Estimation of solar energy based on solar angles: cities of Iraq case study

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ABSTRACT

In this paper, a model was designed to estimate the amount of solar energy based on solar radiation angles. The model was applied to five Iraqi cities (Baghdad, Basrah, Nineveh, Dyala, and Anbar). The amount of solar energy reaching the globe's surface is analyzed through its application. Data from NASA was relied upon for implementation and comparison. The main objective of the research is to find a reliable and low-cost method by which to know the amount of solar energy in the study area to promote sustainable energy. The results were compared with the data available from NASA, and a satisfactory agreement was found based on some statistical processes that prove the validity of the proposed model. Through the results, it is possible to rely on the proposed model to predict the amount of solar energy reaching the study area and to implement solar energy projects.

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1. INTRODUCTION

There is increasing demand for electric power as the world becomes more industrialized and reliant on electricity. At the same time, using traditional fossil fuels such as coal and oil to generate electricity has contributed to climate change and environmental degradation. As a result, researchers and policymakers are looking for ways to generate electricity from alternative sources such as renewable energy sources such as solar, wind, and hydroelectric power [1]–[4]. These energy sources can help reduce our reliance on fossil fuels, mitigate the risk of declining availability, and reduce the negative environmental impacts of electricity production [5]–[7].

Iraq is located in the Middle East [8], with a generally sunny and dry climate [9]. The country receives significant solar radiation throughout the year, particularly in the summer when the sun is highest in the sky [6], [9]. Solar radiation levels in Iraq can be quite high, with an average daily total of around 6 to 7 KWh/m^2. This makes it a good location for solar energy generation. Solar radiation levels in Iraq can vary depending on several factors, including the time of year, the altitude of the location, and the presence of clouds or other atmospheric conditions. In general, solar radiation tends to be higher in the southern and eastern parts of the country, where the sun is directly overhead for a longer period each day. Solar radiation tends to be lower in the northern and western parts of the country, where the sun at a lower angle in the sky.

The intensity of solar radiation that falls on a particular location on the earth's surface is one of the main factors determining the feasibility and efficiency of solar energy production in that location. Solar panels rely on photons of light from the sun to generate electricity; the more solar radiation available, the more electricity can be produced. The solar radiation intensity is measured in power per unit area, such as watts per square meter (W/m^2). The amount of solar radiation that reaches the earth's surface is determined by several factors, including the distance from the sun, the angle at which the sun's rays strike the earth's surface, and the presence of clouds or other atmospheric conditions.

Solar radiation intensity can vary significantly depending on the location [10], with higher intensity levels typically found in sunny, dry regions near the equator [11]. These conditions favor solar energy production because they allow solar panels to receive high direct sunlight throughout the year. Predicting the amount of solar radiation available at a particular location is important in determining the feasibility of building a solar power plant. Several methods can be used to predict solar radiation, including satellite data, ground-based measurements, and computer models.

Satellite data can be used to measure the amount of solar radiation received at the earth's surface [12], [13]. This data can create maps showing the average solar radiation levels for different locations worldwide. Ground-based measurements involve using instruments such as pyranometers and pyrheliometers to measure the amount of solar radiation received at a specific location. These measurements can be taken over time to get an accurate understanding of the amount of solar radiation available at a particular location. Computer models can also be used to predict solar radiation levels. These models use algorithms to simulate the amount of solar radiation received at a particular location based on the location's latitude, longitude, elevation, weather patterns, and atmospheric conditions [14]–[18].

In this research, a system was built based on the equations of solar radiation through which the amount of solar radiation falling on any region of the earth's surface is predicted. The purpose is to study the effect of changing solar radiation and its impact on the production of electrical energy. Investigating local case studies is important before proposing the suitability of solar energy installation systems in the targeted area. The investigation on solar energy based on solar angles is yet available in consideration of case studies of cities in Iraq. Thus, the findings based on these case studies will differ from the existing works in this area.

