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On the prediction of the daily global solar radiation intensity on south-facing plane surfaces inclined at varying angles

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ABSTRACT

Over the years, some authors have used different models to estimate the solar radiation intensity over inclined surfaces, but none of them has tested and evaluated the accuracy of these models for various inclinations. In this study, by using the acquired data from Meteonorm, five best models studied previously by the authors have been used in order to predict the daily global solar radiation intensity DGSRI received on an inclined surface to the south and to evaluate the day by day performance of these models using a statistical analysis performed by several statistical indicators. The analysis of results revealed that the selected models haven't the same accuracy, and it is concluded that there are models that can be preferred for the prediction of the DGSRI received on a tilted surface with different angle of inclination at the considered site, Tetuan city in northern Morocco. Empirical correlations between solar radiation intensity fallen on south-facing plane surfaces with various inclination and that receive on horizontal surfaces have been developed. As mean of results of the statistical indicator errors and excluding 20°, 60° and 70° inclinations and the coefficient of determination R^2 values, El Mghouchi model is performing *comparatively* better than the others for all inclinations ranging from 0° (horizontal plane) to 90° (vertical plane) in steps of 10°.

1. Introduction

Solar radiation energy incident on an inclined plane is more appropriate than that incident on an horizontal one. It varies according to the tilt and orientation of the receiver. The diurnal (daily rotation of the Earth around its polar axis) and seasonal movement of the Earth affect the radiation intensity on the solar systems. In addition, to receive a maximum of solar radiation energy the numerical simulation and available data show that the tilt and orientation of the receiver should be varied according to the solar declination and solar azimuth. For this reason, many researchers propose to develop a new Sun tracking system, which is based on a monitoring used to track the Sun's direction during day and throughout the year [1–4]. Sun trackers move the solar systems to compensate for these motions, keeping the best orientation relative to the Sun.

Many researchers have tested the performance of few developed solar radiation models in the literature to predict solar radiation intensity fallen on inclined surfaces to the south or to the west. i.e., Efim et al. [5] have tested 11 empirical models by using measured data in Beer Sheva, for a south-oriented surface tilted at 40°. Noorian et al. [6] have evaluated the performance of 12 models to estimate hourly diffuse solar irradiation on inclined surfaces from those measured on horizontal surfaces and compared it with the measured tilted data of the same period for two tilted surfaces 45° south-facing and 40° west-facing in Iran. Posadillo and López Luque [7] have used three diffuse hourly irradiation models on tilted surfaces and a database of hourly global and diffuse solar irradiations on an horizontal surface, as well as global solar irradiation on a tilted surface, recorded in a solar radiation station located at Córdoba University (Spain) for tilted surface 35° south-facing. The presented approaches by these researchers show a complexity of the task of converting solar radiation intensity on an horizontal surface to that on a tilted surface by using geometrical relationships between the two surfaces noted as the conversion factors, but none of them has tested and evaluated the accuracy of their approaches for various inclinations.

The main objective of the present study is to compare the obtained results by using five selected solar radiation models and some conversion factors with the measured data for predicting the daily global solar radiation intensity DGSRI on south-facing plane surfaces inclined at varying angles for Tetuan city, in northern Morocco (35.57361 latitude, −5.37528 longitude). The

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Nomenclature

G	global solar flux received on an horizontal surface (W/m^2)
I	direct solar flux received on an horizontal surface (W/m^2)
D	diffuse solar flux received on an horizontal surface (W/m^2)
G_{dm}	daily measured global solar radiation (kW h/m^2/day)
G_{dp}	daily predicted global solar radiation (kW h/m^2/day)
I_{sc}	solar constant (W/m^2)
E_0	eccentricity correction-factor of the Earth's orbit (dimensionless)
θ_z	Zenith angle (°)
h	solar altitude (°)
ψ	solar azimuth (°)
δ	solar declination (°)
β	tilt angle (°)
Γ	turbidity factor (dimensionless)
τ_o	atmospheric transmittance (dimensionless)
τ_{dir}	direct atmospheric transmittance (dimensionless)
τ_{dif}	diffuse atmospheric transmittance (dimensionless)
m_a	air masse (dimensionless)
a^*	ground albedo (dimensionless)
Γ	turbidity factor (dimensionless)
$\mathcal{R}_I$ and $\mathcal{R}_G$	(dimensionless) are the direct and global tilt factors, respectively

accuracy of these models has been tested and evaluated for various inclinations to the south ranging from 0° (horizontal plane) to 90° (vertical plane) in steps of 10°. The global solar radiation on an inclined plane consists of direct, sky diffuse and ground-reflected radiations that it is supposed null for the horizontal surfaces.

