INTERNATIONAL JOURNAL of RENEWABLE ENERGY RESEARCH
Ersan Omer Yuzer and Altug Bozkurt, Vol.14, No.1, March, 2024

Comparison of Regional Empirical Models Based on Sunshine Duration for Determining Solar Irradiance

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Received: 10.06.2023 Accepted:03.08.2023

Abstract- Solar radiation is a crucial parameter required in various fields, particularly for obtaining energy from solar power plants. In this context, the primary objective of this study is to compare commonly used empirical models based on sunshine duration to determine solar radiation for neigh boring provinces centered around Van, a province in eastern Turkey, known for its high solar energy potential. Six empirical models developed based on sunshine duration, utilizing meteorological data obtained from the Turkish State Meteorological Service, were used to estimate solar radiation. Performance evaluation of the models was carried out using several statistical metrics, including Mean Bias Error (MBE), Root Mean Square Error (RMSE), normalized Root Mean Square Error (nRMSE), Mean Absolute Bias Error (MABE), Mean Absolute Percentage Error (MAPE), t-statistic (t-stat), and Coefficient of Determination (R^2). Results obtained from the regression analysis revealed that the lowest value of the coefficient of determination was 0.6444 for Ağrı, while the highest value was 0.8674 for Siirt. In these provinces, "exponential" and "linear" models yielded the most successful results, respectively. Additionally, the predictions made using the "logarithmic" model resulted in significantly poor outcomes in all study regions, with Van having the lowest coefficient of determination at 0.2430. Hakkari demonstrated the best results with a coefficient of determination of 0.7230 using the "cubic" model, and Şırnak yielded the highest result of 0.6795 with the "linear" model. The results indicate that empirical models based on sunshine duration possess varying prediction capacities depending on the climatic conditions, and therefore, the success of solar radiation estimation relies on the choice of empirical coefficients.

Keywords Empirical models, renewable energy, solar energy, solar irradiance, sunshine.

1. Introduction

Solar energy, due to its high energy potential, is one of the most important renewable energy sources and is rapidly expanding worldwide [1-3]. Photovoltaic (PV) systems is the most significant application that converts solar energy into electricity [4,5]. For the design and determination of optimal energy production of these systems, knowledge of solar radiation data is essential. However, solar radiation data may not be available in every region due to the lack of measurement devices. This situation has led to the development of empirical solar models to estimate solar radiation values [6].

The intensity and availability of solar energy of course varies from one country to another [7]. Empirical solar models are widely used to accurately determine solar radiation in places where solar radiation data is not available or cannot be measured [8]. Empirical solar models based on sunshine duration, temperature, and hybrid structures are existing models in the literature. However, empirical solar models based on sunshine duration are the most preferred for solar energy applications and predictions due to their simplicity and accuracy [9]. Table 1 shows an example of an empirical solar model and the parameters used in the model.

Table 1. Example Empirical Solar Model and its Parameters

Sunshine-Based Models	Temperature-Based Models	Hybrid Models
$\frac{H}{H_o} = a + b * \left(\frac{S}{S_o}\right)$	$\frac{H}{H_o} = a * ln(T_{max} - T_{min}) + b$	$\frac{H}{H_o} = a + b * \left(\frac{S}{S_o}\right) + c * \left(\frac{T_{min}}{T_{max}}\right) + d * RH$
H : Global solar radiation H_o: Extra-terrestrial radiation S_o : Monthly average day length S : Sunshine duration a, b: Empirical coefficients	H : Global solar radiation H_o: Extra-terrestrial radiation ΔT: Mean air temperature T_{max}: Maximum temperature T_{min}: Minimum temperature a, b: Empirical coefficients	H : Global solar radiation H_o: Extra-terrestrial radiation ΔT: Mean air temperature T_{max}: Maximum temperature T_{min}: Minimum temperature RH: Relative humidity a, b, c, d: Empirical coefficients

Historically, global solar radiation was mathematically expressed for the first time by Angström [10]. Later, Prescott introduced some parameter changes to the original Angström relation, resulting in a different mathematical model [11]. The Angström model was subsequently referred to as the Angström-Prescott equation (Equation 5), known as a sunshine duration-based model [12-14].

Numerous studies have been conducted to predict global solar radiation (GSR) at different locations worldwide using various empirical or statistical models. Starting with the Angström model to the present, several empirical models have been proposed in the literature for estimating GSR on a global and local scale during specific time intervals [15-21]. The results indicate that the performance of these models varies across different regions of the world, and requires the analysis and adoption of appropriate models for different areas. In this study, six empirical models (Equations 5-10) based on sunshine duration have been utilized to predict GSR in the southern part of Turkey's Eastern region, focusing specifically on Van province, known for its high solar energy potential, and its neighboring provinces. The objective of this study is to identify the most suitable empirical model(s) for the stations selected in the study area. The models were chosen based on data from sunshine duration, obtained from relevant literature studies conducted in Turkey. Nevertheless, there is a lack of prior comparative study carried out using this approach in the selected regions.

