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Technical note

Estimating global solar radiation using common meteorological data in Akure, Nigeria

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ABSTRACT

In this study, the global solar radiation on horizontal surface in Akure, Nigeria (Latitude 7.25° N and Longitude 5.2° E) using 22-year data (July 1983–June 2005) was analysed. Simple empirical correlations for evaluating the monthly average daily global solar radiation were developed. The calculated monthly clearness index values indicates that prevailing weather condition in Akure is partly overcast but can become heavily overcast during the months of July–September. The Angstrom–Page correlation predicted the monthly average daily global solar radiation better than the other correlations developed in this study. However, in the absence of the sunshine hour data, it was found that temperature only based correlations (especially the average temperature based correlation) and precipitation based correlation can be used to predict the global solar radiation within reasonable level of accuracy in Akure. The correlations presented in this study could be applied to locations with comparable weather condition to Akure.

1. Introduction

The quest to reduce environmental impacts of the convectional energy resources and more importantly meeting the growing energy demand of the global population, had motivated considerable research attention in a wide range of environmental and engineering application of renewable form of energy. Considering the geographical location of Nigeria, solar energy is one of the most viable renewable resources in this country. The amount of solar energy (or solar radiation) available on the earth surface depends on many factors which includes the distance between the earth and sun, tilt of the earth's axis with respect to its orbit round the sun and the atmospheric conditions. For a given location, the solar radiation is strongly dependent on its latitude and the time of the year.

For the design and selection of solar energy conversion systems (for heating and electricity), architectural design, greenhouse structures and selection of cooling systems in a country like Nigeria, the knowledge of solar radiation is very essential. However, in Nigeria, solar radiation measurements are only available in selected locations across the country. Therefore, it is essential to be able to determine solar radiation based on readily available meteorological data such as sunshine hours, relative humidity and ambient temperature. In Nigeria, many empirical correlations between the extraterrestrial global solar radiation and meteorological data have been developed for different locations. Most of these correlations are either in form of single variable linear expressions [1–8] or polynomial expressions of up to third-order degree [e.g., 4,9,10]. In addition, multi-variable correlations have been developed for some locations in Nigeria in both linear and polynomial in mixed variables form [e.g., 11–13]. The most commonly use variables are sunshine duration hours, temperature and relative humidity.

Despite the amount of work done on the development of empirical correlation for determination of monthly averaged daily global solar radiation in locations across Nigeria, no empirical correlation have been found for Akure in open literature and the global solar radiation data in this location have not been analysed in detail. The correlations developed in this study will enable the easy estimation of solar radiation which is essential in the design of solar devices and passive solar heating structures. Therefore, the aim of this study is to develop simple empirical correlations based on readily available meteorological data for predicting the monthly average daily global radiation.

2. Materials and methods

The site considered in this study is Akure, Nigeria and it is located on latitude 7.25° N and longitude 5.2° E and it is 384 m above sea level. The average daily global solar radiation on horizontal surfaces,

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average daily relative humidity, average daily amount of rainfall (or precipitation) as well as the daily ambient temperatures (average, minimum and maximum) were obtained from the archives of National Aeronautics and Space Administration (NASA) [14] for a 22-year period (1983–2005). The monthly averaged daily sunshine hours based on 30-year period (1961–1990) are obtained from the International Water Management Institute (IWWI) website [15]. The bias and root-mean square errors in the average daily global solar radiation obtained from NASA websites when compared with data from the Baseline Surface Radiation Network (BSRN) data are 0.3% and 8.7% respectively, for a region that falls within 60° equator-ward [14]. The sunshine hours are obtained by using Campbell-Stokes sunshine recorder (burn method). The Campbell-Stokes sunshine recorder consists of a glass sphere mounted concentrically in a section of a spherical bowl, the diameter of which is such that the sun's rays are focused sharply on a card held in grooves in the bowl. The length of the burn trace left on the card represents the sunshine duration (in hour). In order to obtain valuable results, both the spherical part and the sphere should be made with great precision, the mounting should be designed so that the sphere can be accurately centred on it. The achievable measurement uncertainty in this instrument is the larger of 0.1 h or 2% of the reading [16].

