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Estimation of Monthly Solar Radiation in Bangkok by Computational Models

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ABSTRACT

Global solar radiation represents the combined output of direct and diffuse solar energy. Gathering data on solar radiation serves various purposes, such as facilitating solar applications, aiding architectural design, and supporting renewable technology. Estimating solar energy often involves empirical models, which incorporate meteorological and geographical parameters into the calculation process.In this work, three models based on sunshine duration hour were employed to develop a provisional solar radiation data for Bangkok, Thailand. Statistical analysis revealed that the Elagib & Mansell model exhibited the most accurate fit for this selected location, with RMSE = 3.770 MJ/m^2.day, MBE=7.291 MJ/m^2.day, MABE = 7.719 MJ/m^2.day, and MPE=50.286. It can be concluded that Bangkok experiences solar radiation conditions akin to those in Sudan, as assumed by Elagib and Mansell, considering seasonal variations and period, geographical coordinates, and atmospheric pollution levels. Similarly, the Peninsular Malaysia case study and the achievable forecast from modelings showed a similar tendency in correlation.

Keywords: Global Solar Radiation (GSR); Soler Model; Elagib & Mansell Model; Almorox Model

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Nomenclatures

H	monthly average daily global radiation on horizontal surface (MJ/m^2 day)
H_0	monthly average daily extraterrestrial radiation on horizontal surface (MJ/m^2 day)
S	monthly average daily bright sunshine duration (h)
S_0	monthly average maximum possible daily sunshine duration (h)
L	latitude of the location (rad)
Z	altitude of site (km)

Introduction

Solar radiation, originating from the Sun, constitutes the primary natural energy input to Earth. The local climatic conditions of a particular site significantly influence the amount of solar radiation penetrating Earth's atmosphere, making precise prediction crucial. The incoming solar energy experiences absorption and scattering; moreover, it can be changed the direction by atmospheric components [1, 2]. Solar radiation is commonly categorized into three forms: 1) direct solar radiation, which remains unscattered by atmospheric constituents; 2) diffuse solar radiation, resulting from scattering or reflecting effects onto the surface ; and 3) global solar radiation, representing the combined impact of direct and diffuse solar radiation [3]. Accurate knowledge of solar radiation is invaluable for a wide range of applications, including agriculture, architectural design, meteorological, industries, irrigation system, and renewable technology [4, 5].

For centuries, humans have measured solar irradiance, necessitating advanced equipment like Pyranometers, Pyrheliometers, Sunphotometers, and Pyradiometers to observe solar energy [6]. However, in many developing nations, direct measurement of solar exposure is challenging due to the cost and unavailability of sophisticated instruments. Thailand, confronting similar obstacles, faces limited local solar radiation data due to the expenses, maintenance, and calibration demands of measurement tools. Consequently, computational methods relying on accessible meteorological and geographical data are increasingly employed to estimate solar radiation indirectly. These methods such as empirical models, are commonly used to observe solar radiation across diverse climatic conditions [7, 8]. Various empirical models, tailored to different climatic parameters like sunshine duration, cloud cover, and temperature, have been developed by solar researchers [9].

Sunshine duration is a frequently utilized parameter for estimating global solar radiation, owing to its ease of measurement and widespread availability of data [10]. In this study, we explored three models; Soler, Elagib & Mansell, and Amorox et al. for predicting solar radiation using sunshine hour data and geographical parameters. Furthermore, statistical tests were employed to analyze and validate the obtained solar radiation values, aiming to identify the most accurate models for monthly solar radiation forecast in Bangkok.

Materials and Methods

The Thai Meteorological Department in Bangna, Bangkok, situated at 13.40 °N, 100.37 °E, and approximately 1.5 - 2 meters above mean sea level, collected daily solar radiation measurements for the years 2010 and 2011. A Pyronometer (Kipp & Zonen, model CM 121) was used to measure global solar radiation. Subsequently, the daily data were averaged to generate monthly values, ensuring a dependable reference based on authentic measurements. The three solar radiation models are presented below:

Soler model [11]

Soler applied Rietveld's model to estimate the monthly average daily global radiation on horizontal surfaces across 100 European stations. Subsequently they formulated the modified Angstrom-type equations as follows:

January; $$\frac{H}{H_0} = 0.18 + 0.66\left(\frac{S}{S_0}\right) \quad (1a)$$

February; $$\frac{H}{H_0} = 0.20 + 0.60\left(\frac{S}{S_0}\right) \quad (1b)$$

March; $$\frac{H}{H_0} = 0.22 + 0.58\left(\frac{S}{S_0}\right) \quad (1c)$$

April; $$\frac{H}{H_0} = 0.20 + 0.62\left(\frac{S}{S_0}\right) \quad (1d)$$

May; $$\frac{H}{H_0} = 0.24 + 0.52\left(\frac{S}{S_0}\right) \quad (1e)$$

June; $$\frac{H}{H_0} = 0.24 + 0.53\left(\frac{S}{S_0}\right) \quad (1f)$$

July; $$\frac{H}{H_0} = 0.23 + 0.53\left(\frac{S}{S_0}\right) \quad (1g)$$

August; $$\frac{H}{H_0} = 0.22 + 0.55\left(\frac{S}{S_0}\right) \quad (1h)$$

September; $$\frac{H}{H_0} = 0.20 + 0.59\left(\frac{S}{S_0}\right) \quad (1i)$$

October; $$\frac{H}{H_0} = 0.19 + 0.60\left(\frac{S}{S_0}\right) \quad (1j)$$

November; $$\frac{H}{H_0} = 0.17 + 0.66\left(\frac{S}{S_0}\right) \quad (1k)$$

December; $$\frac{H}{H_0} = 0.18 + 0.65\left(\frac{S}{S_0}\right) \quad (1l)$$

Elagib & Mansell model [12]

Elagib and Mansell conducted observations on global solar irradiance throughout Sudan, devising monthly-specific equations for the estimation of global solar radiation, presented as follows

January; $$\frac{H}{H_0} = 0.1357 + 0.3204L + 0.0422Z + 0.4947\left(\frac{S}{S_0}\right) \quad (2a)$$

February; $$\frac{H}{H_0} = 0.1563 + 0.3166L + 0.1006Z + 0.4593\left(\frac{S}{S_0}\right) \quad (2b)$$

March; $$\frac{H}{H_0} = 0.7727\left(\frac{S}{S_0}\right)^{0.7263} \quad (2c)$$

April; $$\frac{H}{H_0} = 0.1640 + 0.0397Z + 0.5773\left(\frac{S}{S_0}\right) \quad (2d)$$

May; $$\frac{H}{H_0} = 0.0709 + 0.8967\left(\frac{S}{S_0}\right) - 0.2258\left(\frac{S}{S_0}\right)^2 \quad (2e)$$

June; $$\frac{H}{H_0} = -0.0348 + 1.5078\left(\frac{S}{S_0}\right) - 0.8246\left(\frac{S}{S_0}\right)^2 \quad (2f)$$

July; $$\frac{H}{H_0} = 0.3205 + 0.1444L + 0.0782Z + 0.2916\left(\frac{S}{S_0}\right) \quad (2g)$$

August; $$\frac{H}{H_0} = 0.2720 + 0.0369L + 0.1017Z + 0.3888\left(\frac{S}{S_0}\right) \quad (2h)$$

September; $$\frac{H}{H_0} = -0.3710 + 2.5783\left(\frac{S}{S_0}\right) - 1.6788\left(\frac{S}{S_0}\right)^2 \quad (2i)$$

October; $$\frac{H}{H_0} = 0.1593 - 0.1043L + 0.0609Z + 0.5916\left(\frac{S}{S_0}\right) \quad (2j)$$

