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Research Article

An Improved Approach for Maximum Daily Global Solar Irradiance Estimation

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Abstract

In the current context of climate change, solar energy stands out as a significant alternative to fossil fuels, which are both polluting and non-renewable. However, one of the main challenges in harnessing solar energy is the limited availability of data on solar radiation. Collecting solar radiation data through meteorological stations incurs considerable costs, unlike certain solar irradiation models that can provide such data for free. To facilitate access to solar irradiation information at no cost and to enhance the adoption and competitiveness of solar energy, it is crucial to develop practical daily global solar irradiation models that are applicable worldwide. This study aligns with that objective, aiming to develop a general model for estimating the maximum daily global solar irradiation. We use daily global solar irradiation data collected from 60 sites, spanning the years 2000 to 2023, for horizontal ground surfaces. To evaluate the performance of the proposed model, we conducted a detailed analysis using performance metrics. Two key indicators are highlighted in this manuscript: MAPE (Mean Absolute Percentage Error) and Pearson's correlation coefficient. By utilizing daily global solar irradiation data from the 60 sites, empirical mathematical relationships for extraterrestrial daily solar irradiation, and computational tools, we established a mathematical expression for estimating maximum daily global solar irradiation. This model is specifically designed as a function of latitude and is independent of measured data such as sunshine duration, temperature, or humidity. Based on the performance indicators, the derived mathematical model demonstrates reasonable accuracy and a strong correlation.

Keywords

Energy, Meteorological Stations, Global Solar Irradiation, Model, Performance

1. Introduction

The modern world is confronted with numerous challenges, including environmental conservation and the availability of electrical energy. It is widely recognized that electrical energy can be derived from primary energy sources such as fossil fuels and uranium, as well as from renewable sources like solar, wind, geothermal, and biomass [1-7].

Currently, fossil energy sources like oil, natural gas, and coal are the most commonly used to meet electricity demands

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[1]. However, issues arising from the use of fossil fuels, such as environmental degradation and resource depletion [6, 7], have gradually prompted changes in the global electrical energy production chain, with a greater emphasis on environmental protection. Renewable energies, valued for being non-polluting and replenished on a human timescale, are increasingly being harnessed worldwide, contributing to an ongoing energy transition [3, 4, 6]. Among these, solar energy stands out for its significant potential in many regions across the globe. According to the literature [8, 9], the efficiency of various technologies used to harness solar energy depends on solar irradiation. However, the lack or unavailability of data on solar energy potential in specific sites or locations poses a challenge to its effective use and hinders its development. Meteorological stations offer a significant advantage by providing solar radiation data for specific locations, but they are not always cost-effective. An equally valuable alternative is the use of global solar irradiation models, which can address the issue of solar radiation data without financial investment. However, the drawback of most current global solar irradiation models is their reliance on measurement data such as temperature, humidity, and sunshine duration. Collecting this data requires specialized equipment, which also incurs financial costs. Furthermore, many existing solar irradiation models are site-specific, necessitating the calculation and adaptation of coefficients for different locations. Additionally, there is a shortage of models capable of providing maximum daily global solar irradiance data. Such models could be instrumental in enhancing the use of solar technologies.

The objective of this study is to develop a mathematical model that does not rely on measurement data and can be used to estimate the maximum daily solar irradiation values over the past twenty years, applicable to any location globally.

The manuscript is organized into three sections: the first part outlines the methodology, the second part presents the results, and the final part is dedicated to the conclusion.

2. Materials and Methods

2.1. Methodology

In this study, we employed a methodology that involved collecting daily global solar irradiance measurement data from multiple sites, identifying appropriate tools for model performance evaluation, and developing the model using computer software.

2.2. Available Daily Global Solar Irradiation Models

The solar resource is a crucial factor in solar energy, determining the profitability and reliability of its use. Today, various methods are available for assessing the solar potential of a specific site. Among these, modeling stands out as an ideal approach for locations without meteorological stations to gather solar data. Commonly used models estimate average monthly values of daily global solar irradiation, relying on measurements such as sunshine duration, ambient temperature, humidity, and atmospheric pressure.

For models based on sunshine duration, the Angström model [10-12], developed in 1923, is a notable example. This model laid the groundwork for the Angström-Prescott model [11-15], an enhancement by Prescott in 1940. Variations within this type of model include quadratic, cubic, logarithmic, and exponential forms, created by researchers such as Ögelman and al. [16, 17], Samuel [17, 18], Ampratwum and Dorvlo [17, 19], and Almorox and Hontoria [17, 20, 21].