2.1. Data analysis and correlation models

The modeling of monthly global solar radiation involves the correlation of the ratio of the monthly averaged daily global solar radiation (H_m) to the monthly averaged daily extraterrestrial solar radiation (H_o) or clearness index to solar and meteorological data such as sunshine hours, temperature, and relatively humidity. Since, H_o can be determined using appropriate mathematical expressions (presented later), H_m can easily be calculated based on this correlation. The actual value of H_o is a site specific and depends on the latitude of the site and day of the year. The Angstrom–Page linear equation which relates the clearness index to fraction sunshine hour is commonly used to determine the monthly global solar radiation in a given location. The Angstrom–Page equation is given as:

$$\text{Model 1}: \quad \frac{H_m}{H_o} = a + b\frac{S}{S_o} \tag{1}$$

where S is the monthly averaged daily sunshine hour, S_o is the monthly averaged daylight hours and, a and b are the derived coefficients to be determined. In order to use the above equation to determine the monthly global solar radiation, the monthly averaged daily sunshine hour must be known. In estimating the above coefficients for a site, measured solar data and sunshine hour are required. However, in some locations only the sunshine hour may be readily available and in such locations, another approach is to use readily available solar data from other sources (e.g. NASA SSE) in combination with measured sunshine hour data to estimate the above-derived coefficients. This approach is used in this present study. This approach is even more useful in situations where measured sunshine hours are not available. In these situations, this approach can be used to relate the clearness index to other meteorological data (e.g. temperature and relative humidity) that can easily be measured and/or readily available.

In order to avoid the use of sunshine hours in the determination of the global solar radiation, Hargreaves and Allen [17] proposed a simple equation which relates the clearness index to the square root of the difference between the monthly averaged daily maximum and minimum temperatures. This correlation expression is given as:

$$\text{Model 2}: \quad \frac{H_m}{H_o} = a(\Delta T)^{0.5} \tag{2}$$

where $\Delta T = T_{max} - T_{min}$, T_{min} is the minimum temperature, T_{max} is the maximum temperature and a is the correlation constant with a value of 0.16 generally adopted for locations in Nigeria [5,18]. Due to that fact the solar radiation and temperature could vary significantly from one location to another, it is likely that the value of 0.16 may not be applicable for all locations in Nigeria. Therefore, similar expression is proposed for Akure in this study.

In addition to the Angstrom–Page and Hargreaves type models, the following correlation expressions which are based on common weather parameters are investigated in this study and their performances are evaluated statistically:

Model 3: relative humidity (RH) based model:

$$\frac{H_m}{H_o} = a + b\left(\frac{RH}{100}\right) \tag{3}$$

Model 4: average temperature (T_{ave}) based model:

$$\frac{H_m}{H_o} = a + b(T_{ave}) \tag{4}$$

Model 5: temperature ratio ($TR = T_{min}/T_{max}$) based model:

$$\frac{H_m}{H_o} = a + b(TR) \tag{5}$$

Model 6: relative humidity and temperature ratio based model:

$$\frac{H_m}{H_o} = a + b(TR) \times \frac{RH}{100} \tag{6}$$

Model 7: precipitation P (mm) based model:

$$\frac{H_m}{H_o} = a + b(P) \tag{7}$$

The daily average extraterrestrial global solar radiation H_o is given as:

$$H_o = \frac{24}{\pi} I_{sc}\left(1 + 0.033\cos\left(\frac{360N}{365}\right)\right) \times \left(\cos\phi\cos\delta\sin\omega + \frac{2\pi}{360}\sin\phi\sin\delta\right) \tag{8}$$

where I_{sc} is the solar constant, 1.367 kW/m^2; φ is the latitude of the location (in degree); δ is the solar declination angle (in degree); ω is the sunset hour angle and N is day of the year, starting with 1 for January 1st and 365 for December 31st (i.e. $1 \le N \le 365$). The solar declination angle can be determined from any of the following equations [e.g. 3,19,20]:

$$\delta = -23.45 \times \cos\left[\frac{360}{365}(N + 10)\right] \tag{9}$$

$$\delta = -23.45 \times \sin\left[\frac{360}{365}(N + 284)\right] \tag{10}$$

$$\delta = (0.006918 - 0.399912\ \cos\gamma + 0.070257\ \sin\gamma - 0.006758\ \cos 2\gamma + 0.0009072\ \sin 2\gamma - 0.002697\ \cos 3\gamma + 0.00148\ \sin 3\gamma) \tag{11}$$

where $\gamma = 2\pi/360(N-1)$.

For a low latitude ($\varphi < 60°$) region, Eqs (9)–(11) give roughly the same value of the declination angle [21]. The sunset hour angle is given as: