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Estimation of Solar Energy Using Different Empirical Models at Okhaldhunga, Nepal

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Abstract: Accurate estimation of global solar radiation (GSR) is essential for the effective design, sizing, and performance evaluation of solar energy systems. However, such data is often lacking in many regions of Nepal due to the high cost of measurement. This study investigates the performance of various empirical models to estimate daily GSR in the eastern mid-hill region of Okhaldhunga (27.3081°N, 86.5042°E, 1731 m) using data from 2021 to 2023. Models based on sunshine duration, temperature, and relative humidity were evaluated using regression analysis and statistical indicators such as Root Mean Square Error (RMSE), Mean Bias Error (MBE), Mean Percentage Error (MPE), and the coefficient of determination (R^2). Among the tested models, Model G—using maximum temperature and relative humidity—performed best, with the lowest RMSE and the highest R^2 value (0.6998). The empirical constants for Model G were determined as: a = 0.1056, b = 0.3136, c = 0.0186, and d = −0.0024. These constants can be effectively used to predict GSR in other regions of Nepal with similar geographic and climatic conditions.

Keywords: Global Solar Radiation, Sunshine hours, Regression technique, Empirical constants, Statistical tools.

1. Introduction

The Sun is a powerful source of energy, essential for all forms of life on Earth. Solar energy is produced through a thermonuclear fusion process that converts about 5 million tons of hydrogen into energy every second [1]. When this energy reaches the Earth as GSR, it is influenced by several atmospheric conditions such as relative humidity, temperature, water vapor, clouds, ozone, and aerosols [2, 3]. Among these, clouds play a major role in reducing the amount of solar radiation that reaches the surface [4]. In addition, geographical factors like solar zenith angle, altitude, latitude, longitude, day length, declination, and local weather conditions also affect solar radiation levels [5]. Since cloud cover is closely linked to sunshine duration, it directly impacts solar radiation. Temperature is another important factor—solar radiation tends to be higher in the summer than in the winter due to warmer conditions [4].

In Nepal, around 83% of the population lives in rural areas [6], where many people still lack access to modern energy sources such as electricity, petroleum products, and renewable energy. Despite global advancements, about 83.7% of Nepal's total energy use still comes from traditional sources like firewood, agricultural waste, and animal dung, mainly for cooking and heating in rural areas [7]. Solar energy offers a clean and sustainable alternative. As the largest renewable energy source on Earth, it can be converted into electricity using photovoltaic (PV) cells. Promoting solar and other alternative energy sources can improve living standards and help reduce environmental damage [8, 9]. Therefore, estimating the solar energy potential at specific locations is important for modern agriculture, climate change studies, hydrology, environmental research, and the development of solar energy systems [10, 11].

Accurate daily data on solar radiation and other weather conditions are important for estimating the long-term performance of solar energy systems. However, such data is often unavailable in many locations due to the high cost, maintenance, and calibration needs of measurement equipment [12]. In areas without direct measurements, GSR is usually estimated using empirical models based on available weather data. One of the most commonly used parameters for this purpose is sunshine duration. Angstrom [13] introduced a widely used linear model that relates GSR to sunshine duration by comparing the measured values to those on a completely clear day.

Prescott later modified Angstrom's model by using extraterrestrial solar radiation instead of clear-sky radiation [14]. Such models are useful for estimating and predicting GSR in places where direct measurements are not available. Many empirical models have been developed using easily accessible meteorological and climatological data such as sunshine duration [8, 15, 16, 17], temperature [18, 19, 20, 21], latitude [22, 23], relative humidity [24, 25], rainfall [26], and cloud cover [27]

In Nepal, due to the limited availability of solar radiation data and low research activity, only a few studies have focused on GSR estimation. However, some efforts have been made using empirical models and software like RadEst v3.0 [28]. For example, Rajbanshi et al. used RadEst 3.0 to estimate daily GSR in various regions, including Taplejung (eastern upland) [29], Dhankuta (eastern hilly region) [30], and Biratnagar (eastern lowland city) [31]. Similarly, Kharel et al. applied the same software to Jumla, a hilly region in western Nepal [32].

Given Nepal's diverse geography and rapidly changing climate conditions, it is important to develop reliable empirical constants for different regions. To improve accuracy, it is also recommended that these constants be established for every 200 meters of altitude difference [33]. This approach can help produce more accurate GSR estimates across Nepal's varied landscapes.

The main goal of this study was to assess different models for estimating daily average hourly GSR on a horizontal surface using bright sunshine hours, temperature, and relative humidity. The study aimed to identify the most suitable model for the Okhaldhunga region. Linear regression was used to develop predictive models, and the estimated GSR values were then statistically compared with the observed data recorded at the same location.

2. Methods and Instrumentation

2.1 Site Location

Nepal is one of the best places in the world for solar energy. Okhaldhunga, a district in eastern Nepal, is located at about 27.3081°N latitude and 86.5042°E longitude. It sits at an average height of 1,731 meters above sea level, with elevations ranging from 390 to 3,636 meters. The area covers 1,074 square kilometers and has different climate zones, from subtropical in lower areas to alpine in higher regions. The weather is generally mild, with most rain falling during the monsoon season from June to

September, while winters are mostly dry.

Daily data on GSR, sunshine hours, humidity, rainfall, and temperature (both maximum and minimum) on a flat surface were collected from 2021 to 2023. This data came from the Alternative Energy Promotion Centre (AEPC) under the Government of Nepal, the Department of Hydrology and Meteorology, and partners like the World Bank Group. Solar radiation was measured using a CMP21 pyranometer. Temperature and humidity were recorded with a CS215 device from Campbell Scientific. Rainfall was measured by a 52203 R M Young tipping bucket rain gauge. Based on various studies, some empirical models (listed in Table 1) can be useful to estimate constants specific to this location.

Table 1: List of models used

Model	Symbol	Relation
Angstrom-Prescott Model	A	$\frac{H_g}{H_0} = a + b\left(\frac{n}{N}\right)$
Garica model (1994)	B	$\frac{H_g}{H_0} = a + b\left(\frac{\Delta T}{N}\right)$
Swarthman- Oguniade Model	C	$\frac{H_g}{H_0} = a + b\left(\frac{n}{N}\right) + c(RH)$
Modified Angstrom Model	D	$\frac{H_g}{H_0} = a + b\left(\frac{n}{N}\right) + c(\Delta T)$
Modified Angstrom Model	E	$\frac{H_g}{H_0} = a + b\left(\frac{n}{N}\right) + c(T_1)$
Olomiyesan-Oyedum Model	F	$\frac{H_g}{H_0} = a + b\left(\frac{n}{N}\right) + c\left(\frac{\Delta T}{N}\right)$
Abdalla model	G	$\frac{H_g}{H_0} = a + b\left(\frac{n}{N}\right) + c(T_1) + d(RH)$
Modified Angstrom (new)Model	H	$\frac{H_g}{H_0} = a + b\left(\frac{n}{N}\right) + c(\Delta T) + d(RH)$
Modified Angstrom (new)Model	I	$\frac{H_g}{H_0} = a + b\left(\frac{n}{N}\right) + c\left(\frac{\Delta T}{N}\right) + d(RH)$

2.2 Extraterrestrial Radiation

The extraterrestrial GSR (Ho) can be calculated from the following equations: [33]

$$H_0 = \frac{24}{\pi} I_{sc}\left[1 + 0.033\cos\left(\frac{360 n_d}{365}\right)\right]\left[\cos\phi \cos\delta \sin\omega + \frac{\pi}{180}\omega \sin\phi \sin\delta\right] \quad (1)$$

Where,

I_{sc} = solar constant (=1367 W m^{-2}),

φ = the latitude of the site (rad),

Δ = the solar declination (rad),

Ω = the mean sunrise hour angle for the given month, and

n_d = the Julian day number of the year starting from the first of January.