Other models, essential for acquiring solar data, rely on ambient temperature. Examples include those developed by Hargreaves and Samani [17, 22], Chen and al. [17, 23], Pandey and Katiyar [24, 25], and Bristow and Campbell [24, 26]. Additionally, models by Swartman and Ogunlade [17, 27], and El-Sebaii and al. [17, 28], incorporate both relative humidity and sunshine duration. Some models, such as those by Gopinathan [17, 29] and Abdalla [17, 30], account for maximum and minimum temperatures, sunshine duration, and relative humidity.

Most of these models are expressed in terms of measurable parameters, which require the availability of observational data. The use of such models depends on obtaining sensors, which involve financial investment to collect measurement data. Furthermore, while most daily global solar irradiance models can estimate monthly mean values, models that estimate maximum daily values independently of measurement data are rare. The aim of this study is to develop a general model for estimating maximum daily global solar irradiance values based solely on-site latitude, independent of other measurement data.

2.3. Model Performance Indicator Tool

There are several tools available for evaluating model performance. These tools assess model accuracy by comparing estimated values to actual measurements. Examples include root mean square error (RMSE), mean error (ME), mean percentage error (PME), mean absolute percentage error (MAPE), and mean absolute error (MAE) [11-13, 17, 21].

Additionally, there are tools for evaluating the quality of a model's correlation with measurement values, such as the Pearson correlation coefficient (r) and the coefficient of determination (R^2) [17, 21]. In this study, we utilize the statistical methods involving the mean absolute percentage error (MAPE) and the Pearson correlation coefficient (r). The expressions for MAPE and Pearson's correlation coefficient (r) are represented by equations (1) and (2), respectively.

$$\mathrm{MAPE} = \frac{1}{n} \times \sum_{i=1}^{n} \left(\frac{\left| H_{i,c} - H_{i,m} \right|}{H_{i,m}} \times 100 \right) \quad (1)$$

Where $H_{i,c}$ and $H_{i,m}$ are respectively the ith calculated and measured values of global daily solar irradiation on a horizontal surface. Table 1 Displays MAPE values as a function of model accuracy.

***Table 1**. MAPE indicator.*

values of MAPE (%)	Level of precision
0 to 5	Very good
5 to 10	Good
10 to 20	Fairly good
20 to 30	average

$$r = \frac{\sum_{i=1}^{n}(H_{i,c} - H_{avg,c}) \times (H_{i,m} - H_{avg,m})}{\sqrt{\sum_{i=1}^{n}(H_{i,c} - H_{avg,c})^2 \times \sum_{i=1}^{n}(H_{i,m} - H_{avg,m})^2}} \quad (2)$$

Where $H_{avg,c}$ and $H_{avg,m}$ are respectively the mean calculated and measured values of global daily solar irradiation on a horizontal surface. Table 2 shows r values as a function of model correlation quality.

***Table 2**. Pearson correlation coefficient indicator.*

Pearson's correlation coefficient values	Correlation quality
0 to 0.1	No correlation
0.1 to 0.3	Low correlation
0.3 to 0.5	Average correlation
0.5 to 0.7	High correlation
0.7 to 1	Very high correlation

2.4. Study Sites and Type of Operating Data

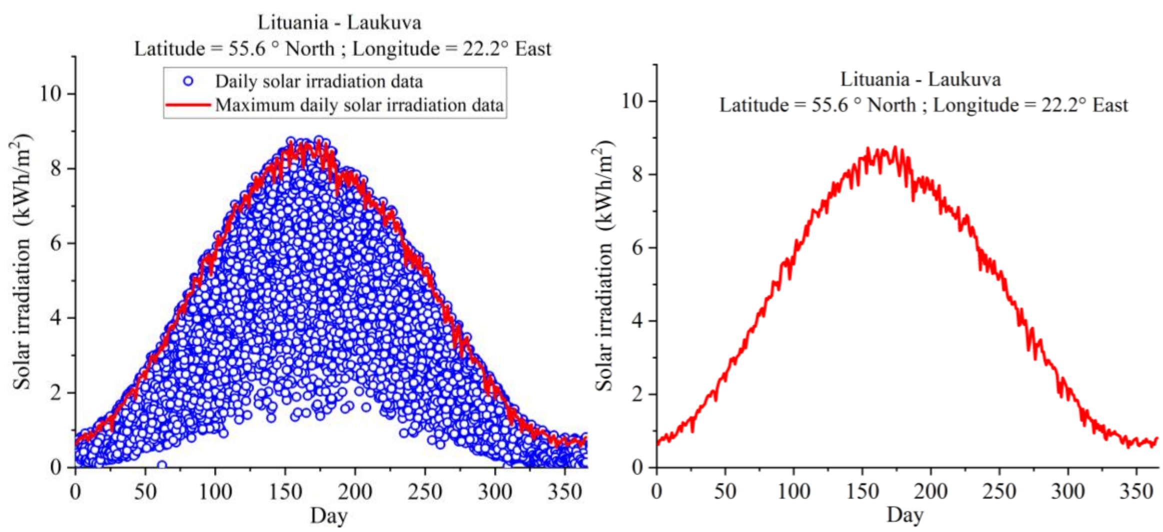
The research presented in this manuscript utilizes solar resource data from various global locations, chosen based on their geographic characteristics and the availability of solar radiation data. The sites included in the study are listed in Table 4 below. The data used consists of global daily solar irradiation measurements for a horizontal surface, covering the years 2000 to 2023, sourced from NASA.