2. CASE STUDY DATA

The simulation was applied to five Iraqi cities (Baghdad, Nineveh, Basra, Diyala, and Anbar), which were chosen to represent the center and the four directions (north, south, east, and west), as shown in Table 1. The results were matched with the data on the NASA website. The international database on the NASA SSE power project website contains data and information on renewable resources and meteorology from 1981 until the present [19]. The solar energy data available on this site is used to compare with the findings in this study.

Table 1. Latitude and longitude for case study

Name of cities	Latitude φ (degree)	Longitude Ψ (degree)
Baghdad	33.3	44.42
Basrah	30.5	47.8
Nineveh	36.19	43.3
Anbar	33.42	43.19
Dyala	33.74	44.62

3. METHODOLOGY

The methodology assumed in the formation of this research consists of three stages: i) the first stage is to find a mathematical model using the equations for solar radiation; ii) the second stage is the implementation of simulations for study cases; and iii) the third stage is to analyze the accuracy of the performance of the proposed model through some statistical measures. Through the above methodology, the places that are suitable for building future solar energy projects are determined in the study cases.

3.1. Mathematical model

The value of solar radiation reaching the photovoltaic panels depends on several factors, including (latitude and longitude, daytime angles, direction of the panels, concentration of gases in the atmosphere, dust, water vapor, and clouds). Some factors are determined by analytical equations related to solar engineering. Others are determined by statistical treatments based on the results of long observations of measurement processes. The proposed model reduces the equipment used to collect solar radiation while providing data collection with great flexibility.

The declination angle, δ of the sun, is the angle between the equatorial plane and the line connecting the centers of the sun and the earth. The highest inclination value for the angle (+23.45°) and the lowest inclination value for it (-23.45°) [20], which is a variable angle between these two limits for the number of days (N) and according to the approximate sinusoidal equation that assumes the year 365 days, as in (1). The tabulation of the declination angle from January to December, as recommended by [20], [21], is shown in Table 2. The plot of the relationship between the declination angle, δ, and the number of days in a year, N, is shown in Figure 1.

$$\delta = 23.45 \sin\left[\frac{360}{365}(284 + N)\right]\left(\frac{\pi}{180}\right) \text{ rad} \tag{1}$$

Table 2. Declination angle for *n* day based on recommendation [20], [21]

Month	*n* for *i*-th day of the month	For an average day of the month		
		date	*n*	δ
January	i	17	17	-20.9
February	i+31	16	47	-13.0
March	i+59	16	75	-2.4
April	i+90	15	105	9.4
May	i+120	15	135	18.8
June	i+151	11	162	23.1
July	i+181	17	198	21.2
August	i+212	16	228	13.5
September	i+243	15	258	2.2
October	i+273	15	288	-9.6
November	i+304	14	318	-18.9
December	i+334	10	344	-23.0

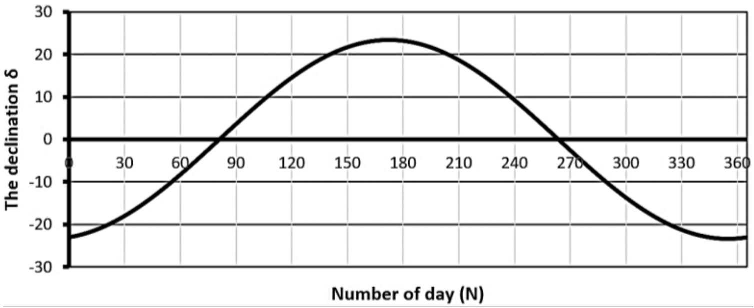

Figure 1. The relationship between the δ and N

The solar hour angle, ω is the angular measure of the hour angle of the sun. It can be used to calculate the time of sunrise, sunset, and other solar events. It is important to note that the solar hour angle is not the same as the standard time hour, which is based on the rotation of the earth to the sun, whereas one hour of hour angle corresponds to 15 degrees of angular displacement.

$$\omega = (15 * [(time\ hr - 12 - (Dif\ GMT) - EoT] + \Psi)(\frac{\pi}{180}) \text{ rad} \tag{2}$$

Where $(time\ hr)$ is daytime in hours, $(Dif\ GMT)$ is a different time between Greenwich Meridian and other locations; for Iraq = 3, Ψ represents longitude in degree, and EoT is the equation of time. Throughout the year, the Earth's velocity in orbital motion is represented by the time equation, EoT, as shown in (3) and Figure 2.

$$EoT = \frac{9.87 \sin 2B - 7.53\ \cos B - 1.5 \sin B}{60} \text{ Hours} \tag{3}$$

The value of B is determined by (4).

$$B = \frac{360}{365}(N - 81)\left(\frac{\pi}{180}\right) \tag{4}$$

The incidence angle, θ, is the angle at which light or other energy waves strike a surface. It is the angle between the incoming energy and a vertical line to the surface. It describes the direction in which the energy comes from relative to the surface and can influence how it is absorbed or reflected by the surface.

$$\theta = \cos^{-1}[(\sin\delta . \sin\varphi . \cos\beta) + (\cos\delta . \sin\varphi . \sin\beta . \cos\gamma . \cos\omega) - (\sin\delta . \cos\varphi . \sin\beta . \cos\gamma) + (\cos\delta . \sin\beta . \sin\gamma . \sin\omega) + (\cos\delta . \cos\varphi . \cos\beta . \cos\omega)] \text{ rad} \tag{5}$$

Where φ is the latitude angle, β is the slope angle with horizontal for the receiving surface, γ is the azimuth angle of the surface. In this paper, β and γ are equal to zero. The zenith angle, θ_z is the angle between the zenith and an object or a point in the sky. The zenith is a point in the sky directly overhead, and the zenith angle is the angle between the zenith and an object or point in the sky, measured from the vertical. $\theta_z = \theta$ for the horizontal surface. It is calculated by (6).

$$\theta_z = \cos^{-1}[(\sin\delta \,.\, \sin\varphi) + (\cos\delta \,.\, \cos\varphi \,.\, \cos\omega)] \text{ rad} \tag{6}$$

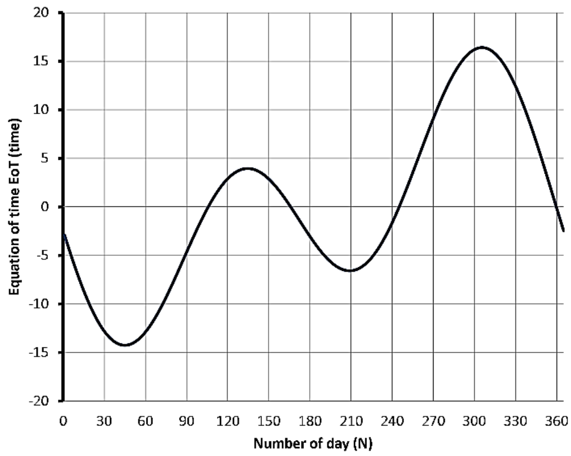

Figure 2. The relationship between the *EoT* and *N*

The zenith angle is used in astronomy and other fields to describe the position of an object or point in the sky. It is related to the altitude angle, h, which is the angle between the horizon and an object or point in the sky, measured from the horizontal. The altitude and zenith angles are complementary, meaning their sum is always 90°.

$$h = \left(\frac{\pi}{2}\right) - \theta_z \text{ rad} \tag{7}$$

Using trigonometry's relationships, (7) can be given as (8).

$$h = \sin^{-1}[(\sin\delta \,.\, \sin\varphi) + (\cos\delta \,.\, \cos\varphi \,.\, \cos\omega)] \text{ rad} \tag{8}$$

The arrival of solar radiation to the Earth's surface is affected by a few random factors, such as the diffusion index K_D and the clear sky insolation clearness index K_T. The clear sky insolation clearness index measures the amount of solar energy received by the Earth's surface in each location on a clear day. Also, it is obtained from the NASA SSE database. It is calculated based on the amount of solar radiation received at the surface, the amount of solar radiation that would be received if the sky were clear, and the atmospheric conditions that affect the transmission of solar radiation. The clearness index is used to predict the amount of solar energy solar power systems can generate and assess the feasibility of solar energy projects.

$$K_T = \frac{H}{H_0} \tag{9}$$

$$H = K_T(H_O) \tag{10}$$

Where H is the average daily radiation at a horizontal surface, and H_O is the average daily extra atmospheric insolation at a horizontal surface.

$$H_0 = \left(\frac{24 * G_{SC}}{\pi}\right)\left(1 + \left[0.033\cos\left(\frac{360 * N}{365}\right)\right]\right) \left((\sin\delta \,.\, \sin\varphi \,.\, \omega_{ss}) + (\cos\delta \,.\, \cos\varphi \,.\, \cos\omega_{ss})\right) \text{Wh/m}^2 \tag{11}$$

Where the G_{SC} is constant = 1367 W/m^2; ω_{ss} is the angle of the sunset hour defined as (12).

$$\omega_{ss} = \cos^{-1}(-\tan\varphi \,.\, \tan\delta) \tag{12}$$

3.2. Model performance and statistical tests

To evaluate the performance of the proposed model, statistical tests that are commonly used in the literature are also used in this study. Eight methods were used to analyze and determine the accuracy of the proposed model. Those are the mean absolute error (MAE) [22], [23], mean bias error (MBE) [22], [24], root mean square error (RMSE) [23], [25], mean percentage error (MPE) [25], [26], relative percentage error (RPE) [27], correlation coefficient (r) [28], coefficient of determination (R^2) [25], [26], and t-student distributions (t) [26] tests. The related equations governing all the test methods are shown in Table 3.

Table 3. Statistical methods for determining performance accuracy

Statistical methods	Sample	Equation	The acceptable range of accuracy
Mean absolute error [22], [23]	MAE	$MAE = \frac{1}{n}\sum_{i=1}^{n}\lvert X_i - Y_i\rvert$	Smaller value
Mean bias error [22], [24]	MBE	$MBE = \frac{1}{n}\sum_{i=1}^{n} X_i - Y_i$	(-) underestimation (+) overestimation (0) exactitude
Root mean square error [23], [25]	RMSE	$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(X_i - Y_i)^2}$	Smaller value
Mean percentage error [25], [26]	MPE	$MPE = \left[\frac{1}{n}\sum_{i=1}^{n}\left(\frac{X_i - Y_i}{Y_i}\right)\right](100)$	Range ±10
Relative percentage error [27]	RPE	$RPE = \left(\frac{X_i - Y_i}{Y_i}\right)(100)$	Range ±10
Correlation coefficient [28]	r	$r = \frac{\sum_{i=1}^{n}(X_i - \overline{X})(Y_i - \overline{Y})}{\sqrt{\sum_{i=1}^{n}(X_i - \overline{X})^2 (Y_i - \overline{Y})^2}}$	Range ±1
Coefficient of determination [25], [26]	R^2	$R^2 = 1 - \left(\frac{\sum_{i=1}^{n}(Y_i - X_i)^2}{\sum_{i=1}^{n}(Y_i - \overline{Y})^2}\right)$	Closer to 1
T-student distribution test [26]	t	$t = \sqrt{\frac{(n-1)MBE^2}{RMSE^2 - MBE^2}}$	Smaller value

n is the month's number per year; *i* is the analyzed month number; *X* is the value calculated from the suggestion model as in (10); *Y* is the value of reference (from the database of NASA SSE); $\overline{X}$ and $\overline{Y}$ are total average yearly radiation.

4. RESULTS AND DISCUSSION

The (1)-(12) were used to construct a solar radiation model that simulates solar energy for five Iraqi cities, as information included in Table 1. Some inputs that represent the angles of solar radiation were relied upon, and the data of the clearness index from NASA were used to obtain the daily rate of solar radiation reaching the horizontal surface to compare the results with the results of the proposed model. The results of the simulation process for the proposed model are shown in Tables 4 and 5 and Figures 3 to 7. The results were compared to the data in the NASA database by applying statistical tests in Table 3.

Through Table 4, there is a temporal and spatial variation in the amount of solar radiation due to the change in the incidence angle of solar radiation, the length of the day and the clearness of the weather, where solar energy begins to be obtained gradually in the first three months of the beginning of the year. The energy increases from the beginning of the fourth month until the end of the ninth month, when the maximum energy value is in the sixth month (8.05, 7.89, 8.2, 8.06, and 7.82). The gradual decline in energy begins in the last three months of the year.

Based on the annual energy rate, the northwestern region has less energy production than the central, eastern, and southern regions. Despite this disparity in energy, the study areas are considered to be energy-abundant areas that enjoy suitable solar radiation rates for constructing electric power plants through solar energy. From statistical equations (MAE, MBE, RMS, MPE, r, R^2, and t) as shown in Table 5, it was found that the resulting values are among the accepted values, as values were recorded for the Baghdad City (0.005, -0.01, 0.043, -0.17, 0.9997, 0.999, and 0.394) respectively, and for the Basra City (0.005, -0.005, 0.057, -0.17, 0.9994, 0.998, and 0.284) respectively, for the Nineveh City (0.004, -0.004, 0.045, -0.045, -0.09, 0.9997, 0.999, and 0.323) respectively, for the Anbar City (0.014, -0.01, 0.049, -0.31, 0.9996, 0.999, and 0.953) respectively, and the Diyala City (0.031, -0.03, 0.064, -0.77, 0.9997, 0.998, and 1.835), respectively. The values support the validity and reliability of the proposed model in estimating solar energy in the study areas.

Table 4. Comparison of average monthly solar radiation between the model and NASA SSE

Cities	Details	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Yearly
Baghdad	Model	3.65	4.60	5.80	6.84	7.55	8.05	7.67	7.18	6.00	4.66	3.67	3.28	5.75
	NASA	3.64	4.63	5.85	6.85	7.53	7.98	7.68	7.13	6.02	4.73	3.73	3.25	5.75
	RPE	0.34	-0.63	-0.78	-0.19	0.33	0.91	-0.14	0.76	-0.39	-1.50	-1.54	0.82	
	KT	0.68	0.69	0.69	0.68	0.68	0.70	0.68	0.69	0.67	0.65	0.65	0.66	0.68
Basrah	Model	3.97	4.81	5.92	6.83	7.44	7.89	7.53	7.03	6.07	4.83	4.03	3.59	5.83
	NASA	3.95	4.85	5.98	6.87	7.48	7.81	7.44	6.97	6.08	4.94	4.04	3.59	5.83
	RPE	0.45	-0.77	-0.95	-0.55	-0.49	1.01	1.22	0.91	-0.22	-2.29	-0.35	0.01	
	KT	0.68	0.68	0.68	0.67	0.67	0.69	0.67	0.67	0.66	0.64	0.66	0.66	0.67
Nineveh	Model	3.42	4.49	5.82	7.12	7.87	8.20	8.02	7.31	5.99	4.53	3.57	3.08	5.79
	NASA	3.42	4.51	5.90	7.09	7.85	8.22	7.99	7.25	6.02	4.62	3.57	3.04	5.79
	RPE	0.00	-0.53	-1.35	0.37	0.28	-0.19	0.37	0.87	-0.53	-1.89	0.06	1.46	
	KT	0.68	0.69	0.69	0.68	0.68	0.70	0.68	0.69	0.67	0.65	0.65	0.66	0.68
Dyala	Model	3.60	4.56	5.77	6.82	7.55	8.06	7.67	7.17	5.97	4.62	3.63	3.23	5.72
	NASA	3.64	4.63	5.85	6.85	7.53	7.98	7.68	7.13	6.02	4.73	3.73	3.25	5.75
	RPE	-1.03	-1.61	-1.35	-0.43	0.31	0.99	-0.11	0.61	-0.83	-2.33	-2.79	-0.70	
	KT	0.68	0.69	0.69	0.68	0.68	0.70	0.68	0.69	0.67	0.65	0.65	0.66	0.68
Anbar	Model	3.59	4.52	5.71	6.73	7.44	7.82	7.56	6.87	5.72	4.51	3.60	3.21	5.61
	NASA	3.58	4.55	5.79	6.78	7.39	7.80	7.48	6.90	5.78	4.56	3.65	3.19	5.62
	RPE	0.15	-0.62	-1.36	-0.71	0.72	0.31	1.03	-0.45	-1.02	-1.20	-1.28	0.75	
	KT	0.67	0.68	0.68	0.67	0.67	0.68	0.67	0.66	0.64	0.63	0.64	0.65	0.66

Table 5. Statistical methods result

Cities	MAE	MBE	RMS	MPE	r	R^2	t
Baghdad	0.005	-0.005	0.043	-0.17	0.9997	0.999	0.394
Basrah	0.005	-0.005	0.057	-0.17	0.9994	0.998	0.284
Nineveh	0.004	-0.004	0.045	-0.09	0.9997	0.999	0.323
Dyala	0.031	-0.031	0.064	-0.77	0.9997	0.998	1.835
Anbar	0.014	-0.014	0.049	-0.31	0.9996	0.999	0.953

Figures 3 to 7 illustrate the comparison of the results between the proposed model and NASA's data for the study areas (Baghdad, Basra, Nineveh, Diyala, and Anbar), respectively. The solar radiation (in kWh/m^2/day) was presented throughout the year. We observe a significant agreement between the proposed model and the actual data from all the figures. The overall agreement between the proposed model and the actual data indicates that the model accurately estimates solar radiation in all study areas. It also indicates that Iraq enjoys abundant solar energy, with an average radiation quantity estimated to be more than 5.5 (kWh/m^2/day). The highest solar radiation occurs during the hottest months, July and August. The lowest solar radiation occurs during the coldest months, January and February. The proposed model can be used to obtain solar radiation data to guide the planning of solar energy projects in Iraq. Additionally, this data can help identify optimal locations for installing solar panels and determine how much solar energy can be generated.

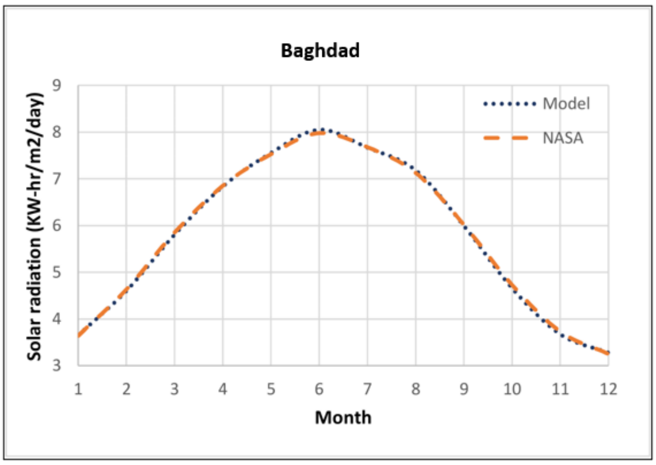

Figure 3. Comparison of the proposed solar radiation model results with NASA for Baghdad City

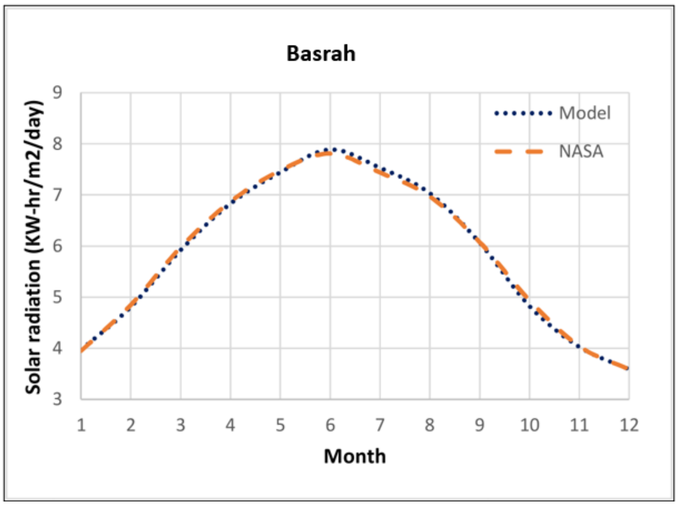

Figure 4. Comparison of the proposed solar radiation model results with NASA for Basrah City

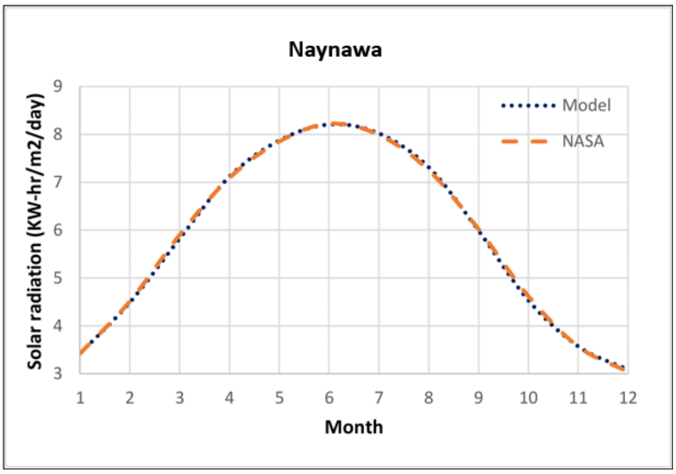

Figure 5. Comparison of the proposed solar radiation model results with NASA for Nineveh City

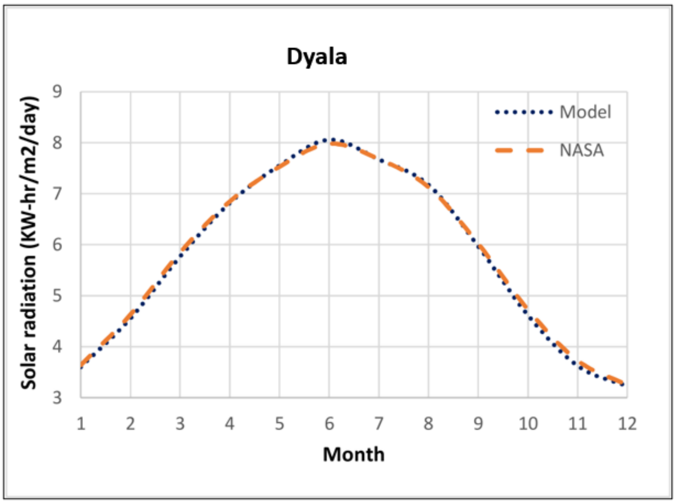

Figure 6. Comparison of the proposed solar radiation model results with NASA for Dyala City

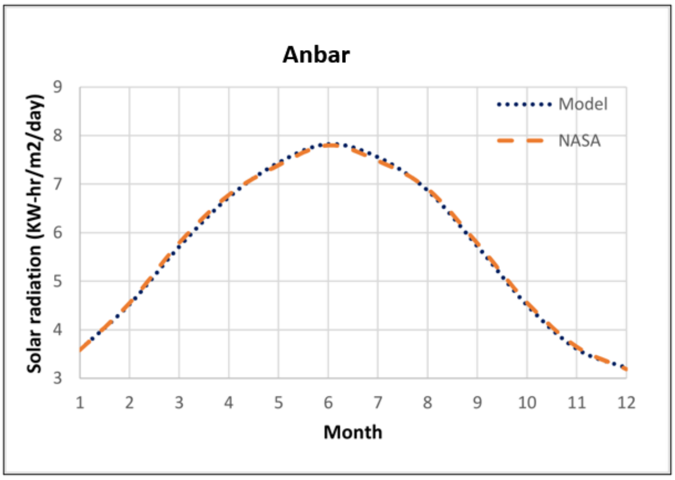

Figure 7. Comparison of the proposed solar radiation model results with NASA for Anbar City

5. CONCLUSION

Solar energy-based electricity production projects are important, but they have a high initial cost in design and construction. A system was developed in this study to predict the amount of solar energy reaching the study areas. The system used solar radiation angle equations to calculate the amount of solar radiation reaching the study area's horizontal surface. The Excel environment simulated these angles to display the results for all days of the year. Some statistical processes were used to test the system's reliability. The results demonstrated the system's accuracy in predicting the amount of solar radiation reaching the study areas, as evidenced by the clear convergence of the results with NASA data. The proposed system's data can be used in solar energy simulation systems.

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