



NBRRI REPORT NO. 8

DEVELOPMENT OF SOLAR RADIATION MODELS FOR NIGERIA

FOREWORD

This report describes the development of solar radiation models for Nigeria undertaken by the Nigerian Building and Road Research Institute. The models are based on data from direct measurement undertaken by the Institute (Chandra and Oguntuase, 1986)* and from meteorological data collected over the period 1951 - 1986 from forty stations in Nigeria maintained by the Meteorological Department, Federal Ministry of Aviation, Oshodi, Lagos.

These models can be used in evaluating future direct measurements of solar radiation and estimating solar radiation in remote areas where there are no direct measurements. Furthermore, these models provide mathematical expressions which can be used in theoretical analysis of solar energy related problems.

I recommend this report as deserving close study by Nigerian scientists working in this field.

A. O. Madedor
Director

February, 1993

*Chandra, M and Oguntuase, O. 1986: Measurements of global solar radiation in Nigeria. NBRI Report No.7, 186pp.

BACKGROUND

A reliable estimate of the amount of solar radiation in Nigeria will be of significant use in the development of economical and efficient solar devices. The resulting data will be found useful by building designers and engineers in the design of energy efficient buildings with excellent indoor thermal comfort and in the design of other solar energy devices.

The Nigerian Building and Road Research Institute established thirty solar stations in Nigeria where pyranometers and other major equipment were installed to provide such data. Equipment malfunction at some of the stations and lack of spare parts hampered measurements. The erratic nature of direct measurement of incident solar radiation in many of these places necessitates the search for models that can be used in obtaining these data. Also, there is need for solar radiation estimates in remote areas where there are no direct measurements. The models developed here can be used to improve past and present solar radiation records in Nigeria.

Methods are proposed to take care of the erratic nature of direct measurements. Using regression techniques, models are developed correlating available measurements of global solar radiation with meteorological data. The models are then used to determine values of solar radiation incident on horizontal and tilted surfaces.

1.0 INTRODUCTION

In the design of solar energy systems and devices for applications in various facets of human needs, such as providing reliable and adequate power supply for agriculture, telecommunications, industrial and economic development of the rural communities; solar radiation data are required. The minimum and maximum bounds of solar radiation design data will also be useful in the selection of advance materials for solar energy systems design. Also, the availability of adequate solar radiation data forms the bedrock of solar technology applications in buildings.

There is need for models that can be used in evaluating these data on horizon-

tal and tilted surfaces. The global (Total) insolation, the diffuse and direct components of the solar radiation are needed in evaluating the solar load on flat-plate collectors, solar stills, solar cells panels, window panes and louvers, walls and in designing shading devices. These models are being developed for use in areas where such data are not available.

Sayigh (1) listed a compendium of models, some of which use temperature, relative humidity, sunshine hours, latitudes, rainy days and air mass. The Angstrom - Page and the Liu and Jordan models (2) turn out to be mostly used. Some models were used for specific stations in Nigeria with limited satisfaction (3 - 6). Ezeilo and Ezekwe (3) used the modified Swatman and Ogunlade's formula for Nsukka. Sanbo (4) used same for Kano and Bamiro and Ideriah (5,6) developed some empirical relations for Ibadan.

Models developed here use multiple regression techniques in correlating the measured solar radiation with meteorological data. The models are used to estimate the solar radiation incident on horizontal and inclined surfaces. This work is meant to improve the quality of current and past records of solar radiation in Nigeria.

The mean monthly values of sunshine hours (S), maximum and minimum temperatures (T), relative humidity (R), cloud cover (C), mean number of rainy days (r), altitude and latitude of the stations are obtained for 40 stations/towns in Nigeria over a period of about 36 years (1951 - 1986). Measured values of global solar radiation are also obtained for all the stations for 1976 - 1986 (7). The observations were obtained from the published and unpublished normals of The Meteorological Department, Federal Ministry of Aviation, Oshodi - Lagos; and Nigerian Building and Road Research Institute, Lagos which has thirty solar stations all over Nigeria (7, 8).

1.1 Solar Radiation

The amount of solar radiation reaching the earth from the sun is inversely proportional to the square of its distance from the sun. The revolution of the earth around the sun in an elliptical

orbit results in eccentricity in the earth's orbit. The rotation of the earth about the polar axis results in diurnal variations in incident radiation while the rotation in the elliptic plane results in seasonal changes (1, 8).

The mean monthly extraterrestrial radiation on a horizontal surface for a period of one day from sunset to sunrise is computed using the expression

$$H_0 = \frac{24 \times 3600}{\pi} \times I_0 \times E_0 \left[\cos \theta \cos \delta \sin w_s + \frac{2\pi w_s \sin \theta \sin \delta}{360} \right] \dots\dots\dots(1)$$

where I_0 , the intensity of solar radiation on a surface normal to the sun rays beyond the atmosphere at mean sun-earth distance is called the solar constant. The National Aeronautical and Space Agency (NASA) value of I_0 is 1353 W/m^2 and the World Radiometric Reference (WRR) is 1367 W/m^2 (8-10), the eccentricity factor E_0 of the orbit as used by Duffie and Beckman (8, 12) is

$$E_0 = 1 + 0.033 \cos (2\pi N/365) \dots\dots\dots(2)$$

The solar declination, δ , is given in degrees by the Copper's formula (8, 13)

$$\delta = 23.45 \sin \left[\frac{360}{365} (N + 284) \right] \dots\dots\dots(3)$$

the sunrise and sunset hour angle, w_s is given by

$$w_s = \cos^{-1} (-\tan \delta \tan \theta) \dots\dots\dots(4)$$

and the length of day, N_0 (the actual maximum possible sunshine duration in hours) is given by the Copper's formula (8, 12)

$$N_0 = \frac{2}{15} \cos^{-1} (-\tan \delta \tan \theta) \dots\dots\dots(5)$$

θ is the latitude of the place, n is the duration of possible sunshine in hours and N is the number of days (relative to January 1) or number of days in the month. Variations in the solar constant, I_0 , the solar declination, δ and the length of day, N_0 are given in cable 1 for Lagos Lat 6.45°N. This compares favourably with the values given in table 2 due to Iqba (8).

The trigonometric relations describing the relation between the sun, the horizontal and the inclined/tilted surfaces as shown in Fig.1, are fully discussed in references (1) and (8).

The following accurate expressions for δ (in radians) and E_0 were developed by Spencer (8, 9, 14).

$$\delta = 0.006918 - 0.399912 \cos \sqrt{\quad} + 0.07257 \sin \sqrt{\quad} - 0.006758 \cos 2\sqrt{\quad} + 0.000907 \sin 2\sqrt{\quad} - 0.002697 \cos 3\sqrt{\quad} + 0.00148 \sin 3\sqrt{\quad} \dots\dots(6)$$

$$E_0 = 1.00011 + 0.034221 \cos \sqrt{\quad} + 0.001280 \sin \sqrt{\quad} + 0.000719 \cos 2\sqrt{\quad} + 0.000077 \sin 2\sqrt{\quad} \dots\dots(7)$$

$$\text{where } \sqrt{\quad} = 2\pi(N-1)/365 \dots\dots\dots(8)$$

$\sqrt{\quad}$ is called the day angle in radians.

The monthly maximum possible sunshine duration in hours as recorded on a Campbell - Stokes sunshine recorder, N'_0 , is given as (9, 15)

$$N'_0 = \frac{2}{15} \cos^{-1} \left(\frac{\cos 85^\circ - \sin \theta \sin \delta}{\cos \theta \cos \delta} \right) \dots\dots(9)$$

In equation 9, Hay (15) took into account the effect of multiple reflections between the Earth's surface and the atmosphere, and that the chart of the Campbell - Stoke's sunshine recorder does not burn when the elevation of the sun is less than 5°. This helps to reduce the spatial and temporal scatter often observed in the values of regression parameters (16). Table A1 (Appendix) shows the values of H_0 , N_0 and N'_0 .

The spectral distribution of solar radiation corresponds to the energy output of a blackbody at a temperature of about 6000° K. It is distributed thus:

- 9% in the invisible ultraviolet region with wavelength between 0.29 - 0.40 μm
- 40% in the visible region with wavelength between 0.4 - 0.7 μm , and
- 50% in the infrared region with wavelength between 0.7 - 3.7 μm . The peak intensity of about 2074 $m^{-2} \mu m^{-1}$ is reached at 0.49 μm in the green part of the visible spectrum. (1, 8, 12).