3. Results

3.1. Example of Maximum Data of Daily Global Solar Irradiation for the Priod 2000-2023

For each of the 60 sites listed in Table 4 below, we have daily global solar irradiation data for the period 2000 to 2023, i.e., 24 years of data.

Data on maximum daily global solar irradiation values were determined by carrying out a comparison study of daily values obtained over the period 2000 to 2023. The highest daily values are then retained for each of the 365 days of the year. Figure 1 shows an example of a case maximum daily global solar irradiation values of determined at the Laukuva site in Lithuania.



a) *Daily global solar irradiation and maximum values for the period 2000 to 2023*

b) *Maximum daily solar irradiation curve for the period 2000 to 2023*

***Figure 1**. Daily global irradiation and maximum values.*

3.2. Maximum Daily Global Solar Irradiation as a Function of Latitude and Longitude

Daily global solar irradiation changes over the course of a year and from one site to another. Certain factors, such as dust clouds or thunderstorms, have an impact on daily global solar irradiation. These types of factors are difficult to predict and therefore complicated to exploit in models, not like latitude and longitude, which are constant in a site. The aim of the work carried out in this section is to determine the effect of latitude and longitude on the maximum and monthly mean values of daily global solar irradiation. To this end, we carried out an investigation that produced the curves shown in Figure 2, Figure 3 below.

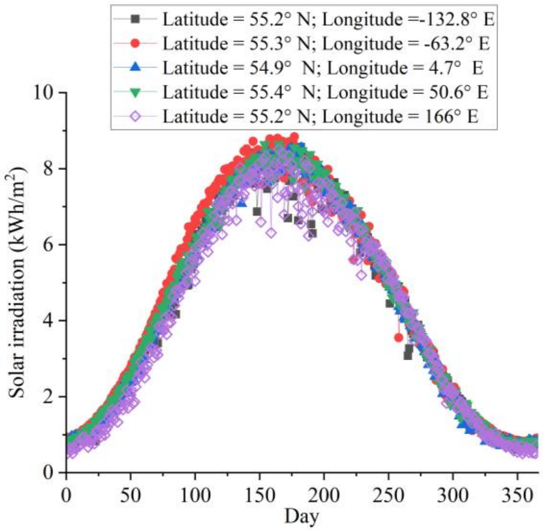


Figure 2. *Curves of the maximum daily global solar global solar irradiation values as a function of longitude.*

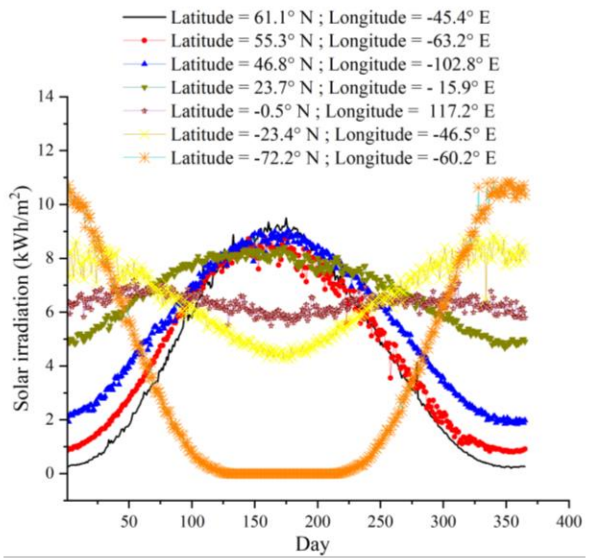


Figure 3. *Curves of the maximum daily irradiation values as a function of the latitude.*

