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A comparative study of total, direct and diffuse solar irradiance by using different models on horizontal and inclined surfaces for Cairo, Egypt

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ABSTRACT

The measured hourly daily data of total, direct and diffuse solar irradiation incident on a horizontal and an inclined surface for Cairo, Egypt (Lat. 30°05′N and Long. 31°15′E), during the period (1990–2010) are analyzed. The regression equations between (G/G_o) and meteorological variables along with the values of MBE, RMSE, MPE, R^2 and the *t*-test statistics are summarized in this research. The values of correlation coefficients (R^2) are higher than 0.95 and the values of the RMSE are found in the range 3.13–6.34, thus indicating a good agreement between measured and calculated values of the total solar radiation (G). The models of Eqs. (10), (11) and (14) have well estimated the total solar irradiation in the selected location during the time period in the present study. For all models, the absolute values of the MPE indicate very good agreement between measured and calculated values of the diffuse solar fraction (G_d/G) or the diffuse solar transmittance (G_d/G_o) and clearness index K_t, relative number of sunshine hours (S/S_o) and their combination. The models of Hay (Ha), Skartveit and Olseth (SO) and Perez et al. (P9) give the most accurate predictions for the south-facing surface, and Hay (Ha) and Perez et al. (P9) models performs better as estimated for the west-facing surface.

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1. Introduction

Solar irradiation is measured at many locations around the globe. Unfortunately, these locations are mainly concentrated in developed countries, and are scarce within the developing world; solar irradiation data are fundamental inputs for solar energy applications such as photovoltaics, solar thermal systems, and passive solar design. Daily data on horizontal and tilted surface are required for day-to-day performance monitoring in applications such as solar gains from vertical glazing, day lighting and agricultural processes; these data are also useful to engineers in designing of various solar energy conversion devices and accurate modeling of the impact of solar gains through glazing which is imperative especially when simulating the thermal behavior of these buildings. Empirical validations of solar gain models are therefore an important and necessary endeavor to provide confidence to developers and modelers that their respective algorithms simulate reality [1–3].

Solar energy consists of two parts: extraterrestrial solar energy which is above the atmosphere and global solar energy which is under the atmosphere. The measured solar energy values can be used for developing solar energy models which describe the mathematical relations between the solar energy and the meteorological variables such as ambient temperature, humidity and sunshine ratio. These models can be later used to predict the direct and diffuse solar energy using historical metrological data at sites where there is no solar energy measuring device installed. Solar energy of daylight utilization for any site is dependent upon the quality of the available flux. Obviously, the flux impinging upon any arbitrary surface undergoes monthly as well as diurnal variations. The measurements of solar energy received from the sun, on horizontal as well as on sloped surface, are an expensive affair. As such, few locations in the world have reliable, long-term measured irradiation data sets. Daylight records are even scarcer. Most radiation data are given as the energy received on a horizontal surface. Since only very few applications use this configuration, there is a genuine need for insolation estimation to be carried out for sloped surface of any given aspect; the accuracy of these models varies from 40% to 50% for abbreviated techniques to limits set out by the accuracy of the measuring equipment for modern sophisticated models [4,5]. The total solar radiation on a horizontal surface is called global irradiance and is the sum of incident diffuse radiation plus the direct normal irradiance projected onto the horizontal surface. If the surface is tilted with respect to the horizontal, the total irradiance is the incident diffuse radiation plus the direct normal irradiance projected onto the tilted surface plus ground reflected irradiance that is incident on the tilted surface [6–9].

Many empirical models have been used to estimate solar radiation, utilizing the available data on meteorological [10,11], geographical and climatological parameters. Among these parameters, sunshine duration [12–15], air temperature [16], latitude and longitude [17], precipitation [18], relative humidity [16,19,20], wind speed and cloudiness [21–26] were used. Of these, the most commonly used parameter for estimating total solar radiation is sunshine hours. In this respect, the modified version of Angstrom equation, among various correlations, has been widely used to estimate the total solar irradiation on horizontal surface [27–35].

In most of the solar energy applications, inclined surfaces at different angles are widely employed. The solar irradiance on a horizontal surface has been measured in many meteorological stations around the world, but there are only a few stations that measure the solar component on inclined surfaces [36–38]. There are a number of models available to estimate solar irradiation on inclined surface from corresponding horizontal data. This requires, in general, the availability of detailed information on the magnitude of diffuse and direct horizontal irradiance. A number of diffuse fraction models are available as documented in [39–43]. These models are usually expressed in terms of polynomial functions relating the diffuse fraction to the clearness index. An inclined surface solar irradiation model developed by Olmo et al. [44] requires only the horizontal surface solar irradiation, with incidence and solar zenith angles as input parameters.

Many solar energy models have been presented in the literature using mathematical linear [45–53] and nonlinear functions [54–60], artificial neural network [61–71] and fuzzy logic [72–74]. An important aspect in modeling solar energy is the accuracy of the developed model which is evaluated using statistical errors such as the mean absolute percentage error (MAPE), mean bias error (MBE) and root mean square error (RMSE). The MAPE is an indicator of accuracy in which it expresses the difference between real and predicted values to the real value. The calculated MAPE is summed for every fitted or forecasted point in time and divided again by the number of fitted points; n. MBE is an indicator for the average deviation of the predicted values from the measured data. A positive MBE value indicates the amount of overestimation in the predicted total solar energy and vice versa. On the other hand, RMSE provides information on the short-term performance of the model and is a measure of the variation of the predicted values around the measured data. RMSE also shows the efficiency of the developed model in predicting future individual values [3,71]. A large positive RMSE implies a big deviation in the predicted value from the measured value. Part of this study was used before to evaluate the statistical comparison models of solar energy on horizontal and inclined surfaces [3]; in the present work, the average hourly daily data of solar irradiation models on horizontal surface and various inclined surface in the selected site will be studied, using empirical models which were selected to estimate the solar radiation on horizontal and inclined surfaces.

2. Instrumentations and climate site

In the present work, the global, direct and diffuse solar radiation incident on a horizontal surface at Cairo, Egypt (Lat. 30°05′N and Long. 31°15′E), during the time period from January 1990 to December 2010 is used. The radiation data of the corresponding periods are obtained from the Egyptian Meteorological Authority. The data sets used consist of mean hourly and daily values of global and diffuse solar irradiations on a horizontal plane. Total solar radiation was measured using Eppley high-precision pyranometer responsive at 300–3000 nm, while another precision pyranometer equipped with a special shading device, SBS model, was used to measure diffuse irradiation. The shadow band stand is constructed of anodized aluminum, which weighs approximately 24 lb and uses a 300 band of approximately 2500 diameter to shade the pyranometer. Because the shadow band screens the sensor from a portion of the incident diffuse radiation coming in from the sky, a correction was made to the measurements following Batlles et al. [3,75,76]. Total solar radiation data were recorded by the Eppley Precision Spectral Pyranometer (PSP) at all stations. The accuracy of these pyranometers corresponds to the first class according to the World Meteorological Organization classification [77]. These instruments are calibrated each year against a reference instrument traceable to the World Radiometric Reference (WRR) maintained at Davos, Switzerland [78,79]. According to the calibration certificate of the manufacturers, sensitivity is approximately 9 μV/W/m^2, temperature dependence is ±1% over ambient temperature range −20 to +49 °C, linearity is ±0.5% from 2800 W/m^2, and cosine is ±1% from normalization 0–70° zenith angle and ±3% for 70–80° zenith angle. The absolute accuracy of calibration is ±3–4%.