The solar declination (δ) and the mean sunrise hour angle (ω) can be calculated by the following equations.

$$(\delta \text{ degree}) = 23.45\sin\left[\frac{360}{365}(284 + n_d)\right] \quad (2)$$

$$\omega = \cos^{-1}(-\tan\phi \tan\delta) \quad (3)$$

The relation of the day length is

$$N = \frac{24}{\pi}\omega = \frac{24}{\pi}\cos^{-1}(-\tan\phi \tan\delta) \quad (4)$$

2.3 Statistical Approach

The daily average hourly extraterrestrial radiation and the length of the day were calculated using the given equations. Empirical constants for different models were determined using regression analysis, and then these models were used to estimate the global solar radiation. The accuracy of each model was checked using statistical measures such as RMSE, MPE, MBE, and the R^2. These statistical tools are explained as follows [12].

$$\text{RMSE} = \sqrt{\frac{1}{N}\sum\left(H_{i,c} - H_{i,m}\right)^2} \quad \text{MJ/m}^2\text{/day} \quad (5)$$

$$\text{MBE} = \frac{1}{N}\sum\left(H_{i,c} - H_{i,m}\right) \quad \text{MJ/m}^2\text{/day} \quad (6)$$

$$\text{MPE} = \frac{1}{N}\left[\sum\left(\frac{H_{i,c}-H_{i,m}}{H_{i,m}}\right) \times 100\right] (\%) \quad (7)$$

$$R^2 = \sum_{k=0}^{n}\binom{n}{k}x^k a^{n-k} = \frac{\sum(H_{i,m}-\overline{H_m})(H_{i,c}-\overline{H_c})}{\sqrt{\sum(H_{i,m}-\overline{H_m})^2(H_{i,c}-\overline{H_c})^2}} (\%) \quad (8)$$

$$\text{CRM} = \frac{\sum H_{i,m} - \sum H_{i,c}}{\sum H_{i,m}} (\%) \quad (9)$$

Where,

$H_{i,m}$ = measured value,

$H_{i,c}$ = estimated value, is the number of data,

$\overline{H_m}$= the average of measured solar radiation,

$\overline{H_c}$= the average of estimated solar radiation.

3. Results and Discussion

The empirical constants for different models were found using linear regression analysis based on data from 2021 to 2023, as shown in Table 1. The accuracy of these models was checked using four statistical tools: MBE, RMSE, MPE, and the R^2, also listed in Table 1.

A good model has lower values of MBE, RMSE, and MPE, and a higher value of R^2. The R^2 shows how well the model fits the data by explaining how much of the variation in the results can be predicted by the model. MBE shows the average bias, indicating whether the model tends to overestimate or underestimate the GSR over the long term. MPE shows the average percentage difference between the model's predictions and the actual values. RMSE measures how much the predicted values differ from the observed values in the short term.

The calculated values for these statistical errors are summarized in Table 2.

Table 2: The empirical constants and statistical tools for different models for Okhaldhunga (Optimal values are bold-faced)

Models	**Empirical constants**				**Statistical tools**			
	a	**b**	**c**	**d**	**MBE ($MJ/m^2/day$)**	**RMSE ($MJ/m^2/day$)**	**MPE (%)**	**R^2**
A	0.2835	0.3895			0.0323	3.8573	8.8459	0.4850
B	0.1520	0.4177			0.03026	4.3704	11.5168	0.33642
C	0.5093	0.3269	-0.0023		0.02950	3.7705	9.4816	0.5081
D	0.1898	0.2896	0.0158		0.02859	3.7548	8.7044	0.5120
E	-0.1247	0.3807	0.0185		0.02973	3.0663	6.3140	0.6746
F	0.2426	0.3380	0.0899		0.0302	3.8288	9.4264	0.4917
G	**0.1056**	**0.3136**	**0.0186**	**-0.0024**	**0.0293**	**2.9457**	**5.8943**	**0.6998**
H	0.3637	0.2719	0.0119	-0.00158	0.0351	3.7211	8.7907	0.5207
I	0.4711	0.3071	0.0421	-0.00217	0.0196	3.7637	9.2243	0.5093

Based on the statistical test results, the estimated daily GSR values generally matched well with the measured daily average GSR for all models except model B, which showed the highest MPE of 11.517%. While the errors in all nine models were quite similar, model G performed the best, having the lowest MBE, RMSE, and MPE values. It also had the highest R^2 at 0.6998. Therefore, model G is recommended for estimating the daily average GSR in Okhaldhunga, Nepal.