Bulut and Büyükalaca, have developed a simple model based on a trigonometric function with the day of the year to determine daily global solar radiation. The model has been tested for sixty eight locations in Turkey using a 10-year dataset, and they observed that it exhibits a high level of agreement with long-term measured data. In the study, which includes provinces of Ağrı, Van, Hakkari, and Siirt, except Şırnak, no calculations or comparisons have been conducted using empirical models [22].

Using data obtained from seven different meteorological stations, Düzen and Aydın evaluated several sunshine-based regression models to predict monthly average daily global solar radiation on the horizontal surface of the Vangölü region in Eastern Anatolia, Turkey, The researchers found that cubic and second-degree regression models were the most suitable regression equations for predicting the monthly average daily global solar radiation on the horizontal surface [23].

Kaba et al., utilized a deep learning (DL) method to predict solar radiation across a total of 30 stations, including Van province. To evaluate the performance of the DL model, they compared its results with those of four well-known Angström-type empirical models, namely linear, quadratic, cubic, and exponential models. The study demonstrated that the results of DL model were more accurate than those generated by the empirical models, and among the four empirical models, the quadratic model proved to be the most successful in predicting solar radiation. In the study in which only Van province was utilized similarly, a more limited performance metric was employed, and model development was carried out using deep learning [24].

Gürel et al., evaluated the performance of three Angström models, namely linear, quadratic, and cubic equations, to predict daily global solar radiation using station data from a total of four cities in Turkey with different climatic regions, including Şırnak province. The empirical models used to predict solar radiation in Şırnak province yielded successful results with determination coefficients exceeding 98%. In the study, in which only Şırnak province was considered, three empirical models were used, but the validity of these models in the study area was not determined [25].

This and many other recent studies demonstrate that empirical models for solar radiation prediction far exceed the prediction limits with varying performance in different regions around the world [17]. Therefore, determining the most accurate models for any specific location is a current topic of interest. However, instead of developing new models for global solar radiation prediction, it would be more appropriate to determine suitable models from the literature. Hence, this study focuses on evaluating the performance of six empirical models selected from the literature for predicting solar radiation. The contributions of this study are listed below:

- ➢ This study has enabled the determination of the performance of developed empirical solar models based on sunshine duration in the study area.
- ➢ The results of the models used in five different provinces with varying climatic conditions but neighboring each other have been evaluated and verified.
- ➢ The accuracy of the prediction performance in the models used has been investigated through statistical indicators.
- ➢ The validity of the empirical coefficients tested in the models used in the study area has been determined by evaluating with different data set values.

The rest of the study is organized as follows. Section 2, gives information about the study area and the data used, as well as the prediction methods employed and the performance indicators used in the evaluation of the obtained results. In Section 3, the observations regarding the research findings are examined and discussed. The conclusions are provided in Section 4.

2. Material and Method

2.1. Study Area and Data

The geographical location of Turkey, especially in the Eastern Anatolia and Southern regions, enables the production of solar energy in many areas. Therefore, the selected locations within the scope of the study have a high solar energy potential [26]. This study investigates and validates the performance of empirical models based on sunshine duration for the estimation of solar irradiance in the provinces of Ağrı, Hakkari, Siirt, Şırnak and Van, which have different climatic conditions and altitudes between 895 m and 1790 m. The geographical and meteorological characteristics of the selected provinces are shown in Fig. 1.

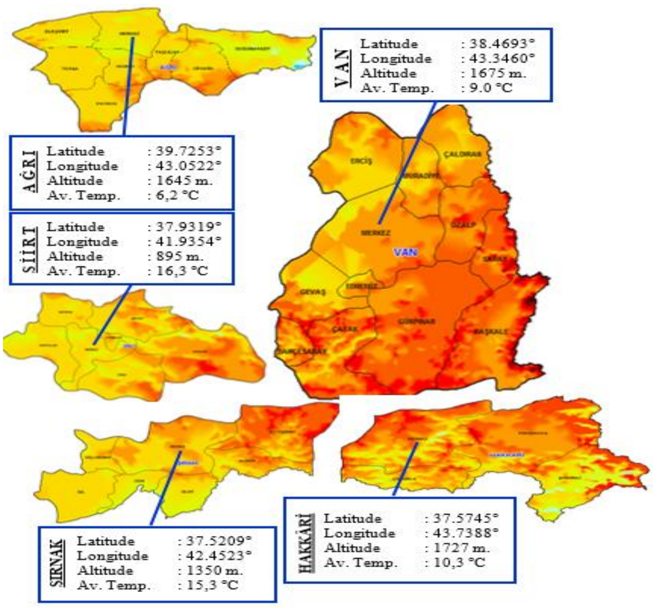

Fig. 1. Geographical and meteorological characteristics of the study area [26].

