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Estimation and Validation of a Clear Sky Hourly Global Solar Radiation in Beni-Suef, Egypt

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Abstract

The availability of hourly and daily solar radiation data is considered one of the important design tools for several solar energy applications. The objective of this work is to develop a model to calculate the hourly solar radiation falling on a horizontal surface in Beni-Suef City, Egypt via a validated simulation model. This model will help the researchers in Upper Egypt's universities along with the designing of solar energy projects in the Beni-Suef City residential and industrial zones. The average solar radiation is calculated daily on hourly basis throughout the year, then the monthly average solar radiation is estimated. The results indicated the maximum value of average solar radiation is in June, 2019 as 8.1 kWh/m^2/day. Solar radiation is also calculated with several tilt angles to find out the optimum tilt angle that enables the surface to receive maximum solar radiation. The calculations focused on empirical equations of solar radiation and the experimental measurements obtained from the nearest station to the location. The model describes solar equations that can be used to estimate global irradiance. Also, it shows the parameters of the system and climate change of the specific site (Beni-Suef City). Results are validated by comparison between the measured, calculated, and published reference data for the specific site and obtained good agreement with each other. It is found also that the optimal tilt angle that receives maximum solar radiation is 29 deg. which comply with the latitude angle of Beni-Suef City.

Keywords: Hourly Global Solar Radiation, Beni-Suef City, Egypt, Mathematical Model

Introduction

Solar energy is a renewable, efficient, economic, friendly, pollution free and generous source of energy on earth's surface. Sun releases this energy and some of it hits the planet. The geometrical relation between earth and sun can be analytically calculated by taking into account the solar angles and other solar radiation parameters [1]. In some countries, the solar radiation has a great potential to be utilized in various solar energy applications. Exact information on the availability of solar radiation is critical for researchers. The development of solar energy systems, including global solar radiation, evaluated their long-term efficiency and estimate the accurately productivity of photovoltaic modules that turn solar energy directly into electricity or thermal solar systems [2]. Solar energy especially in remote and arid areas is the more suitable choice for water desalination and wastewater treatment via systems such as an integrated solar greenhouse [3]. At any location, satellite imagery and measurements using appropriate measures are the best method of learning and understanding about the availability of the solar radiation. Another way is to establish a relation between a given location' s astronomical, physical, meteorological and geological parameters in order to estimate the Global Solar Radiation (GSR) with time. The correlation between these parameters and GSR can be used. This way allows the development of

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statistical model for earth's surface through varies parameters in the calculation of GSR. These parameters include duration of sunshine, extraterrestrial radiation, ambient temperature, relative humidity, soil temperature, altitude and latitude. The model is used for measuring GSR in the case of sunshine period to obtain amount of solar radiation. If the sunshine is not long, then other parameters may be useful alternative these parameters include hours of sunshine, extraterrestrial radiation and relative humidity as reported by Bakirci, 2009 [4]. Unfortunately, Bayrakçi et al, 2018 indicated that solar radiation measurements are not easily recorded in several developing countries because of the high cost of equipment and the maintenance [5]. The global solar irradiations consisted of the direct beam and diffuse one [6]. Solar radiation models may be categorized according to varies parameters to obtain optimum radiation. These parameters include some of input and output parameters like meteorological data, climate data, timing including daily, monthly averages weekly, hourly, ground inclination including horizontal, inclined surfaces, weather type during clear sky and sky conditions, and global, beam radiation or diffuse [7]. GSR can be determined in different cases such as horizontal and inclined surfaces by using specific model. The major parts of setup the model depend on the latitude and the longitude [8]. Since the evaluation model was greatly affected by position latitude, it is major to find the exact model in each area. The researchers, generally, select some models in previous studies using various latitudes close to their latitude region [9-11]. Obtaining the optimum tilt angle is considering the most efficient way to receive maximum solar radiation on photovoltaic module [12]. The Model could be adapting with some parameters of location as latitude and longitude [13]. Kais et al. [14] estimated of HSR of specific day 15^{th} in all months of a year and compared the obtained data with the measured. Gad [15] applied an effective model on hourly solar radiation linked with the performance of specific system, and choose 21^{th} day of some months such as (June, March and December) at different latitude angles to reach the maximum value of solar radiation as 920, 810, and 510 W/m^2, respectively. He explored the same results at different tilt angles. Matasane et al. [16] presented a theoretical study of specific system and mathematical modeling depends on solar radiation. They also showed effective of environmental impact as temperature, solar radiation and humidity through all months of a year and calculate annual of solar radiation. The annual direct and diffused were found to be 21.3 MJ/m^2 and 6.3 MJ/m^2, respectively. Mohamed [17] studied the artificial neural network (ANN) models for validating and predicting global solar radiation (GSR) on a horizontal surface of three Egyptian cities. It is found that ANN-based model is an efficient method which has higher precision. The statistical indicators are used to investigate the performance of ANN models. Basic backpropagation (Bp) with momentum and learning rate coefficients model is the most suitable for predicting GSR on a horizontal surface of all cities. In this study, the estimation and experimental validation of global hourly solar radiation on a horizontal surface for all days of the year 2019 are presented. The comparison between calculated and measured data were found in good agreement with each other for some months. Also, the calculated data were compared with the measured data from geographical program, RET Screen [18] and another referenced published article. These comparisons showed significant agreement with the current study.

Theoretical model of solar radiation data

Figure 1, and Figure 2 illustrate solar energy map of Egypt and the geographical data of Beni-Suef City, Egypt, respectively. Geographical data for Beni-Suef in Egypt has coordinate longitude (31.1086578°) and latitude (29.0419507°) that used to evaluate the current model. The flow chart of the model for calculation of the GSR on horizontal surface is given in Fig. 3. The Measured data of hourly GSR for 2019 are obtained from the nearest station from the specific site (Beni-Suef).

The Hourly global solar radiation is incident on a horizontal surface $(G_{h=} B_h + D_h)$ where B_h and D_h are the beam and diffuse solar radiation, respectively, and can be determined as [19].

$$G_h = G_{oh}\, 0.7^{m^{0.678}} \quad (1)$$

which G_{oh} is defined as the extraterrestrial irradiance on a horizontal surface and *m* is the air mass.

$$G_{oh} = G_{sc} + [1 + 0.033\cos(2\pi N / 365)] \sin \alpha \quad (2)$$

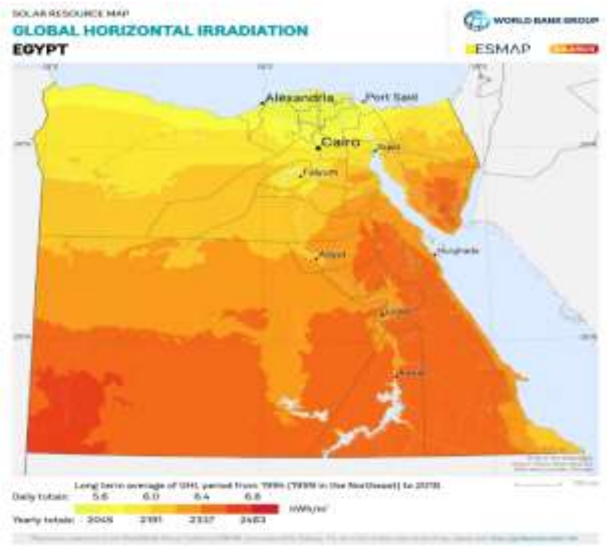

Fig. 1. Solar Energy map of Egypt [24]

where G_{sc} is the solar constant =1367 W/m^2 and N is the day number starting from January.

$$m = [1229 + (614 \sin \alpha)^2]^{0.5} - 614 \sin \alpha \quad (3)$$

where α is refers to altitude angle which is given by [20].

$$\sin \alpha = (\cos L \cos \delta \cos H + \sin L \sin \delta) \quad (4)$$

L is the latitude of the place, H is solar hour angle and δ is defined as declination angle given by Cooper's equation [20].

$$\delta = 23.45 \sin\left(2\pi \frac{N+284}{365}\right) \quad (5)$$

Fig.2. Geographical location of Beni-Suef City.

The hour angle (H) is equivalent to 15°/H with positive sign in the morning (+) and negative sign at afternoon (-) and based on local solar time and is given by [20].

$$H = (\text{local time} - 12)\, 15^{o} \quad (6)$$

The model which used for determination GSR at tilt angle is I_T is the global solar radiation intensity on the tilted surface represents the beam, diffuse and reflected radiation and can be calculated from [20].

$$I_T = R_b * I_b + I_d \left(\frac{1+\cos\beta}{2}\right) + I \rho_g \left(\frac{1-\cos\beta}{2}\right) \quad (7)$$

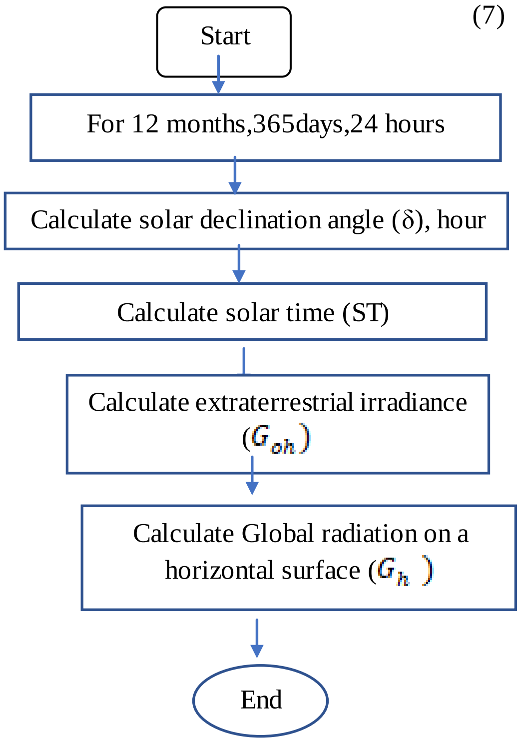

Fig.3. Flow chart for GSR on horizontal surface.

Dividing equation 7 by I

$$R = \frac{I_T}{I}$$

$$= R_b * \frac{I_b}{I} + \frac{I_d}{I}\left(\frac{1+\cos\beta}{2}\right) + \rho_g \left(\frac{1-\cos\beta}{2}\right) \quad (8)$$

Where I_b and I_d are beam and diffuse solar radiation respectively on a horizontal surface and R_b is the beam tilt factors respectively given by

$$R_b = \frac{\cos(L-\beta)\cos\delta\cos H + \sin(L-\beta)\sin\delta}{\cos L \cos\delta \sin H + \sin L \sin\delta} \quad (9)$$

Where, L is the latitude angle of the place and β is the array tilt angle, H solar hour angle defined by H=(12-t) x15° (t is the local time ,h) , δ is solar declination angle given by equation (5).

$$I_h = A e^{\frac{-B}{\sin\alpha}} \quad (10)$$

$$I_d = C B_h \quad (11)$$

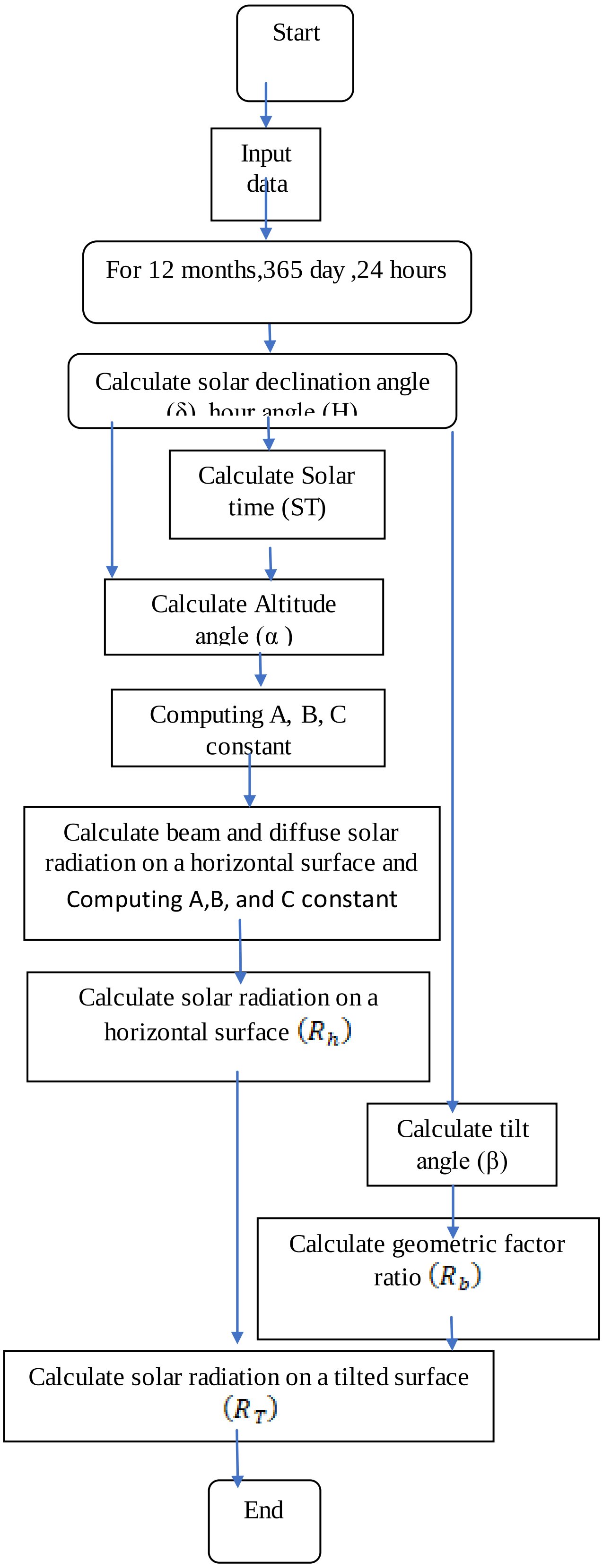

Fig.4 Flow chart for solar radiation at different tilt angles.

Where A, the apparent solar extraterrestrial irradiation, B, the atmospheric extinction coefficient, are functions of the date and take into account the seasonal variation of the earth-sun distance and the air's water vapor content. C is ratio of the diffuse radiation on a horizontal surface to the direct beam normal irradiation [21]. The steps of calculation global solar radiation at tilt angles are shown in the following flowchart which given by Fig. 4. The absorbed energy by the tilted absorber plates can be presented as follows [22]

$$S = I_b R_b (\tau\alpha)_b + I_d (\tau\alpha)_d \frac{1+\cos\beta}{2} + \rho_g (I_b + I_d)(\tau\alpha)_g \frac{1-\cos\beta}{2} \qquad (12)$$

Results and discussions

The hourly solar radiation is calculating based on the presented mathematical model after taking all the assumptions and affecting parameters into consideration. The calculations are done on daily basis throughout the year. Large No. of solar radiation data is delivered from the simulation program from first January to 31st of December. Figure 5 illustrates a sample of 5 days-data of each season to represent the solar radiation variation throughout the year incident on horizontal surface. It is clear from the figure that the solar radiation variations comply with the nature of the solar radiation spectrum as it is started from sunrise and increased gradually until reached its maximum value at noon and decreased gradually to zero value after sunset.

In order to make validation of the mathematical model, the output calculated data are compared with actual measuring data using solar pyranometer as shown in Figs. 6-9.

The pyranometer measures the global horizontal solar irradiance (GHI); which is composed of diffuse horizontal solar irradiance (DHI) from the sky and surrounding and direct normal solar irradiance (DNI) from the sun. Its specifications can be tabulated in Table 1.

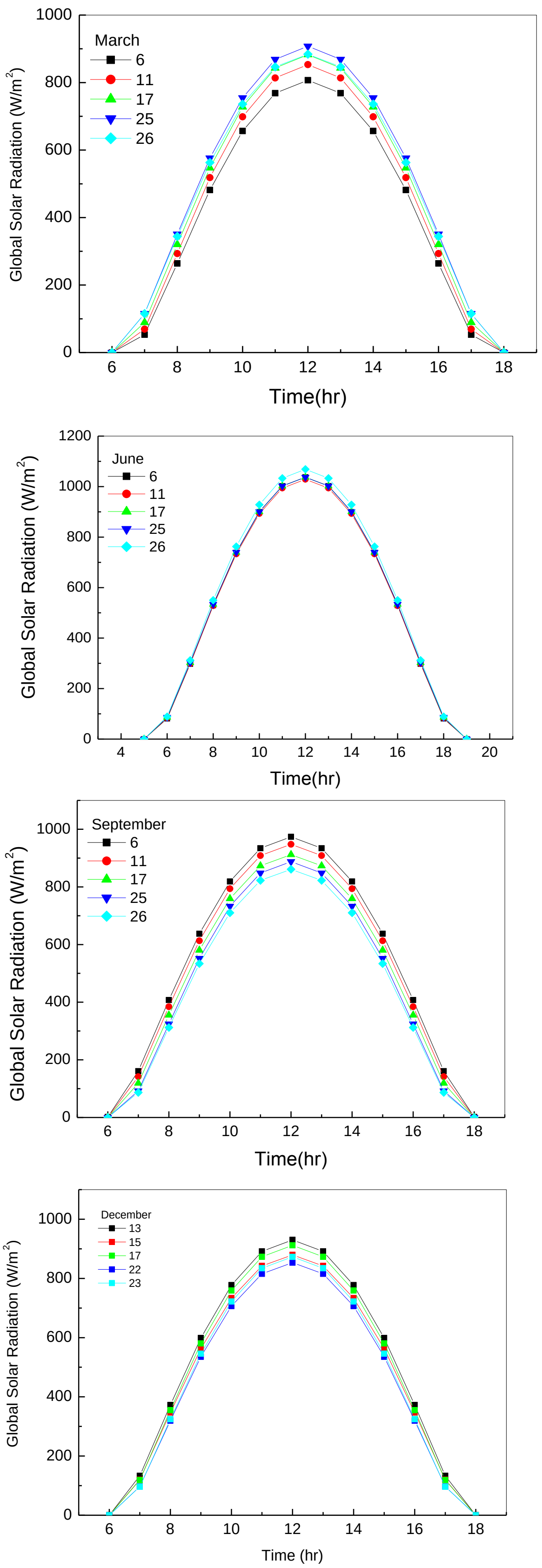

Fig. 5 Calculated data of hourly global solar radiation at some days of each month for Beni-Suef City.

Table 1 Solar Pyranometer Specifications

sensitivity	5 to 20µV/W/m2
Impedance	20 to 200Ω
Expected output range (0 to 1500 W/m2)	0 to 30mV
Maximum operational irradiance	2000 W/m2
Response time (63%)	< 6 s
Response time (95%)	< 18 s
Spectral range (20% points)	285 to 3000nm
Spectral range (50% points)	300 to 2800nm
Directional response (up to 80 ° with 1000 W/m2 beam)	< 20 W/m2
Spectral selectivity (350 to 1500 nm)	< 3%
Tilt response (0 ° to 90 ° at 1000 W/m2)	< 1%
Temperature response	< 5% (-10 °C to +40 °C)
Field of view	180 °
Accuracy of bubble level	< 0.2 °
Detector type	Thermopile
Operating and storage temperature range	-40 °C to =80 °C
Ingress Protection (IP) rating	67

A sample day in each season is presented. Fig. 6 represents a comparison between calculated and measured hourly global solar radiation in summer season while Fig. 7, Fig. 8, and Fig. 9 represent this comparison in autumn, spring and winter seasons respectively. All the presented figures are showed good agreement between calculated and measured data of hourly solar radiation throughout the day.

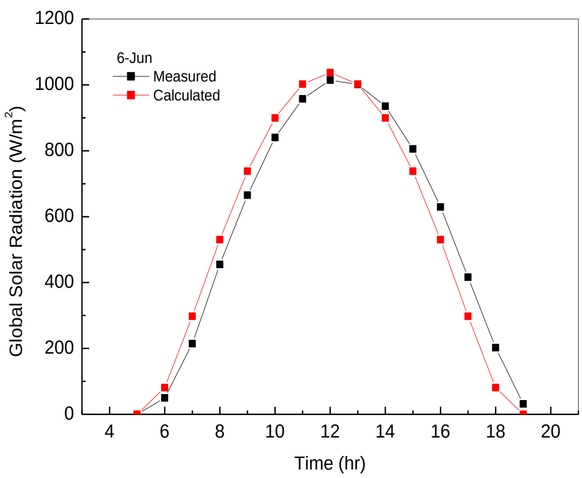

Fig. 6. Comparison between calculated and measured hourly global solar radiation.

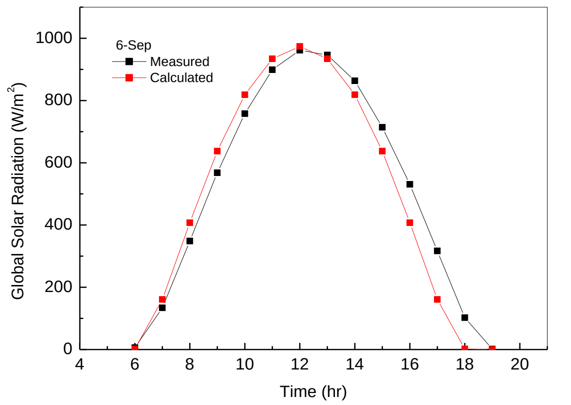

Fig. 7. Comparison between calculated and measured hourly global solar radiation.

Another comparison was made to confirm validation of the calculated mathematical model is to compare the calculated data with the output data of commercially available software for daily average solar radiation (RET Screen Software) [18] and author published referenced article (Ibrahim et. al. [23]. The comparison was made for Beni-Suef city, Egypt as shown in Fig. 10.

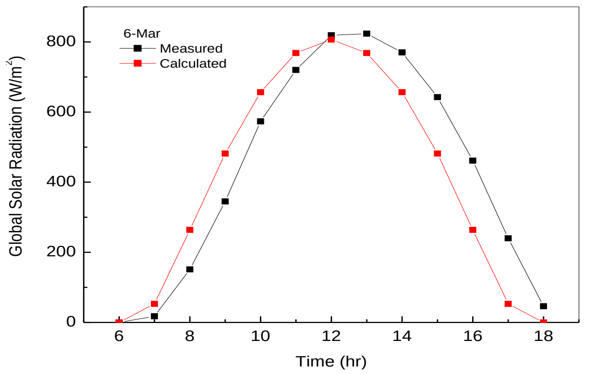

Fig. 8. Comparison between calculated and measured hourly global solar radiation.

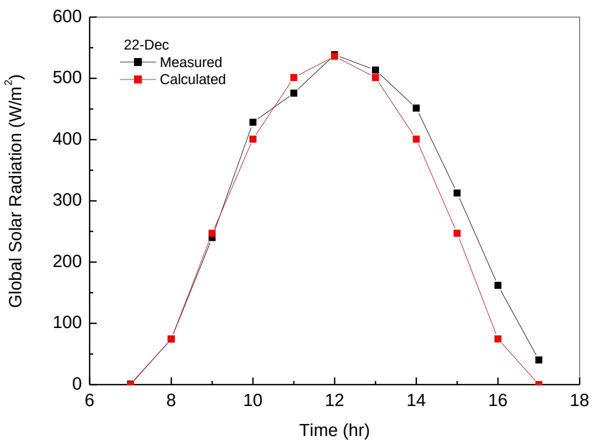

Fig. 9. Comparison between calculated and measured hourly global solar radiation.

It is clear from the figure that there is good agreement between the calculated mathematical model and the previously published references which provide good confidence in the calculation procedure and the output data of solar radiation can be utilized in the research work in Beni-Suef city, Egypt either in the academic field or in designing solar systems in industrial field. It is concluded also that the maximum value of the daily solar radiation falling on horizontal surface is 8.2 kWh/m^2/day.

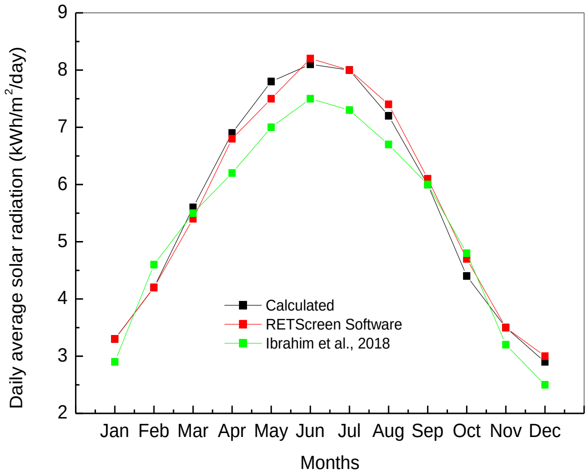

Fig.10 Comparison between the calculated average solar radiation data on horizontal surface with RET Screen Software [18] and Ibrahim et al. [23]

As the tilt angle is considered one of the most important parameters that affect the value of the estimated hourly or daily solar radiation. The present mathematical model was run to deliver the measured values of the average daily global solar radiation to provide annual, seasonal, monthly and daily values either on horizontal and tilted surfaces.

Figure 11 represents the daily average global solar radiation values with different tilt angles Beni-Suef City, Egypt. It is cleared from the figure that the optimal tilt angle was found to be 29^o that received maximum solar radiation of 8.82 kWh/m^2/day and is complied with the latitude angle of Beni-Suef City, Egypt.

It is found also from Fig. 11 that the percentage of the daily solar radiation to the optimal tilt angle was 99.5%, 94.3%, 91.5%, 78.7 %, and 58.3 % corresponding to 25, 30, 0, 60, and 90 tilt angles, respectively.

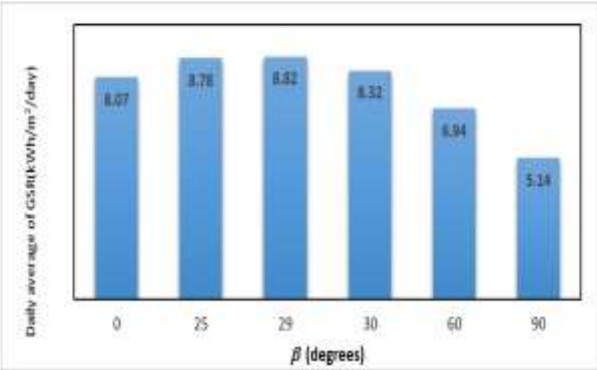

Fig. 11 The daily average of GSR at different tilt angles.

Solar Pyranometer Simplified Error Analysis

The uncertainty components of the solar pyranometer can be expressed as follows:

$$U_{rad} = \sqrt{U_{avg}^2 + (2xU_{std})^2} \quad (13)$$

Where

U_{avg} = mean of base uncertainties (%)

U_{std}, standard deviation, base

$$E+ = 100\ \frac{Rs_{max} - R_s}{R_s} \quad (14)$$

$$E- = 100\ \frac{R_s\ - Rs_{min}}{R_s} \quad (15)$$

Where

RS_{max}, highest responsivity

$RSmin$, lowest responsivity

RS, mean responsivity

The combined The uncertainty can be expressed as

$$U+ =\ + (U_{rad} + E+) \quad (16)$$

$$U- =\ - (U_{rad} + E-) \quad (17)$$

Based on the pyranometer data, the uncertainty is found to be +2.5% to 10 % of full scale 1000 W/m^2 i.e. 25-100 W/m^2

Conclusion

The objective aims of this work are to develop a model to calculate the hourly solar radiation falling on a horizontal surface in Beni-Suef City, Egypt via a validated simulation model. This model will help the researches in Upper Egypt universities along with the designing of solar energy projects in the Beni-Suef City residential and industrial zones. Some concluding remarks are delivered and can be summarized in the following points:

1- The calculated data show the maximum values of solar radiation on horizontal surface at 12 noon in June are 8.1 kWh/m^2/day.

2- The output calculated data are validated through comparing with actual measuring data using solar pyranometer and it is found that there is a good agreement between calculated and measured data of hourly solar radiation throughout the day for all seasons.

3- Another validation was made by comparing the calculated mathematical model with the output data of commercially available software for daily average solar radiation (RET Screen Software) [18] and author published referenced article (Ibrahim S. M. A. et. al. [23]. The comparison was made for Beni-Suef City, Egypt and it is found that there is good agreement between the calculated mathematical model and the previously published references which provide good confidence in the calculation procedure and the output data of solar radiation can be utilized in the research work in Beni-Suef City, Egypt either in the academic field or in designing solar systems in industrial field.

4- It is found that the optimal tilt angle was 29^0 that received maximum solar radiation of 8.82 kWh/m^2/day which is complied with the latitude angle of Beni-Suef city, Egypt. It is found also that the percentage of the daily solar radiation to the optimal tilt angle was 99.5% , 94.3%, 91.5%, 78.7 %, and 58.3 % corresponding to 25, 30, 0, 60, and 90 tilt angles respectively.

Nomenclature

I_b	beam solar radiation, W/ m^2
I_d	diffuse solar radiation, W/ m^2
I	Hourly global solar radiation is incident on a horizontal surface, W/m^2
I_T	The global solar radiation intensity on the array tilted surface, W/m^2
G_{oh}	Extraterrestrial irradiance on a horizontal surface, W/m^2
G_{sc}	Solar constant =1367 W/m^2
R_b	Beam tilt factor (ratio of beam radiation on tilted surface to that on horizontal surface)
A	The apparent solar extraterrestrial irradiation, W/m^2
B	The atmospheric extinction coefficient,
C	Ratio of the diffuse radiation on a horizontal surface to the direct beam

	normal irradiation
DHGSR	Daily Hourly Global Solar Radiation, kWh/m^2
GSR	Global Solar Radiation, W/m^2
H	Hour angle, h
HSR	Hourly Solar Radiation kWh/m^2
L	latitude Angle
m	Air mass
SR	Solar Radiation, W/m^2
S	absorbed energy by the absorber, W/m^2
t	Local time , h
α	Altitude angle
β	Array tilt angle
ρ_g	ground reflectance
N	Day number
δ	Declination angle
τ	transmissivity

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