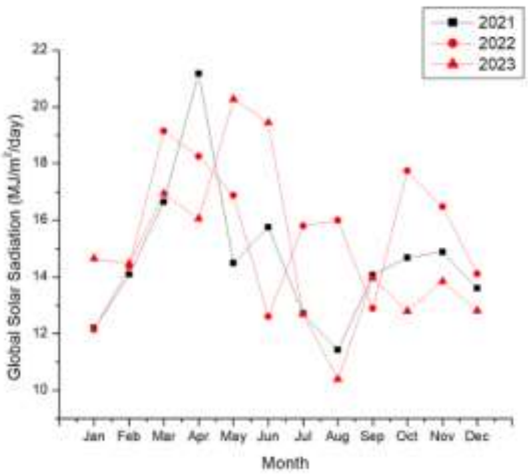

Fig. 1. Variation of measured monthly average daily GSR for 2021, 2022 and 2023

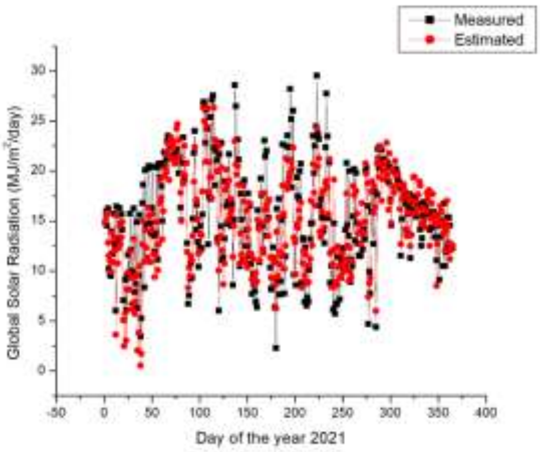

Fig. 2. Graphic representation of variation of measured and estimated daily GSR for 2021

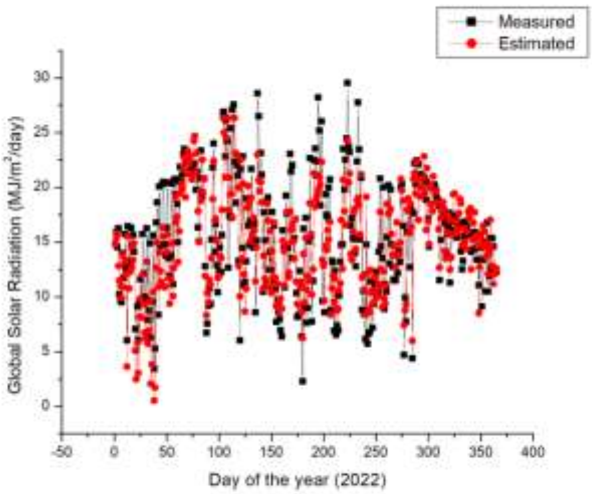

Fig. 3. Graphic representation of variation of measured and estimated daily GSR for 2022

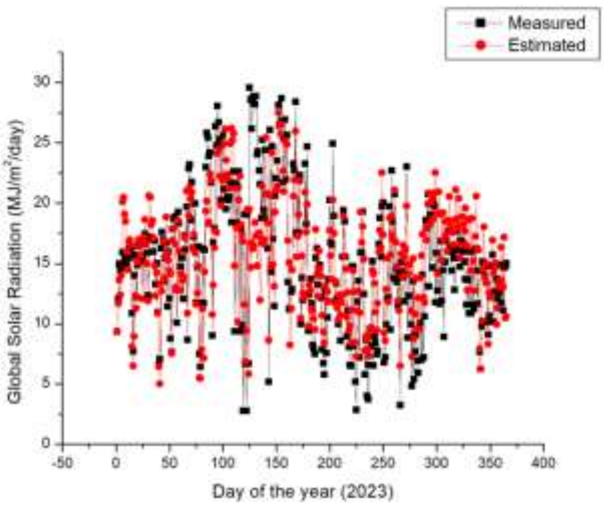

Fig. 4. Graphic representation of variation of measured and estimated daily GSR for 2023