Figure 2 shows the results obtained from the study of the effect of a site's position in relation to its longitude on the maximum values of daily global solar irradiation. This work enabled us to compare the maximum values of daily global solar irradiation for several sites with practically the same latitudes but very different longitudes. We note that the curves of annual evolution of the maximum values of daily global solar irradiation obtained from the period 2000 to 2023 in Figure 2 are practically merged. This indicates that the annual evolution of maximum daily global solar irradiation values practically does not evolve with a change in longitude. In the case of Figure 3, it represents the results of a study carried out on the impact of latitude change on the maximum values of daily global solar irradiation. As in the case of Figure 2, we have shown that the change in longitude has practically no impact on the maximum values of daily global solar irradiation, in Figure 3 we consider only the effect of the variation in latitude. The results of the study in Figure 3 allow us to compare the maximum values of daily global solar irradiation for several sites at different latitudes. We note that the annual evolution curves of the maximum daily global solar irradiation values obtained for the period 2000 to 2023 in Figure 3, are different from each other.

Overall, this study shows that maximum daily global solar irradiance values vary with latitude but hardly at all with longitude.

Based on the results obtained in this section, we will focus on the searches for a model of maximum daily global solar irradiation values that is expressed themselves as latitude function.

3.3. Development of Maximum Daily Global Solar Irradiance Model

In the scientific literature [12, 13], we found that the empirical model of extraterrestrial daily global solar irradiance is used for solar potential modeling studies. According to these manuscripts, the expression of this model of extraterrestrial daily global solar irradiation H_0, is that of formula (3) below [12, 13].

Since this model is used extensively, we carried out a study that compared the curve forms obtained from this model and those relating to experimental solar irradiation data on the ground. We present a sample of the results obtained from equation (3) of the empirical model by simulation in Figure 4.

Indeed, we note that this empirical model presents curve forms almost similar to those of the maximum daily global solar irradiation data in Figure 3. This model is also expressed as a function of latitude. It is practically simple to use. On the basis of these positive points of this empirical model of extraterrestrial daily global solar irradiance, we have taken the option of exploiting it to determine model of the maximum values of daily global solar irradiance on the ground.

$$H_0 = \frac{24 \times I_0}{\pi} \times \left(1 + 0.033 \times \cos(\frac{360}{365} \times J)\right) \times \left(\cos(\varphi) \times \cos(\delta) \times \sin(\omega_s) + \frac{\pi \times \omega_s}{180} \times \sin(\varphi) \times \sin(\delta)\right) \quad (3)$$

Expression (3) is expressed in kWh/m^2.

(I_0) is the solar constant whose value is 1.367 kW/m^2. (δ) is the solar declination angle. (ω_s), the sunset hour angle. (φ), represents the site latitude. And (J) is the day number for a 365 days year.

With (ω_s) determined from relation (4).

$$\cos(\omega_s) = -\tan(\delta) \times \tan(\varphi) \quad (4)$$

(δ) is calculated with formula (5).

$$\delta = 23.45 \times \sin\left(360 \times \frac{284 + J}{365}\right) \quad (5)$$

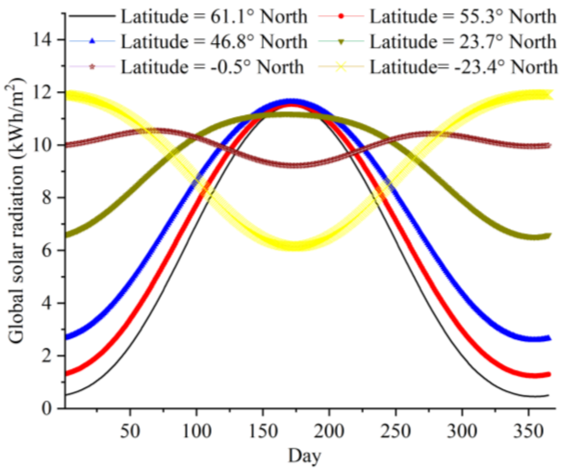


Figure 4. *Curves of the extraterrestrial daily global solar irradiation values as a function of the latitude.*

3.4. Maximum Daily Global Solar Irradiation Values Model

In this section, we set out to determine a model for maximum daily global solar irradiation values. This work is based on computer tools, the empirical model of extraterrestrial irradiation, and data on maximum daily global solar irradiation values of the 60 sites in Table 4. We obtained a suitable expression that expresses himself as follows:

$$H_{max} = H_0 \times \left(A \times Ln(1 + |\varphi|) + B \times \cos(\varphi) + C \times \exp(|\varphi|)\right) \quad (6)$$

H_{max} is the maximum daily global solar irradiation.

A, B and C represent coefficients whose values are shown in Table 3.

Table 3. *Equation 6 coefficients values.*

Coefficient	$-60 \le \varphi < 0$ and $25 < \varphi \le 67$	$0 < \varphi \le 25$
A	0.53	0
B	0.63	0.53
C	0	0.153

3.5. Performance of the Maximum Daily Global Solar Irradiation Established Model

In this section, we present the results obtained from the performance study of the equation (6) model for maximum daily global solar irradiation. The study focuses on calculating the values of performance tools, such as the mean absolute percentage error (MAPE) and Pearson's correlation coefficient (r). We are conducting this work with data from 60 sites. The results show that 55% of the sites have MAPE values less than 5%. 30% of sites have MAPE values between 5% and 10%. 11% of sites have MAPE values between 10% and 20%. And 3% of the sites have MAPE values of more than 20%. According to the results obtained on the MAPE values and the data in Table 1, this model presents an interesting level of accuracy. In the case of the model correlation results, we note that in 90% of the study sites, the model has a Pearson coefficient (r) of more than 0.7. On the other hand, in 8% of sites, the model has a Pearson coefficient (r) between 0.5 and 0.7. And at around 2% of sites, the model has a Pearson coefficient (r) between 0.1 and 0.3. Overall, the model shows a good correlation as shown in Figure 6 which gives the results on the correlation of the model of the 60 sites. In Figure 5 we present a sample of the results obtained. Table 4 shows all the MAPE and r values of the 60 sites.

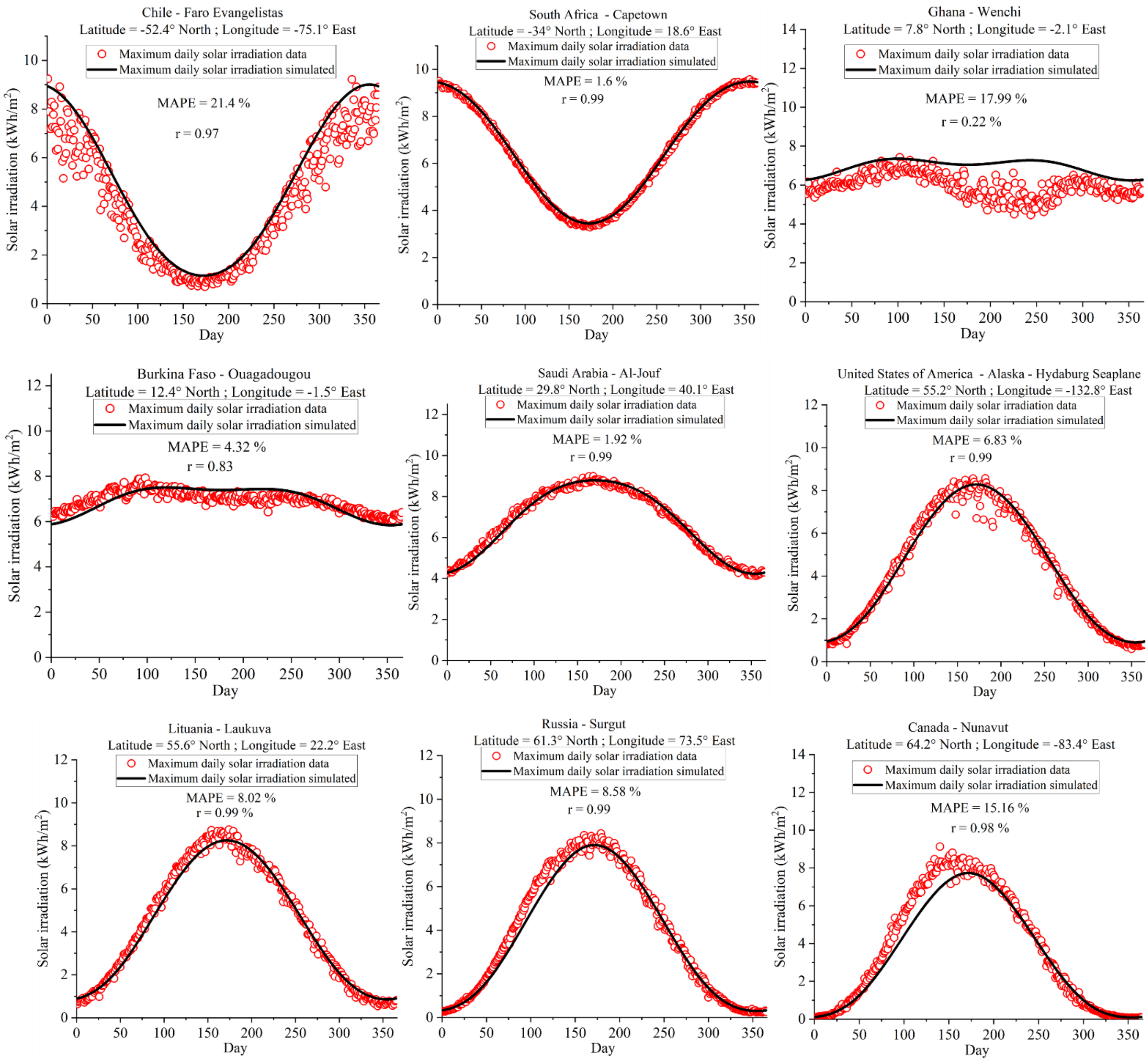


Figure 5. *Estimated and measured maximum daily global solar irradiance at different sites.*

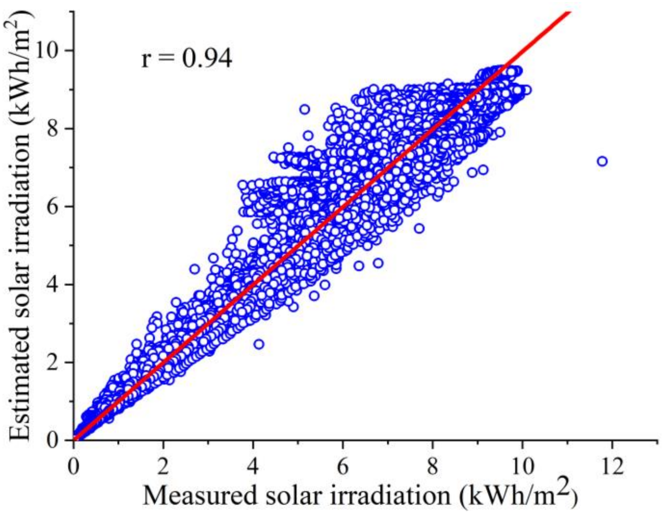


Figure 6. *Scatter plot of all data from the sites of the estimated and measured maximum values.*

***Table 4.** r and MAPE values obtained according to sites.*

Site	Latitude (°)	Longitude (°)	r for maximum data	MAPE for maximum data (%)
Argentina - Ushuaia Aero	-54.8 N	-68.3 E	0.98	15.58
Chile - Faro Evangelistas	-52.4 N	-75.1 E	0.97	21.4
Argentina - Rio Gallegos Arpt	-51.6 N	-69.3 E	0.99	4.89
Chile - Puerto Montt Tepual	-41.4 N	-73.1 E	0.99	4.82
Chile - Temuco Maquehue	-38.8 N	-72.6 E	0.99	3.04
Chile - Concepcion Carriel	-36.8 N	-73.1 E	0.99	1.7
South Africa - Capetown	-34 N	18.6 E	0.99	1.6
Chile - Quelentaro	-34 N	-71.6 E	0.99	2.74
Australia - WA - Ngaanyatjarra-Giles	-25 N	128.3 E	0.99	1.81
Australia - Alice Springs	-23.8 N	133.9 E	0.99	3.6
Chile - Antofagasta Cerro	-23.4 N	-70.4 E	0.99	1.43
Namibia - Walvis Bay	-22.9 N	14.4 E	0.99	2.21
Chile - Calama	-22.5 N	-68.9 E	0.99	9.65
Australia - Northern Territory-Tennant Creek	-19.6 N	134.2 E	0.99	2.84
Australia - Wyndham	-15.5 N	128.1 E	0.97	3.31
Zambia - Kabwe	-14.4 N	28.5 E	0.93	4.13
Brazil - Acre - Rio Branco Medici	-10 N	-67.8 E	0.7	9.73
Brazil - Ceará - Barbalha	-7.3 N	-39.3 E	0.9	5.28
Brazil - Amazonas - Tefe	-3.4 N	-64.7 E	0.67	5.35
Gabon - Lambaréné	-0.7 N	10.2 E	0.51	20.27
Congo, Rép. Démocratique du - Boende	-0.2 N	20.9 E	0.74	4.41
Kenya - Nanyuki	0 N	37.1E	0.79	5.67
Somalia - Mogadisho	2 N	45.3 E	0.75	3.03
Ghana - Wenchi	7.8 N	-2.1 E	0.22	18
Somalia - Garōwe	8.4 N	48.5 E	0.8	4.22
Burkina Faso - Gaoua	10.3 N	-3.2 E	0.6	5.01
Costa Rica - Puerto Limon	10 N	-83.1 E	0.76	11.7
India - Kerala - Kozhikode	11.3 N	75.8 E	0.55	6.84
Sudan - Niyālā	12.1 N	24.9 E	0.75	6.34
Burkina Faso - Ouagadougou	12.4 N	-1.5 E	0.83	4.32
Burkina Faso - Dori	14 N	0 E	0.87	4.72
Honduras - Tegucigalpa Toncont	14.1N	-87.2E	0.83	4.86
Mexico - San Cristóbal de las Casas	16.8N	-92.6E	0.86	5.3
Niger - Arlit	18.8 N	7.3 E	0.97	6.56
Mauritania - Šingati	20 N	-12.4 E	0.97	3.86
Algéria - Tamanrasset	22.8 N	5.4 E	0.98	8.28
Japan - Minamitorishima	24.3 N	154 E	0.99	1.46