November; $$\frac{H}{H_0} = 0.1786 + 0.0199Z + 0.5441\left(\frac{S}{S_0}\right) \quad (2k)$$

December; $$\frac{H}{H_0} = 0.1714 + 0.1329L + 0.0482Z + 0.5015\left(\frac{S}{S_0}\right) \quad (2l)$$

Almorox et al. model [13]

Almorox and colleagues derived monthly-specific equations to forecast global solar energy based on sunshine hours. The equations below were provided forthe area of Toledo, Spain:

January; $$\frac{H}{H_0} = 0.285 + 0.444\left(\frac{S}{S_0}\right) \quad (3a)$$

July; $$\frac{H}{H_0} = 0.329 + 0.406\left(\frac{S}{S_0}\right) \quad (3g)$$

February; $\frac{H}{H_0} = 0.272 + 0.465\left(\frac{S}{S_0}\right)$ (3b)

March; $\frac{H}{H_0} = 0.291 + 0.491\left(\frac{S}{S_0}\right)$ (3c)

April; $\frac{H}{H_0} = 0.266 + 0.495\left(\frac{S}{S_0}\right)$ (3d)

May; $\frac{H}{H_0} = 0.286 + 0.475\left(\frac{S}{S_0}\right)$ (3e)

June; $\frac{H}{H_0} = 0.311 + 0.439\left(\frac{S}{S_0}\right)$ (3f)

August; $\frac{H}{H_0} = 0.313 + 0.410\left(\frac{S}{S_0}\right)$ (3h)

September; $\frac{H}{H_0} = 0.271 + 0.479\left(\frac{S}{S_0}\right)$ (3i)

October; $\frac{H}{H_0} = 0.259 + 0.465\left(\frac{S}{S_0}\right)$ (3j)

November; $\frac{H}{H_0} = 0.279 + 0.431\left(\frac{S}{S_0}\right)$ (3k)

December; $\frac{H}{H_0} = 0.282 + 0.428\left(\frac{S}{S_0}\right)$ (3l)

Statistical validation [9]

The calculations of global solar radiation (GSR) predictions undergo scrutiny and confirmation via five statistical assessments, namely Root Mean Square Error (RMSE), Mean Bias Error (MBE), Mean Absolute Bias Error (MABE), Mean Percentage Error (MPE), and Coefficient of Determination (R^2). RMSE, MBE and MABE use the same units as the dependent output vaiables.The expressions below delineate the definitions of these error evaluations. The subscript i denotes the specific solar radiation value, while n represents the total number of solar energy data. Subscripts c and m correspond to the calculated and measured global solar irradiation values, respectively, and the overline above H_m denotes the mean measured global solar radiation.

$$RMSE = \left[\frac{1}{n}\sum_{i=1}^{n}(H_{i,c} - H_{i,m})^2\right]^{1/2} \quad (4)$$

$$MBE = \frac{1}{n}\sum_{i=1}^{n}(H_{i,c} - H_{i,m}) \quad (5)$$

$$\mathrm{MABE} = \frac{1}{n}\sum_{i=1}^{n}\left|(H_{i,c} - H_{i,m})\right| \quad (6)$$

$$MPE(\%) = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{H_{i,c} - H_{i,m}}{H_{i,m}}\right)\times 100 \quad (7)$$

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(H_{i,m} - H_{i,c})^2}{\sum_{i=1}^{n}(H_{i,m} - \overline{H}_m)^2} \quad (8)$$

For better accuracy of RMSE, MBE, MABE and MPE values, they should converge towards zero, while R^2 should be closer to 1. RMSE, being always positive with an ideal value of zero, offers insight into the short-term performance of each model by enabling a term-by-term comparison of the actual deviation between calculated and measured values. MBE and MABE tests provideinformation regarding the long term performance of the models: a positive value signifies an average overestimation in predicted values, whereasa negative indicates an average underestimation. MPE clarifies the relative difference between measured values and those estimated by each model with lower values showinghigher prediction accuracy. R^2 ranging from 0 to 1, demonstrates a perfect linear relationship between measured andcalculated values when close to 1, while a value around zero specifies the absence of a linear relationship [14].

Results

Estimation of global solar radiation

Table 1a and 1b, along with Fig 1, display the comparison of the estimated total monthly global radiation with the actual data recorded by a Pyranometer in the years 2010 and 2011. The discrepancies between the predicted and measured radiation levels fluctuate throughout each year because of changing seasonal cloud cover and urban air pollution.

Table 1a Monthly GSR data from 3 models in comparison with the measurement in 2010

Model	Monthly global solar radiation in 2010 (MJ/m^2.day)												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ave
Soler	23.868	28.451	28.937	30.122	23.803	20.207	19.437	18.861	20.944	19.417	22.995	24.697	23.478
Almorox et al.	23.035	27.287	29.341	28.930	24.729	20.207	21.568	20.828	22.031	20.141	22.323	23.115	23.628
Elag & Mans	22.076	27.555	27.311	27.938	21.764	17.821	22.385	21.333	16.392	18.121	21.062	22.757	22.210
Measurement	13.091	17.133	18.442	21.219	16.821	15.098	14.475	12.878	13.454	12.675	13.394	13.010	15.141

Table 1b Monthly GSR data from 3 models in comparison with the measurement in 2011

Model	Monthly global solar radiation in 2011 (MJ/m^2.day)												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ave
Soler	28.112	26.289	22.199	23.464	22.079	16.682	20.410	19.405	20.144	21.025	27.730	25.912	22.788
Almorox et al.	25.890	25.617	23.631	23.609	23.120	16.682	22.267	21.229	21.382	21.380	25.409	23.915	22.844
Elag&Mans	25.257	25.906	19.058	21.739	19.992	12.612	22.839	21.712	15.366	19.708	24.964	23.695	21.071
Measurement	15.444	15.240	13.950	15.720	17.013	13.395	15.800	14.963	13.961	12.659	15.324	14.485	14.829

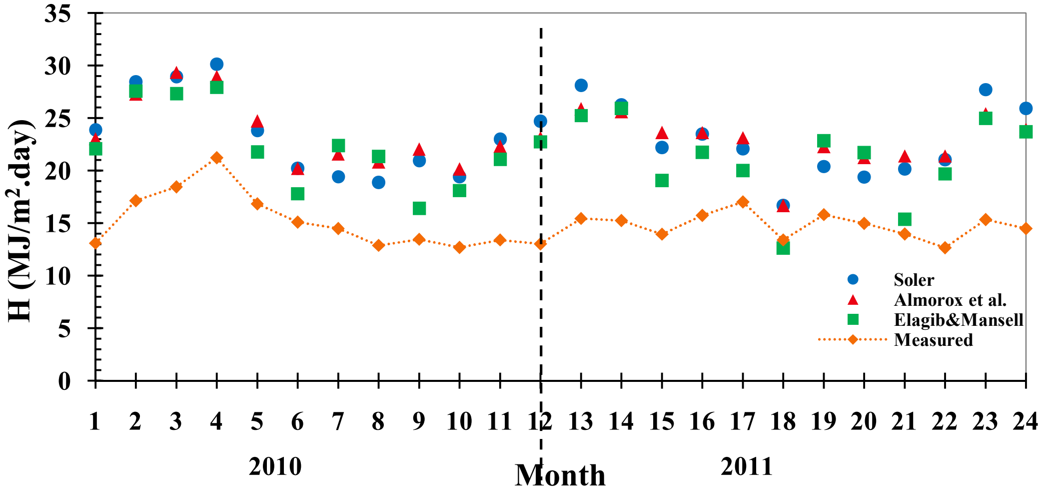

Figure 1 Comparison of monthly average GSR from all models with Pyranometer data.

Statistical validation

The statistical analysis indicates that the monthly global solar irradiation values estimated are strongly correlated with the measurements obtained from the Pyranometer. Fig. 2 - 4 represent the performance of each models in terms of R^2. Table2 displays RMSE values, ranging from 3.770 - 4.399 MJ/m^2.day. MBE values for all models are within the acceptable range of 7.290 - 8.498 MJ/m^2.day. Likewise, the MABE ranges from 7.719 -8.512 MJ/m^2.day. Additionally, MPE varies from 50.286 - 60.857 %. The statistical analysis indicates that the Elagib & Mansell model is the most accurate among the models in estimating solar radiation.

Table 2 Statistical analysisof each model performance on GSR estimation

Models	RMSE (MJ/m^2.day)	MBE (MJ/m^2.day)	MABE (MJ/m^2.day)	MPE(%)	R^2
Soler	4.399	8.485	8.512	58.412	0.589
Almorox et al.	4.076	8.498	8.504	60.857	0.663
Elagib & Mansell	3.770	7.290	7.719	50.286	0.570

On the other hand, the model by Almorox et al. demonstrates the most superior performance with an R^2 =0.663 as depicted in Fig. 2. In contrast, Soler's and Elagib & Mansell's model exhibit R^2 =0.589and 0.570, respectively. Fig. 4 illustrates the comparison of these three models with the actual measurement taken during the period of 2010-2011.

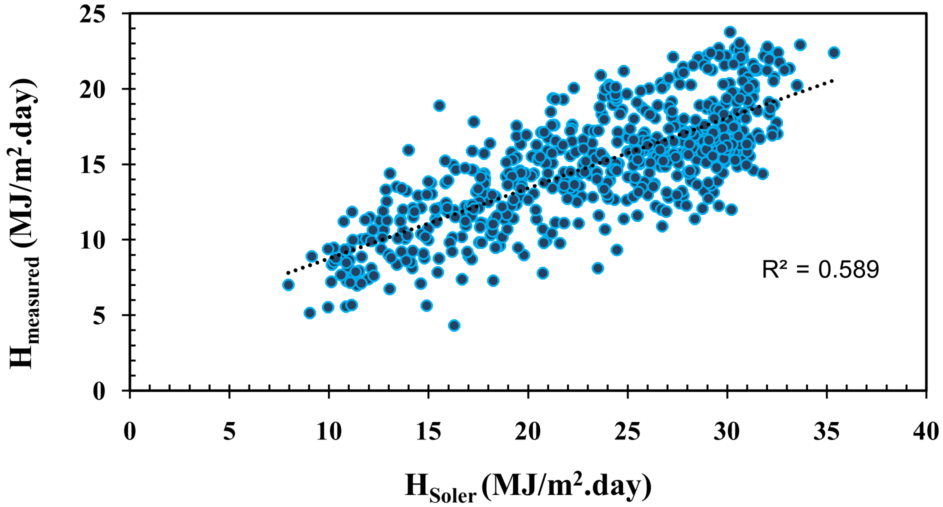

Figure 2 The coefficient of determination (R^2) of Soler's model.

