (the reason why astronauts can see the earth from outer space), scattered (the reason one can read a book in the shade under a tree), and transmitted directly (the reason there are shadows). At the surface of the earth, the sun has a lower intensity, a different color, and a different shape from that observed above the atmosphere. The result is the perception of solar rays as beam solar component or diffuse solar component, which appear to come from all over the entire sky. The sum of beam and diffuse solar component is called the global or total solar irradiance.

Only few stations, out of the total number of stations that record global solar radiation, measure these components. Therefore, it has become pertinent to estimate these components through the use of computational techniques.

For a country like Nigeria, the economical and efficient application of solar energy seems inevitable because of abundant radiant energy, through the year. Several literatures exist on the relation between sunshine duration and global solar radiation, for some selected locations [1] – [7]. Nevertheless information is scarce on the distribution of these components in the country. Therefore, the main objective of this paper is to examine some selected models for estimating the mean monthly components in relation to global solar radiation at the surface across the sudan and fresh water swamp vegetation zones in Nigeria.

II. MATERIALS AND METHODS

A. Site description

As shown in figure 1, the Fresh water swamp vegetation lies along the coast the equatorial maritime air mass influences the climate, which characterized by high humidity and heavy rainfall. Whereas the sudan vegetation zone lies along the northern part of the country, the tropical continental air mass brings dry, dusty winds from the sahara. The temperature varies considerably with season, as does rainfall, which is far less than in the fresh water swamp.
B. Meteorological data

Table 1 gives the description of the sites used in the present analysis, with respect to figure 1. Also, thirty (30) years data of measured global solar radiation were obtained from the archives of the Nigerian Meteorological Agency from 1981 – 2010.

Table I
Geographical locations of selected areas

<table>
<thead>
<tr>
<th>Station</th>
<th>Longitude ('N)</th>
<th>Latitude ('E)</th>
<th>Height (m. a.s.l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kano</td>
<td>8.53</td>
<td>12.05</td>
<td>714</td>
</tr>
<tr>
<td>Sokoto</td>
<td>5.25</td>
<td>13.02</td>
<td>350.75</td>
</tr>
<tr>
<td>Port-Harcourt</td>
<td>7.02</td>
<td>4.85</td>
<td>195.51</td>
</tr>
</tbody>
</table>

C. Theoretical background

Different types of empirical models, for predicting monthly global solar radiation, as a function of readily measured meteorological data have been developed. The daily mean global solar radiation at the top of the atmosphere, $I_0$, was estimated using the empirical equations provided as [8]:

$$I_0 = \frac{I_{so}}{\pi} \left(\frac{d_{oo}}{d}\right)^2 \left(\sin \phi \cos \delta + \cos \phi \cos \delta \sin \phi \sin h\right)$$  \hspace{1cm} (1)

where

$$h = \cos^{-1}(-\tan \phi \tan \delta)$$  \hspace{1cm} (2)

$$\left(\frac{d_{oo}}{d}\right)^2 = 1.000 + 0.0342 \cos \eta + 0.001 \sin \eta + 0.0007 \cos 2\eta + 0.0001 \sin 2\eta$$  \hspace{1cm} (3)

$$\delta = \sin^{-1}(0.398 \times \sin \phi)$$  \hspace{1cm} (4)

$$a_2 = 4.871 + \eta + 0.033 \sin \eta$$  \hspace{1cm} (5)

$$\eta = \left(\frac{2\pi}{365}\right) \times i$$  \hspace{1cm} (6)

the daily accumulated global solar radiation at the top of the atmosphere, $H_o$ (MJ/m$^2$day), was obtained from the daily mean values of $I_0$ by unit adjustment through

$$H_o = I_o \times 24 \times 3600 \times 10^{-6}$$  \hspace{1cm} (7)

where $I_{so}$ Solar constant 1365W/m$^2$

$I_o$ Daily mean global solar radiation at the top of the atmosphere (W/m$^2$)

d$_{oo}$ distance between sun and globe (km)

d Average distance between sun and globe (km)

$h$ Hour angle of the sun between sunrise and altitude and culminating altitude (rad)

$i$ = Julian day (day)

$\phi$ = altitude (rad)

$\delta$ = declination of the sun (rad)

D. Prediction of diffuse solar radiation, $H_d$

The diffuse solar radiation $H_d$ can be estimated by an empirical formula which correlates the diffuse solar radiation component $H_d$ to the daily total radiation $H$. The correlation equation which is widely used is developed as [9]:

$$\frac{H_d}{H} = 1.00 - 1.13K_T$$  \hspace{1cm} (8)

Where $H_d$ is the monthly yearly component of diffuse solar radiation and $K_T$ is the clearness index defined as [10]:

Another commonly used correlation is due to Liu and Jordan [10] as:

$$H_d = 1.3904 - 4.027K_T + 5.53K_T^2 - 3.108K_T^3$$  \hspace{1cm} (9)

However, global solar radiation under cloudless sky conditions $H$ reaching the earth surface is defined as the sum of the direct beam solar radiation and diffuse solar radiation as [2]:

$$H = H_d + H_b$$  \hspace{1cm} (10)

The clearness index, $K_T$, is defined as the ratio of the global horizontal irradiance at the surface and the global horizontal extraterrestrial irradiance as shown below:

$$k_T = \frac{H}{H_0}$$  \hspace{1cm} (11)

where $H$ is irradiance on the surface
III. RESULTS AND DISCUSSION.