Site	Latitude (°)	Longitude (°)	r for maximum data	MAPE for maximum data (%)
India - Bihar - Patna	25.6 N	85.1 E	0.91	9.21
Mexico - Monclova	26.9 N	-101.4 E	0.98	3.74
Algéria - Tindūf	27.7 N	8.2 E	0.99	1.83
Saudi Arabia - Tabuk	28.4 N	36.6 E	0.99	1.59
Saudi Arabia - Al-Jouf	29.8 N	40.1 E	0.99	1.92
Mexico - Puerto Peñasco	31.3 N	-113.5 E	0.99	2.13
China - Henan - Nanyang	33 N	112.6 E	0.97	9.84
United States of America - California	34.3 N	-116.2 E	0.99	3.11
United States of America - Nevada - Mercury	36.6 N	-116 E	0.99	3.96
China - Xinjiang - Andir	37.9 N	83.7 E	0.99	4.11
Spain - Toledo	39.9 N	-4.1 E	0.99	1.65
China - Xinjiang - Urumqi	43.8N	87.7E	0.99	2.77
Canada - Kejimkujik	44.4 N	-65.2 E	0.99	4.62
French - Paris Orly	48.7 N	2.4 E	0.99	5.36
Kazakhstan - Turgaj	49.6 N	63.5 E	0.99	3.87
Netherlands	54.9 N	4.7 E	0.99	9.31
United States of America - Alaska - Hydaburg Seaplane	55.2 N	-132.8 E	0.99	6.83
Lituania - Laukuva	55.6 N	22.2 E	0.99	8.01
Canada - Québec - Inukjuak	58.5 N	-78.1 E	0.99	14.1
Groenland - Narssarssuaq	61.1 N	-45.4 E	0.99	15.23
Russia - Surgut	61.3 N	73.5 E	0.99	8.58
Canada - Nunavut	64.2 N	-83.4 E	0.98	15.16
United States of America - Alaska - Huslia	65.7 N	-156.4 E	0.99	12.45

3.6. Evolution of the Maximum Daily Global Solar Irradiance as a Function of Latitude from Established Models

Since the model developed in this manuscript performs well, this section presents a simulation study using the model derived from equation (6) to examine the variation of maximum daily global solar irradiance with latitude. Additionally, we will explore the annual evolution of the maximum values of the global daily brightness index, which is calculated as the ratio of the maximum daily global solar irradiance at the Earth's surface to the corresponding value on the planet's surface. The results from these studies are displayed in Figure 7 and Figure 8.

In Figure 7, it is evident that the maximum global solar irradiance exhibits different patterns throughout the year, from the North Pole to the South Pole, passing through the equator.

In the northern hemisphere, the trend follows a bell-shaped curve, with peak values in the middle of the year and lower values at the beginning and end. Conversely, in the southern hemisphere, the evolution of maximum daily global solar irradiance resembles an inverted bell curve, with peaks at the beginning and end of the year and lower values during the mid-year. At the equator, the annual variation of maximum daily global solar irradiance is almost a straight line. As shown in Figure 8, the clarity index is low in regions located near or on the equator. It is also low at sites near the poles. The values of the clarity index are high around latitudes 35 °South and 40 °North.