The measured and estimated monthly average daily GSR for all models in Okhaldhunga are shown in Figure 2. As noted in Table 1, model B showed less agreement with the observed values, while the other models matched better. Among them, model G is recommended for estimating daily average solar radiation in Okhaldhunga, Nepal. Figures 2, 3, and 4 illustrate the comparison between measured and estimated daily GSR for the years 2021, 2022, and 2023, respectively. Figures 5, 6, and 7 present the seasonal variations of GSR, rainfall, and average wind speed over these three years.

The GSR is strongly influenced by factors such as relative sunshine duration, temperature, and temperature difference. Maximum temperatures generally rise from January to mid-year and then decrease towards the end of the year. However, GSR does not follow this temperature trend during the middle of the year because of cloud cover and heavy rainfall during the monsoon season. Temperature changes affect GSR throughout the year, except in January and December. Additionally, GSR decreases as relative humidity increases, showing an inverse relationship clearly visible in Figure 4.

Okhaldhunga experiences some of the highest rainfall in Nepal, which also contributes to the decrease in GSR during rainy periods. GSR tends to increase from January to March but fluctuates afterward due to the start of the pre-monsoon season. During summer, although temperatures are higher, GSR decreases because of heavy rainfall and thick cloud cover.

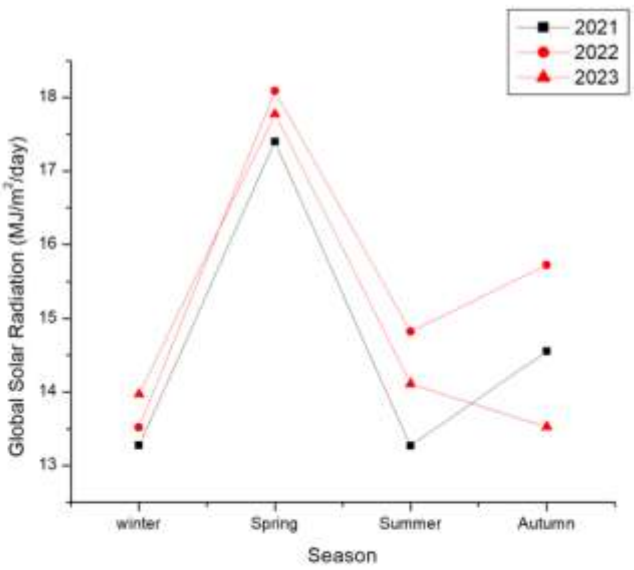

Fig. 5. Graphic representation of variation of seasonal GSR for 2021, 2022 and 2023

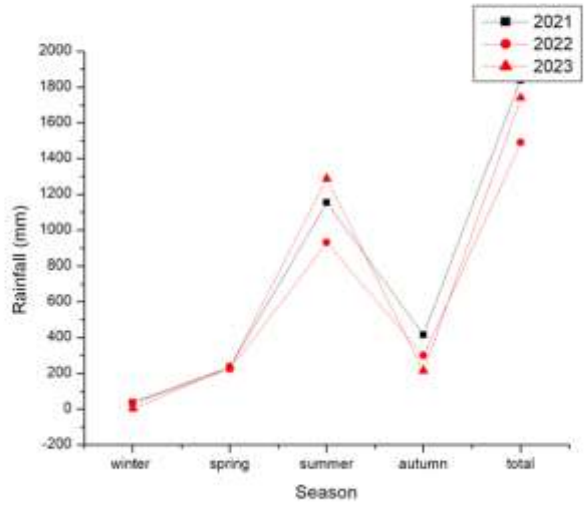

Fig. 6. Graphic representation of variation of seasonal rainfall for 2021, 2022 and 2023