In this study, data obtained from meteorological stations belonging to the Turkish State Meteorological Service (TSMS) of five neighboring cities in Van and its surroundings were used. These data consist of monthly average daily global solar irradiance (MJ/m^2-day) and sunshine duration (hours) measured between 2010 and 2022. The station and parameter information used in the study are detailed in Table 2. Additionally, Fig. 2 illustrates the monthly variation of sunshine hours in the study areas. The maximum values of sunny hours were recorded between June and August. Since meteorological data for Bitlis province and its districts were not measured by TSMS stations, these regions were excluded from the scope of the study.

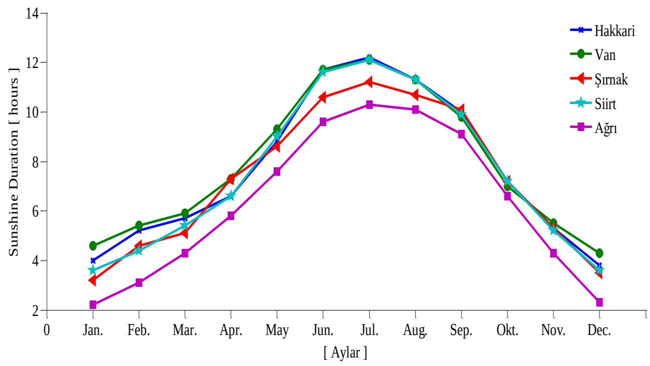

Fig. 2. Monthly variation of sunshine duration in the study areas.

2.2. Method

In the literature, there are numerous linear and nonlinear empirical models developed to predict global solar radiation. However, it is of great importance to determine the most robust and accurate prediction model for a specific purpose and region. Solar radiation and sunshine duration are the most common parameter data used to predict global solar radiation. Literature studies have shown that models based on sunshine duration may provide more accurate solar radiation predictions compared to other empirical models based on factors such as air temperature [29]. Therefore, in this study, the performance of the sunshine-based Angström-Prescott model in the selected study areas, considering their specific characteristics, is evaluated using a statistical error estimation method. The aim of the study is to determine the best model for predicting daily solar radiation. The methodology used for solar radiation prediction in this study is illustrated in Fig. 3.

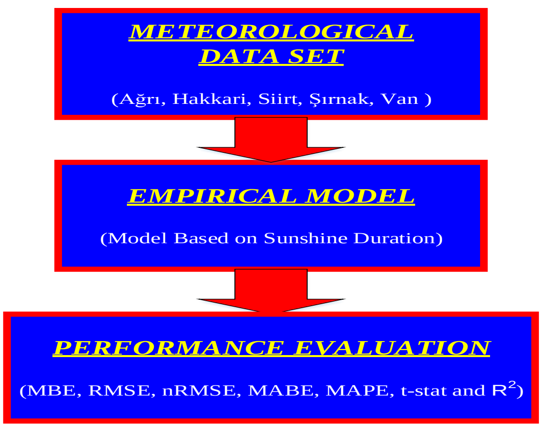

Fig. 3. Methodology for solar irradiance prediction.

Table 2. Meteorological station and parameter information used in the study [27,28].

Station No	Station Name	Climate Zone	Climate Type	Data Range	Daily Average Sunshine Duration $(hour)$	Monthly Average Global Solar Irradiance (MJ/m^2-day)
17099	Ağrı	Eastern Anatolia	Semi dry-Semi humid	2010-2022	6.3	5.364-24.372
17285	Hakkâri	Eastern Anatolia	Semi arid-Less humid	2010-2022	7.6	6.516-25.236
17210	Siirt	Southeastern Anatolia.	Semi dry-Less humid	2010-2022	7.5	6.408-24.120
17287	Şırnak	Southeastern Anatolia.	Semi dry-Less humid	2010-2022	7.3	6.516-24.300
17172	Van	Eastern Anatolia	Semi dry-Less humid	2010-2022	7.9	6.156-25.668

The Angström-Prescott model and the related models based on sunshine duration have been selected among other types of input relationships to assess global solar irradiance on a horizontal surface at any location on Earth. The correlation of the datasets has been observed between the average monthly global solar irradiance (H) expressed as the ratio (H/H_0) or the clearness index (K_t) and the extraterrestrial solar irradiance (H_0) due to their simple functional forms and robust computational capabilities. Consequently, the extraterrestrial solar irradiance value (H_0) H_o (MJ/m^2-day) and the monthly average sunshine duration on a horizontal plane S_o $(hours)$ are calculated as shown in Eq. (1) and (2), respectively [30-32].

$$H_o = \frac{24}{\pi} * I_{sc} * \left[1 + 0{,}033 * cos\left(\frac{360 * d}{365}\right)\right] * \left[\frac{\pi * \omega_s}{180} * sin\varphi * sin\delta + cos\varphi * cos\delta * sin\omega_s\right] \quad (1)$$

$$S_o = \frac{2}{15} * \omega_s \quad (2)$$

Here, (I_{sc}) is consideredd as the solar constant with a value of 1367 W/m^2. (d) represents the number of days starting from the first day of January, (ω_s) denotes the solar hour angle, (φ) represents the latitude of the location where the study is conducted, and (δ) represents the solar declination angle. The solar declination angle (δ) and the solar hour angle (ω_s) can be expressed as shown in Eq. (3) and (4), respectively.

$$\delta = 23{,}45 * sin\left[\frac{360*(284+d)}{365}\right] \quad (3)$$

$$\omega_s = cos^{-1}(-tan\varphi * tan\delta) \quad (4)$$

In the dataset used, for each location within the period from January 1 to December 31 of each year between 2010 and 2022 (d=1 to 365), Eq. (1-4) were separately calculated and prediction values were determined.

Angström [10], proposed an empirical relationship between the ratio of global solar irradiance on a horizontal surface (H/H_o) and the relative sunshine hours (S/S_o) at a given location, which was further modified by Prescott [11] as shown in Eq. (5).

$$\frac{H}{H_o} = a + b * \left(\frac{S}{S_o}\right) \quad (5)$$

The second-degree (quadratic) [33], cubic [34], exponential [35], logarithmic [36], and exponent [37] forms of Eq. (5) can be derived as Eq. (6-10), respectively [38-41].

$$\frac{H}{H_o} = a + b * \left(\frac{S}{S_o}\right) + c * \left(\frac{S}{S_o}\right)^2 \quad (6)$$

$$\frac{H}{H_o} = a + b * \left(\frac{S}{S_o}\right) + c * \left(\frac{S}{S_o}\right)^2 + d * \left(\frac{S}{S_o}\right)^3 \quad (7)$$

(1)

$$\frac{H}{H_o} = a + b * exp\left(\frac{S}{S_o}\right) \quad (8)$$

$$\frac{H}{H_o} = a + b * log\left(\frac{S}{S_o}\right) \quad (9)$$

$$\frac{H}{H_o} = a * \left(\frac{S}{S_o}\right)^b \quad (10)$$

Here, a, b, c, and d are empirical coefficients determined based on the studies found in the literature for the selected regions. Accordingly, for Hakkari and Van, the coefficients from the study conducted by Duzen and Aydın [23] were used, for Şırnak, the coefficients from the study by Gurel et al. [25] were used, and for other locations and missing coefficients, the coefficients determined for Turkey as a whole by Bakirci [37] were used. Although empirical coefficients for Bitlis province are available in the literature [23], this region was not included in the study due to the unavailability of solar irradiance data specific to that region.

2.3. Performance Evaluation

Within the scope of this study, after obtaining the necessary solar irradiance values using the selected Angström-Prescott models, performance evaluation was conducted using statistical metrics. Seven statistical performance criteria were used for model comparisons in this research, namely MBE, RMSE, nRMSE, MABE, MAPE, t-stat, and R^2. The performance evaluation metrics used are shown in Eq. (11-17), respectively [42-46].

$$MBE = \frac{1}{N}\sum_{i=1}^{n}\left(Z_{i_g} - Z_{i_t}\right) \quad (11)$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{n}\left(Z_{i_g} - Z_{i_t}\right)^2} \quad (12)$$

$$nRMSE = \frac{\sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(Z_{i_g} - Z_{i_t}\right)^2}}{\overline{Z_{i_g}}} * 100 \quad (13)$$

$$MABE = \frac{1}{N}\sum_{i=1}^{n}\left(\left|Z_{i_g} - Z_{i_t}\right|\right) \quad (14)$$

$$MAPE = \frac{1}{N}\sum_{i=1}^{N}\frac{\left(Z_{i_g} - Z_{i_t}\right)}{Z_{i_g}} * 100 \quad (15)$$

$$R^2 = 1 - \frac{\sum_{i=1}^{N}\left(Z_{i_g} - Z_{i_t}\right)^2}{\sum_{i=1}^{N}\left(Z_{i_g} - \overline{Z_{i_g}}\right)^2} \quad (16)$$

$$t - stat = \sqrt{\frac{(n-1) * MBE^2}{RMSE^2 - MBE^2}} \quad (17)$$

Here, N represents the number of elements in the dataset, Z_{i_g} represents the actual (measured) value of global solar irradiance Z_{i_t} represents the predicted value of solar irradiance by the model, and $\overline{Z_{i_g}}$ denotes the average of all measured global solar irradiance values in the dataset. The expression 'n' in the t-stat equation refers to the sample size. For the obtained solar irradiance prediction results, a low RMSE value is desirable, while the R^2 value is desired to be the highest within the range of 0-1. If nRMSE evaluated based on RMSE is less than 10%, it indicates a perfect prediction. MAPE, which explains the success of the prediction model, measures the magnitude of errors in percentage, and MAPE≤10% represents a high level of accuracy, while 20%≤MAPE≤50% signifies a reasonable prediction. MBE indicates whether there is an overestimation (positive value) or underestimation (negative value) in the calculated values. Additionally, the t-stat value is used to determine the statistical significance of the model predictions.

In this study, based on the aforementioned statistical error tests, six Angström-Prescott models were compared, and the accuracy of the predicted data for these models was determined using these tests. These statistics should ideally have values close to zero for better data modeling. However, the correlation coefficient R should approach as close to 1 as possible.

The main contribution of this study is that it compares the performance of empirical models in predicting global solar irradiance in the selected study regions. Instead of developing new models for these regions, it was deemed more appropriate to determine the most suitable one from the existing studies in the literature. However, determining the empirical coefficients for these regions is a challenging task. In this context, there are several studies available in the literature. Therefore, the empirical coefficients used in the study, which vary depending on the field, were determined by utilizing the literature information obtained from studies conducted based on similar climatic characteristics.

3. Results and Discussion

In this study, six empirical models based on sunshine duration were evaluated for the estimation of global solar irradiance in five provinces of Turkey with high sunshine duration and solar irradiance potential, suitable for photovoltaic power plant installations. All models were validated using statistical metrics such as MBE, RMSE, nRMSE, MABE, MAPE, t-stat, and R^2 based on MGM data. For higher modeling accuracy, MBE, RMSE, nRMSE (%), MABE, and MAPE (%) indices should approach zero, while the R-value should be close to 1. The performance indicators of the six empirical models for the selected locations are presented in Tables 2-6.

A. Model evaluation results for Ağrı province are as follows

For Ağrı province, the determination coefficients of the linear, quadratic, cubic, exponential, logarithmic, and exponent models range from 0.3155 to 0.6444. The worst result was obtained with the "exponential" model, while the best result was achieved with the "logarithmic" model. All models had low RMSE values. However, the nRMSE values for all models were above 30%, indicating poor performance within the nRMSE>%30 range. The t-statistic value for the "exponential" model, calculated as the minimum of 16.3565, significantly exceeded the critical t-value of 3.106, indicating that this model is not statistically significant. In this study, the lowest MBE value for Ağrı province was -1.2098, obtained with the "exponential" model, the lowest MABE value was 3.8640, obtained with the "quadratic" model, and the lowest MAPE value was 38.9398, obtained with the "exponent" model. Ideally, statistical tests such as MBE, MABE, and MAPE should have values close to zero. When evaluating the models based on these statistical indicators, all models for Ağrı province yielded unsatisfactory results. Table 3 displays the performance indicators' results obtained with empirical models for Ağrı province.

Table 3. Model evaluation results for Ağrı province

Model	MBE	RMSE	nRMSE	MABE	MAPE	R^2	t-stat
Linear	-1.6278	4.9477	31.7025	3.8873	44.5357	0.6410	22.4869
Quadratic	-1.8103	4.9782	31.9047	3.8640	42.1875	0.6367	25.1998
Cubic	NaN	NaN	NaN	NaN	NaN	NaN	NaN
Exponential	-1.2098	4.9255	31.5671	3.9661	50.1300	0.6444	16.3565
Logarithmic	-3.5203	6.3286	37.4097	4.8637	43.7798	0.3155	40.7596
Exponent	-2.8637	5.3306	34.1633	4.1532	38.9398	0.5835	41.1154

B. Model evaluation results for Hakkari province are as follows

For Hakkari province, the highest determination coefficient of 0.7230 was obtained with the "cubic" model, while the lowest determination coefficient of 0.5558 was calculated with the "exponential" model. According to the performance indicator representing moderate prediction success with 20%<nRMSE<30%, the "cubic" model achieved the most successful nRMSE value of 26.2946. The "exponent" model had the lowest MAPE value of 38.4646, meeting the reasonable prediction criterion of 20%<MAPE≤50%. The t-statistic value for the "quadratic" model was 0.6677, significantly below the critical t-value of 3.106, indicating that this model is statistically significant. However, other indicators showed that the values deviated considerably from zero, indicating that the models used for Hakkari province did not yield successful results according to these performance indicators. Table 4 presents the results of the performance indicators obtained with empirical models for Hakkari province.

Table 4. Model evaluation results for Hakkari province

Model	MBE	RMSE	nRMSE	MABE	MAPE	R^2	t-stat
Linear	-0.4549	4.6247	28.8255	3.7239	63.2678	0.6671	6.5419
Quadratic	0.0522	5.1740	32.2495	4.0857	76.5568	0.5833	0.6677
Cubic	-0.9894	4.2180	26.2946	3.3341	45.5869	0.7230	15.9689
Exponential	8.7984	9.9975	62.3146	8.8328	119.0169	0.5558	122.663
Logarithmic	-0.4598	4.5385	26.7758	3.6178	40.5999	0.6379	6.4740
Exponent	-3.0056	4.8587	30.2845	3.8635	38.4646	0.6325	52.1125

C. Model evaluation results for Siirt province are as follows

The calculation results obtained with empirical models for Siirt province are shown in Table 5. Taking these results into consideration, the minimum and maximum determination coefficients were found to be 0.8674 in the "linear" model and 0.7636 in the "logarithmic" model. Overall, when examined in general, the most successful results were obtained for Siirt province with all the empirical models used. The nRMSE value was lowest at 19.8001, calculated in the linear model. Evaluating the results of the performance indicators, the most suitable empirical model for solar radiation prediction in Siirt province was determined to be the "exponential" model. The proximity of the results obtained in MBE, RMSE, and MABE indicators to zero supports this conclusion.

Table 5. Model evaluation results for Siirt province

Model	MBE	RMSE	nRMSE	MABE	MAPE	R^2	t-stat
Linear	-1.0192	3.2105	19.8001	2.6009	40.0549	0.8674	13.2984
Quadratic	-1.1487	3.2187	19.8509	2.5955	37.8111	0.8668	15.1766
Cubic	NaN	NaN	NaN	NaN	NaN	NaN	NaN
Exponential	-0.7402	3.2456	20.0167	2.6387	45.2131	0.8645	9.3052
Logarithmic	-2.2433	4.0283	23.2645	3.1405	34.3137	0.7636	25.5128
Exponent	-1.8502	3.5276	21.7554	2.7488	32.1817	0.8400	24.4708

D. Model evaluation results for Şırnak province are as follows

In Şırnak province, the determination coefficient was calculated to be the lowest at 0.3640 in the "cubic" model and the highest at 0.6795 in the "linear" model. The empirical model evaluation results for Şırnak province are provided in Table 6. Based on these results, the "linear," "quadratic," and "exponential" models can be considered as the most successful models. The t-statistic values for all models ranged from 3.1088 to 28.9503. Therefore, none of the models fell below the critical t-value of 3.106. The lowest MBE of -0.2333 was obtained in the "linear" model, the lowest MABE of 3.5792 was obtained in the "quadratic" model, and the lowest MAPE of 41.4941 was obtained in the "exponent" model. The lowest nRMSE value was also calculated in the "linear" model. In this context, the "linear" model was determined as the most successful empirical model for solar radiation prediction in Şırnak province.

Table 6. Model evaluation results for Şırnak province

Model	MBE	RMSE	nRMSE	MABE	MAPE	R^2	t-stat
Linear	-0.2333	4.8262	29.8709	3.7611	63.3959	0.6795	3.1088
Quadratic	0.2419	4.7618	31.6087	3.5792	68.6281	0.6706	3.3837
Cubic	0.9221	6.6178	43.9381	4.7665	107.3245	0.3640	9.3602
Exponential	-0.3173	4.8749	30.1725	3.8514	69.2719	0.6730	4.1896
Logarithmic	-2.4952	5.8304	33.6429	4.4513	48.2242	0.4599	28.9503
Exponent	-1.9632	5.1762	32.0373	3.9013	41.4941	0.6313	26.3268

E. Model evaluation results for Van province are as follows

Table 7 presents the results of solar radiation prediction using empirical models for Van province. For Van province, the lowest determination coefficient of 0.7131 was obtained in the "logarithmic" model, while the highest determination coefficient of 0.7131 was obtained in the "linear" model. Among the empirical models used for solar radiation prediction in Van province, only the "linear" model produced successful results. According to the MBE indicator, models other than the "quadratic" and "linear" models showed results significantly deviating from zero. Additionally, the t-statistic value of 0.3973 calculated for the "linear" model was considerably higher than the critical value in other models. The MAPE value for the "linear" model resulted in reasonable prediction within the 20%<MAPE≤50% range.

Table 7. Model evaluation results for Van province

Model	MBE	RMSE	nRMSE	MABE	MAPE	R^2	t-stat
Linear	-0.0256	4.2895	24.7084	3.2184	39.6140	0.7131	0.3973
Quadratic	0.8484	5.1075	29.4201	3.6602	52.1446	0.5933	11.1990
Cubic	3.9614	6.1035	35.1573	4.2348	57.7309	0.4186	56.7191
Exponential	6.6291	8.1814	47.1264	6.7335	70.5869	0.4350	91.9135
Logarithmic	-4.2789	6.7355	40.5318	5.4847	41.6594	0.2430	54.7024
Exponent	-4.9380	6.7937	39.1330	5.5955	39.2211	0.2797	70.3592

The statistical comparison results of the models used in this study are presented in Tables 3-6. R^2, which describes the relationship between the measured and predicted values, is desired to be close to 1. When considering R^2 for all models together, it can be observed that the R^2 values for all models are significantly smaller than 1. The best average R^2 values for Ağrı, Hakkari, Siirt, Şırnak, and Van are 0.6444, 0.7230, 0.8674, 0.6795, and 0.7131, respectively.

RMSE provides information about the short-term performance of the models, and it is desirable for its value to be close to zero. Among the models used in the study, the lowest RMSE value of 3.21 (MJ/m^2) and nRMSE value of 19.85% were calculated for Siirt province using "linear" and "quadratic" models. The "cubic" model showed the best performance with an RMSE of 4.21 (MJ/m^2) and an nRMSE value of 26.29% in Hakkari province. Calculation could not be performed for Ağrı and Siirt provinces using this model as no previous study using this model was conducted in the literature, and thus the empirical coefficients could not be determined. In the "exponential" model, the best performance was achieved in Siirt province with an RMSE of 3.24 (MJ/m^2) and an nRMSE value of 20.01%. However, the worst performance results were observed in Van province when evaluated using this model. In the "logarithmic" model, similar performance was observed with RMSE values of 4.02 (MJ/m^2) and 4.53 (MJ/m^2) and nRMSE values of 23.26% and 26.77% in Siirt and Hakkari provinces, respectively. The "exponent" model exhibited the best performance in Siirt province with an RMSE of 3.52 and an nRMSE of 21.75%. However, for other provinces, this model showed significantly higher error indicators. The low performance of these models has also been noted in previous literature studies conducted in similar regions.

In terms of MAPE evaluation, most of the models for all provinces were found to be below 50%. In the literature, when the MAPE value falls within the range of 20% to 50%, the results are classified as "reasonable accuracy." In this context, most of the models used in this study exhibit reasonable accuracy in terms of MAPE. For Ağrı, except for the "exponential" model, the other models; for Hakkari, the "cubic", "logarithmic", and "exponent" models; for Siirt, all models; for Şırnak, the "logarithmic" and "exponent" models; and for Van, the "linear", "logarithmic" and "exponent" models yielded results with reasonable accuracy based on the MAPE values. Furthermore, in terms of MABE results, all model outcomes for Siirt province were successful. Among these models, the linear model performed the best with an MABE value of 2.60 (MJ/m^2) for Siirt province.

In this study, the t-statistic (t-stat) method was also considered to evaluate the models in terms of statistical significance. The calculated t-stat values from the models should be smaller than the critical t-value. In this study, the critical t-value was found to be 3.106 for α=0.01 and n=12 based on statistical tables. The evaluation of model results was conducted based on this value. If the obtained t-statistic values are smaller than the critical t-value of 3.106, the models are statistically significant. In this context, for Hakkari, the "quadratic" model; for Şırnak and Van, the "linear" model; the t-stat values are 0.6677, 3.10, and 0.3973, respectively. The calculated t-stat values for these models are smaller than the critical t-value. However, according to this method, the calculated t-stat for Siirt province resulted in a value exceeding the critical t-value, indicating poor performance.

Figure 4-8 depicts the variation of the monthly average of measured daily global solar irradiance in the selected study areas and the corresponding values obtained from Eq. (5-10). The calculated daily global irradiance values from the models were compared with the corresponding measured values. It can be observed from the figure that the deviation between the measured and calculated values is generally consistent for the designated study areas. However, it is clearly evident from the figure that the deviation is very small, especially in Siirt province.

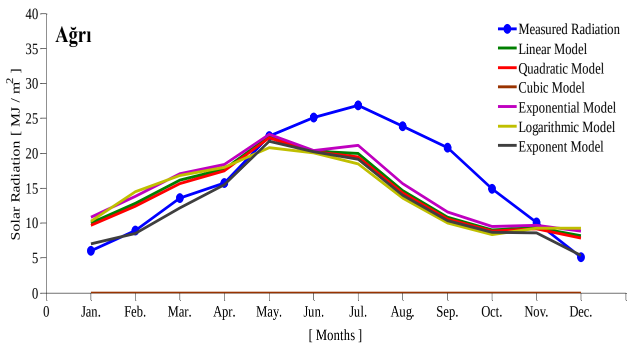

Fig. 4. Monthly trends of prediction models for Ağrı.

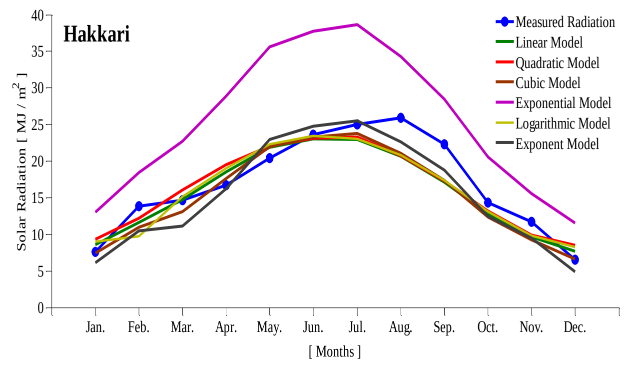

Fig. 5. Monthly trends of prediction models for Hakkari.