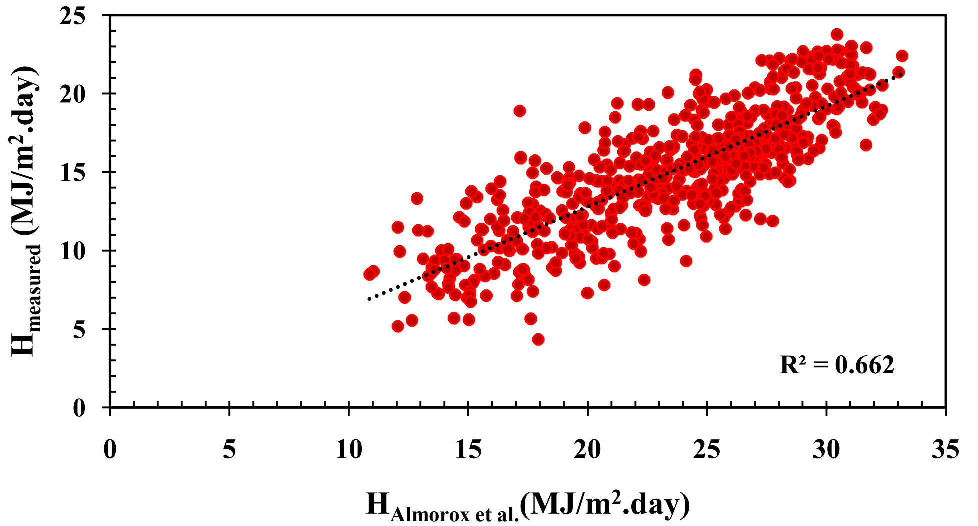

Figure 3 The coefficient of determination (R^2) of Almorox et al.'s model.

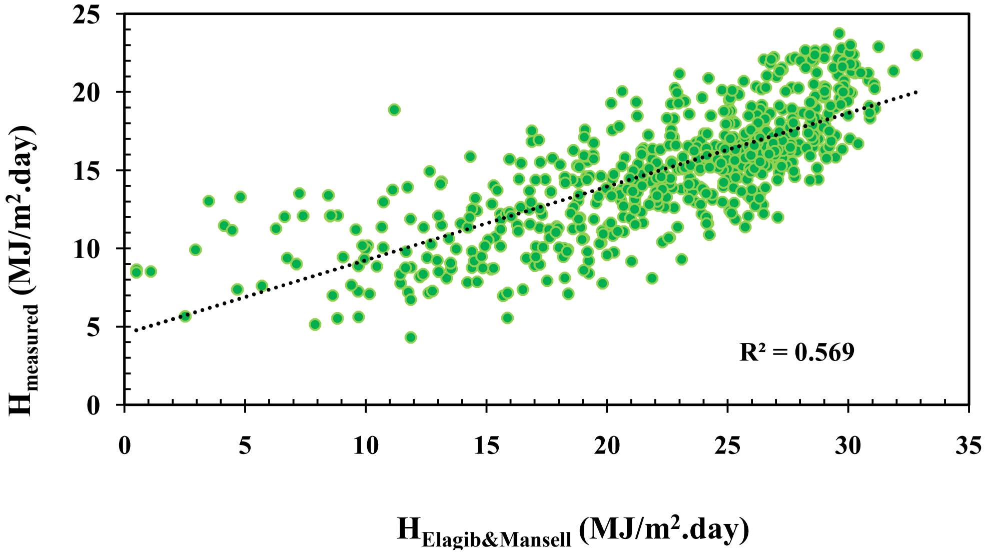

Figure 4 The coefficient of determination (R^2) of Elagib & Mansell model.

Discussion and Conclusions

Determining solar energy levels is crucial for various purposes like solar technology and renewable energy. One effective method to calculate solar radiation involves using empirical models along with specific meteorological and geographical data which is spatial and temporal. Comparing measured and calculated solar radiation values helps in accurately estimating global solar radiation on a horizontal surface.

In Bangkok, Thailand, three models based on sunshine duration hour were preliminary tested by using the available data in 2010 and 2011, with the Elagib and Mansell model proving to be the most accurate for solar radiation estimation due to its superior performance confirming by RMSE, MBE, MABE and MPE values.This model, which focuses on sunshine duration, is particularly suitable for Bangkok due to its similar climate conditions with Sudan, in terms of seasonal changes, latitude, and concentration level of air pollutants [12]. Moreover, acorrelation between the predicted models and the actual measurement was satisfiedas well as the case study of Peninsular, Malaysia [15].

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