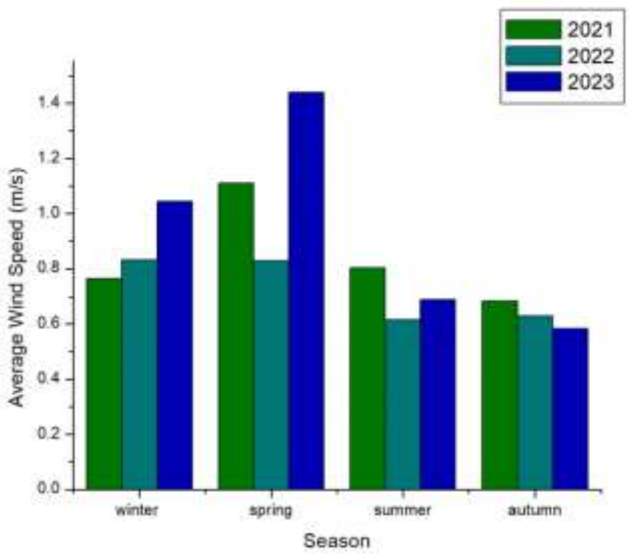

Fig. 7. Graphic representation of variation of seasonal average wind speed for 2021, 2022 and 2023

This study demonstrates that GSR is influenced by sunshine duration, temperature, and relative humidity. The linear model developed has empirical constants of a = 0.1056, b = 0.3136, c = 0.0186, and d = -0.0024. Based on the statistical analysis, this model is recommended for estimating the daily average GSR in Okhaldhunga. The determined empirical constants can also be applied to predict GSR in areas with similar geographic conditions to Okhaldhunga. The average yearly GSR at this location is calculated to be 15.18 MJ/m^2 per day.

Okhaldhunga receives an average GSR of 4.22 $kWh/m^2/day$, which is lower than Jumla (5.44 $kWh/m^2/day$) [32], Taplejung (4.42 ± 0.09 $kWh/m^2/day$) [29], Dhankutta (4.36 ± 0.07 $kWh/m^2/day$) [30], and Biratnagar (4.28 ± 0.07 $kWh/m^2/day$) [31]. Although Okhaldhunga lies at a moderate altitude that usually favours higher solar radiation, the region experiences **high humidity, frequent cloud cover, and heavy rainfall**, especially during the monsoon. These factors reduce the amount of sunlight reaching the ground by increasing atmospheric moisture, which scatters and absorbs solar radiation. On the other hand, **Jumla**, with higher altitude and **dry weather**, has clearer skies and less cloud cover, resulting in higher solar radiation [32]. While Okhaldhunga has less pollution than lowland cities like Biratnagar, it may still be affected by **seasonal dust and biomass burning**, slightly lowering its solar potential. Overall, **Okhaldhunga's lower GSR is mainly due to its moist and cloudy hill climate**.

4. Conclusion

The objective of this study was to evaluate different models and determine empirical constants for estimating the daily average global solar radiation on a horizontal surface in Okhaldhunga, Nepal. To achieve this, data on relative sunshine hours, temperature, and relative humidity were collected and analyzed using linear regression techniques. These variables were chosen because they significantly influence solar radiation levels. By applying the regression analysis to data from Okhaldhunga, empirical constants were calculated for various models, allowing for more accurate estimation of solar radiation specific to this region's climatic conditions.

Different empirical constants were identified and applied to various models, which were then evaluated using several statistical measures. Among all the models, Model G performed the best, with a mean bias error (MBE) of 0.0293, MPE of 5.8943, RMSE of 2.9457, and a R^2 of 0.6998. Based on these statistical results, a new, simple multiple-parameter model derived from the Abdalla model (Model G) is highly recommended for estimating daily GSR in the mid-hill region of Okhaldhunga, Nepal.

$$\frac{H_g}{H_0} = 0.1056 + 0.3136\left(\frac{n}{N}\right) + 0.0186\,(T_1) - 0.0024(RH)$$

The derived empirical constants can also be applied to other regions in Nepal with similar geographical conditions. In Okhaldhunga, the annual average solar insolation was found to be 4.22 kWh/m²/day, which is relatively high. This indicates a strong potential for solar energy, confirming that the region is well-suited for the promotion and development of solar energy technologies.

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