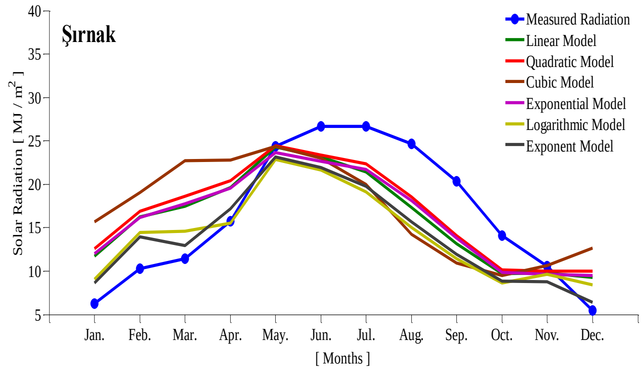

Fig. 6. Monthly trends of prediction models for Şırnak.

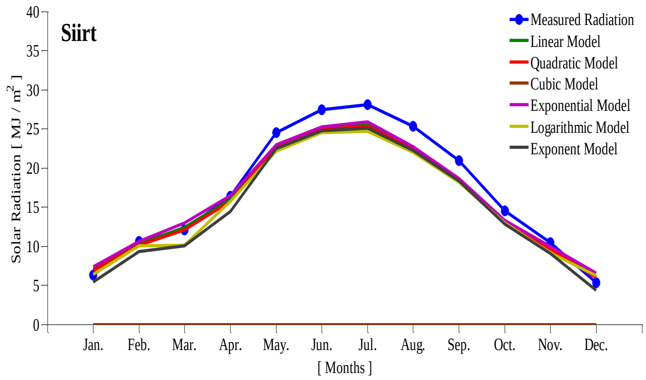

Fig. 7. Monthly trends of prediction models for Siirt.

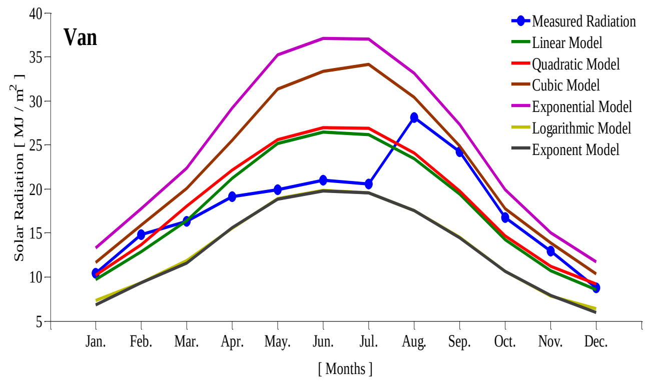

Fig. 8. Monthly trends of prediction models for Van.

4. Conclusion

The empirical model is the most commonly used method for estimating global solar irradiance. This study comprehensively reviewed six empirical models used for predicting global solar irradiance, based on the widely and primarily measured meteorological variables of solar irradiance and sunshine duration in Van and bordering provinces. To determine the most suitable model for the study area, data covering the years 2010-2022 from five meteorological stations, provided by the General Directorate of Meteorology, were used. The results indicate that the performance values of the selected models are relatively high for some regions.

The best average R^2 values for Ağrı, Hakkari, Siirt, Şırnak, and Van were calculated as 0.6444, 0.7230, 0.8674, 0.6795, and 0.7131, respectively. Among the sunshine-based models, the "linear" and "quadratic" models showed the lowest RMSE values of approximately 3.21 (MJ/m^2) and nRMSE values of 19.85% for Siirt province. The "cubic" model demonstrated the best performance with RMSE and nRMSE values of 4.21 (MJ/m^2)and 26.29%, respectively, in Hakkari province. In the "exponential" model, the best performance was achieved in Siirt province with RMSE and nRMSE values of 3.24 (MJ/m^2)and 20.01%, respectively.

Regarding the MAPE evaluation, most models for all provinces were below 50%. In terms of MABE values, all models showed successful results for Siirt province. Among the models, the "linear" model was the most successful model for Siirt province with an MABE value of 2.60 (MJ/m^2). Based on these results, the most successful prediction performance was achieved with the "linear" and "exponential" models in Ağrı province, "linear" and "quadratic" models in Siirt province, followed by the "cubic" and "linear" models for Hakkari and Şırnak provinces, respectively. For Van province, the "linear" model was determined as the most successful prediction model, considering the climatic conditions.

The results obtained in this study indicate that revisions made to the structure of the Angström-Prescott model, changing it from linear to non-linear forms, are generally ineffective and do not cause significant changes in the performance results of the model. The main factors determining the estimation of global solar irradiance are the empirical coefficients included in the models. When these coefficients are accurately determined, linear equation models can be preferred to calculate the global solar irradiance in another area with similar climatic conditions.

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