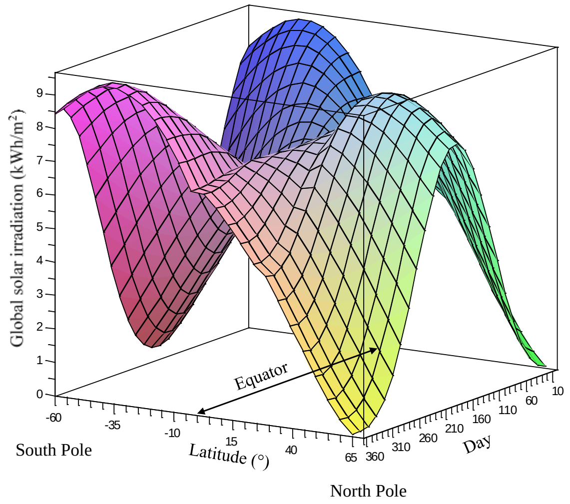


Figure 7. *Maximum daily global solar irradiation as a function of latitude.*

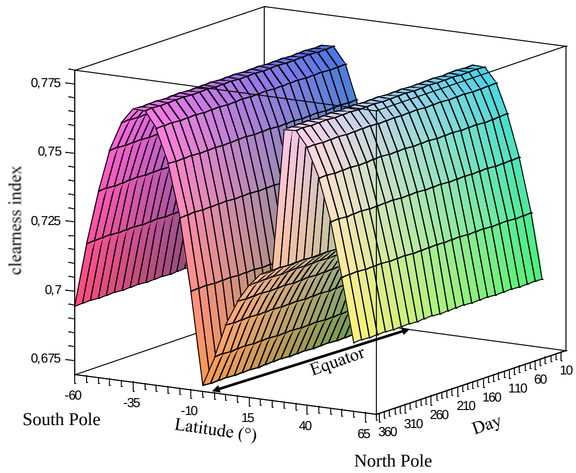


Figure 8. *Daily clarity index as a function of latitude.*

4. Discussion

While it's true that fossil fuels are still all the rage, the fact remains that we need to focus more on developing renewable energies, particularly solar power. It's clear that harnessing solar energy not only reduces greenhouse gas emissions, but also enables us to gradually free ourselves from the grip of fossil fuel sources. However, access to solar resource data is a key factor in optimizing the use of solar energy, and this remains a problem in some locations. One solution to the problem of inaccessible solar potential in certain locations is the use of mathematical models. This solution is ideal if it doesn't entail a financial cost that not everyone can afford. Indeed, the models that exist in the literature, such as those developed by Angström [10-12], Ögelman and al. [16, 17], Samuel [17, 18], Hargreaves and Samani [17, 22], Chen and al. [17, 23], Gopinathan [17, 29] and Abdalla [17, 30], are expressed as a function of measurement data such as sunshine duration, temperature or relative humidity. The use of these models depends on access to measurement data, which requires financial investment. It should also be noted that these models are site-specific, and using them for other sites means readjusting the values of the coefficients. Also, we note that these models do not allow us to highlight the maximum values of daily global solar irradiation.

The work carried out in this document has made it possible to establish a model of maximum daily global solar irradiation values. This type of model will make it possible to improve the exploitation of solar energy. The special feature of this model is that it is expressed as a function of parameters that do not require financial investment to obtain operating data. What's more, this model doesn't need to readjust coefficients for a given site. It's practical and only works with latitude values. With the current enthusiasm for solar energy, this type of solar irradiation estimation method is a tool that can be used in the development of a solar project.

5. Conclusion

A key challenge in developing solar energy resources is the availability of solar irradiance data at certain sites. The study presented in this manuscript addresses this issue by establishing a general model for estimating maximum daily global solar irradiance values. This model, based on an empirical expression of extraterrestrial daily global solar irradiance, computer software, and solar irradiance data from 60 sites, allows for the estimation of maximum daily solar irradiation values at nearly any location worldwide. The data used in this model spans from 2000 to 2023. Results from the model quality assessment indicate that the mathematical relationship offers reasonable accuracy and strong correlation. There is a significant demand for such data in various solar energy technologies. This information on maximum solar irradiation values is crucial not only for optimizing the sizing of solar technologies but also for determining the financial viability of solar energy projects.

With the future of today's world linked to renewable energies such as solar power, such a model makes it possible to investigate the potential for power generation from solar energy. In fact, this model is a tool that can be implemented in a program to study the behavior of a PV system. The results obtained from this model show its importance in research into the development of solar energy exploitation. These results also point the way to research projects aimed at improving the competitiveness of solar photovoltaic technology.

Abbreviations

RMSE	Root Mean Square Error
ME	Mean Error
PME	Mean Percentage Error
MAPE	Mean Absolute Percentage Error
MAE	Mean Absolute Error

r	Pearson's Correlation Coefficient
R^2	Coefficient of Determination
NASA	National Aeronautics and Space Administration
ω_s	Sunset Hour Angle
δ	Solar Declination Angle
I_0	Solar Constant
φ	Latitude

Author Contributions

Jacques Marie Ilboudo: Conceptualization, Writing – original draft, Investigation, Validation, Methodology, Data curation, Software

Dominique Bonkoungou: Conceptualization, Project administration Writing – review & editing, Investigation, Validation

Wilfried Rimnogdo Ouedraogo: Project administration, Analysis, Visualization

Sosthene Tassembedo: Project administration, Formal Analysis, Visualization

Zacharie Koalaga: Supervision, Validation

Conflicts of Interest

The authors declare no conflicts of interest

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