In the next subsections, five best models tested previously by the authors [8–13] have been used such as Campbell, Ghouard et al., Benjamen et al., Perrin Brichambaut and El Mghouchi models [14–18]. These models have been used to predict all components of the solar radiation intensity fallen on an horizontal surface and using some developed conversion factors in the literature, all components of the solar radiation intensity fallen on south-facing plane surfaces inclined at varying angles are predicted. In addition, based on the obtained values by these models, a comparison between the predicted and acquired data of Tetuan city is made.

Furthermore, in order to evaluate the day by day performance of these models a statistical analysis has been performed using several statistical error indicators namely mean bias error, root mean square error, normal root mean square error, mean absolute percentage error, test statistic and standard deviation. Other analysis is made on the basis of coefficient of determination R^2 and linear regression coefficients (the slope 'a' and the constant 'b').

2. Solar radiation models

The Earth receives most of its energy from the Sun in the form of electromagnetic radiation. A part of this radiation is absorbed, reflected and transferred by the atmospheric components. The determination of the solar irradiance fluxes magnitude at a given position on the Earth's surface is a function of various meteorological, astronomical and geographical parameters such as cloudiness, solar constant, solar elevation, Sun-Earth distance, albedo at ground, sunshine duration, day length, air temperature, Top of Atmosphere Radiation TOA, relative humidity, precipitation, and coefficient of absorption and diffusion by the atmospheric components [19–33]. Other parameters related to the solar radiation prediction have been widely given in the literature.

2.1. Used models

2.1.1. Perrin Brichambaut model

By analyzing several meteorological measures data in the national territory of France, Perrin Brichambaut [14] has proposed three empirical formulas designed to the direct, diffuse and global solar radiation fluxes, which are only in function of astronomical parameters. The above relationships are transformed into the following ones according to the atmospheric conditions, and they are given as:

$$D = 125C \cdot (\sin(h))^{0.4} \tag{1}$$

$$I = R \cdot \exp\left(\frac{-A}{B \cdot \sin(h+1)}\right) \tag{2}$$

$$G = I + D \tag{3}$$

where R (W/m^2) is the apparent extraterrestrial irradiance; A, B and C (dimensionless) are the empirical values for solar irradiance predictions according to Perrin Brichambaut model and they are given in Table 1:

2.1.2. Ghouard et al. model

Ghouard et al. model have proposed empirical formulas designed to predict solar radiation intensity at a given location on the Earth (depending Saighi, 2002) [15], which is based on the disturbing factor evaluations depending on the atmospheric conditions and astronomical parameters.

The direct solar radiation by this model is defined as:

$$I = I_{sc} \cdot E_0 \cdot A_1 \cdot \exp\left(-\frac{A_2}{\sin}(h)\right)\sin(h) \tag{4}$$

The diffuse solar radiation is given by:

$$D = I_{sc} \cdot E_0\left[0.271 - 0.2939 \cdot A_1 \cdot \exp\left(-\frac{A_2}{\sin}(h)\right)\right]\sin(h) \tag{5}$$

The global solar radiation is given by the following equation:

$$G = 0.271 I_{sc} \cdot E_0 \cdot A_1 \cdot \sin(h) + 0.706 I_{sc} \cdot E_0 \cdot A_1 \cdot \sin(h) \times \exp\left(-\frac{A_2}{\sin(h)}\right) \tag{6}$$

A_1 and A_2 are the coefficients of the turbidity factor, and they are given in the following Table 2:

2.1.3. Campbell model

Prediction of the solar radiation components on an horizontal surface according to the proposed model by Campbell[16] requires

Table 1
R, A, B and C values according to Perrin Brichambaut model.

Atmospheric conditions	R (W/m^2)	A	B	C
Clear skies	1210	1.67	3.9	0.67
Normal conditions	1230	1.61	3.1	0.47
Industrial zones	1260	2.23	4	0.45