Figure 2 and 3 present the ratios of diffuse to global solar radiation and extraterrestrial radiation estimated by two different methods Page, and Liu and Jordan methods. The transmission through the atmosphere $K_t$ along with the ratios of diffuse and direct in global solar radiation is shown in figure 2 and 3. From the estimated results, it is very clear that the contribution of fraction of diffuse component of solar radiation is very low throughout the year with the exception of the monsoon (peak of rainy season) months. Liu and Jordan methods predict higher values than Page correlation. However, the transmission of $H_d$ and $H_b$ in extraterrestrial radiation were approximately 22.1 and 18.9 percent, respectively.

Large variations in the intensities of the fraction of diffuse and direct components observed were due to cloudiness. The results of the variation were as indicated in figure 2 and 4 to exhibits the trend of percentage variation of both diffuse and direct components. The maxima for the fraction of direct components are quite appreciable which corresponds with high values of $K_t$. Therefore, for all the zones the percentage of fraction of diffuse radiation contributing to global radiation is low during clear sky months (April to September) and does not exceed 50 percent. These values confirmed the high value of $K_t$ and low values of diffuse component of global solar radiation.

It was equally noticed that for Sudan vegetation the values of $k$, $H_d/H$ (for Page method) for the months of July and August the values are nearly the same, while there are big differences between them for the remaining months. This could be attributed to the fact that July and August corresponds to the peak of rainy season in the zone.

However, the characterization of monthly average values for the ratio of diffuse irradiance for fresh water swamp clearly indicate high diffuse content in the total radiation received. Hence, the influence of solar elevation and clearness index, for any given location, contribute to the amount of solar radiation received, since its intensity is function of clarity of the sky.

From the different vegetation zones under investigation, it can be inferred that the variability of the clearness index increased in the drier/hot season of the year and decreased in the wet/rainy season. The following seasonal ranges for the various zones are: Sudan (0.477-0.664) and fresh water swamp (0.377-0.567).

A. Variation of fraction of direct component with clearness index

The results of variation of ratio of direct component to global solar radiation and clearness index are presented in figure 4 and 5. The plot of monthly mean direct fraction of global solar radiation with clearness index for all the zones appeared to be a linear relationship with dimensionless constant, as indicated by the linear equation. A correlation coefficient of unity was almost achieved for all the zones. However, lower values of diffuse fraction correspond to lower value of clearness index and vice versa. The least variable sky conditions occurred within the months of June and July and the highest within December and January for the zones. Therefore, the variation in sky conditions will be according to prevailing atmospheric conditions in different seasons.

Generally, the high values of correlation of determination, $R^2$, across the variables imply that 99.54% to 100% of the ratio of direct component to global solar radiation can be accounted by the clearness index. This further demonstrate the degree of statistically significant relationships between the ratio and clearness index.
B. Variation of diffuse component with clearness index

The results of variation of fraction diffuse component of global solar radiation with clearness index are presented in figure 6 and 7. From the results, the value of diffuse component decreased with increased clearness index. Also from analysis of results fresh water swamp vegetations received more diffuse radiation than Sudan vegetation zones. The difference could be attributed to the different climatic condition that prevails at these zones. Moreover, the results indicate that the diffuse component is lower in hot/drier season whereas the values increased in the wet/rainy season due to the presence of clouds and high moisture content in the sky. The regression coefficient from linear fit signifies excellent results that could be used to determine the diffuse component within any given vegetation zone.

Correlation determination, $R^2$, of more than 99% existed within the various vegetation zones, which implies that almost one hundred percent of the ratio of diffuse component to the global solar radiation can be accounted for using clearness index.

IV. CONCLUSION

The work reported in this paper indicates the primary importance quantifying the components of global solar radiation and clearness index with respect to social and technological prospective development.

The results of analysis from Page method and Liu and Jordan method indicate similar results for all the vegetation zones. Thus, solar elevation, climatic conditions and season contribute significantly to the percentage of direct and diffuse radiation received at any given location. Also, from both methods, sudan vegetation zones receives higher percentage of direct irradiance compared to fresh water swamp.

From the above results and considerations, the correlation coefficient greater than 99%, for the estimation of direct and diffuse component from clearness index is very encouraging.

REFERENCES