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Original Article

A new technique of estimating global solar radiation[1]

Uma nova técnica para estimativa da radiação solar global

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HIGHLIGHTS:

The data acquisition system monitors the daily variations of solar irradiance and, in real-time, integrated global solar radiation.
Estimated data for global solar radiation is similar to the obtained data.
The methodology can be reproduced worldwide.

ABSTRACT: Global solar radiation (Qg) is of paramount importance for several functions, such as photosynthesis and other biological processes, technologies based on solar energy (production of electricity and hot water), estimation of evapotranspiration (irrigation management), and forecast of crops, among other activities, at zero cost. This study aimed to develop a new methodology to estimate the daily and monthly value of global solar radiation based on the power generated by a 10 W photovoltaic solar panel. The methodology performance was assessed by comparing the Qg values estimated by the new method and the Qg values observed in a weather station, and also calculated by the SunDATA software and observed in the NASA POWER system. High r, R^2, and Willmott coefficient values (close to 1), a low mean absolute error (MAE) of 0.202 kWh m^{-2} per day, a low mean bias error (MBE) of –0.146 kWh m^{-2} per day, a low mean percentage error (MPE) of 3.25%, and a low root mean square error (RMSE) of 0.292 kWh m^{-2} per day were obtained, confirming the excellent accuracy and reliability of the proposed methodology to estimate Qg. The NASA POWER system and SunDATA software presented similar values for the entire study period compared to the observed data, but not as good as the proposed technique. Thus, the proposed methodology had high performance in estimating Qg.

Key words: solar energy; IoT; photovoltaic solar panel

RESUMO: A radiação solar global (Qg) é de suma importância para diversas funções, como fotossíntese e outros processos biológicos, tecnologias baseadas em energia solar (produção de eletricidade e água quente), estimativa da evapotranspiração (manejo da irrigação), previsão de cultivos, entre outras atividades, a custo zero. Este estudo teve como objetivo desenvolver uma nova metodologia para estimar o valor diário e mensal da radiação solar global com base na potência gerada por um painel solar fotovoltáico de 10 W. O desempenho da metodologia foi avaliado pela comparação entre os valores de Qg estimados pelo novo método e os valores de Qg observados em uma estação metereológica, e também pelos valores calculados pelo software SunDATA e os observados no sistema NASA POWER. Altos valores de r, R^2 e coeficiente de Willmott (próximos de 1), baixo erro médio absoluto (MAE) de 0,202 kWh m^{-2} por dia, baixo erro médio da estimativa (MBE) de -0,146 kWh m^{-2} por dia, baixo erro médio percentual (MPE) de 3,25% e baixa raiz do erro quadrático médio (RMSE) de 0,292 kWh m^{-2} por dia foram obtidos, confirmando a excelente acurácia e confiabilidade da metodologia proposta para estimar o Qg. O sistema NASA POWER e o software SunDATA apresentaram valores semelhantes para todo o período de estudo em relação aos dados observados, mas os da presente metodologia foram melhores. Assim, a metodologia proposta apresentou alto desempenho na estimativa da Qg.

Palavras-chave: energia solar, IoT, painel solar fotovoltaico

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Introduction

Life as known is only possible, for the most part, because of the clean and free energy that is gotten from the sun. This energy, which reaches the Earth's surface daily after being partially attenuated as it passes through the atmosphere, is called global solar radiation (Qg). Measuring global solar radiation is of fundamental importance for several activities, such as agriculture (Garcia-Rodrigues et al., 2020; Samanta et al., 2020; Wu et al., 2021; Souza et al., 2023), climate change studies (Farah et al., 2019), electricity production via photovoltaic solar panels (Ben Ammar et al., 2020; Patchali et al., 2022; Bruning et al., 2023), among many others. Its quantification is a procedure that has a considerable cost due to the need for specific instruments such as solarimeters, pyrheliometers, radiometers, actinographs, thermocouple pyranometers, or silicon photodiode pyranometers, in addition to qualified labor for their operation.

Several approaches can be found in the literature to estimate Qg. Angström (1924) proposed a model for estimating the Qg value, and Prescott (1940) improved it. The equation is known as the Angström-Prescott equation (Almorox et al., 2020; Morf, 2018; Silva et al., 2017). Liu & Scott (2001) assessed several models and concluded that the best performance was the one in which temperature and rainfall data were used. Rusen (2018) used satellite imagery to model and analyze Qg and diffuse solar radiation in Turkey. Marzouq et al. (2018) used artificial neural networks to select input variables, such as temperature, relative air humidity, and rainfall, in the solar radiation estimates for Fez, Morocco. Tsung et al. (2019) used the classical Angström-Prescott (A-P) model to estimate Qg from insolation (n) and photoperiod (N) data for the city of Putrajaya in Malaysia. Considering the complexity and/or difficulty in obtaining reliable Qg values, this study aimed to develop a new methodology to estimate the daily and monthly value of global solar radiation based on the power generated by a 10 W photovoltaic solar panel.

Material and Methods

Solar radiation varies continuously from early morning to late afternoon. Therefore, data acquisition every 10 min was standardized to obtain Qg_{estim} by integration, performed by the trapezium rule method, through which the estimated daily global solar radiation was calculated.

The study was carried out at the experimental area of the Departamento de Engenharia de Biossistemas, of Escola Superior de Agricultura "Luiz de Queiroz" - ESALQ, Universidade de São Paulo - USP at 22° 42' 41" S and 47° 37' 45" W, an altitude of 546 m. The regional climate in recent years has been Aw-type (tropical with a dry season) according to the Köppen classification. The experiment was conducted from March to December 2021.

A system based on the Internet of Things (IoT) was used for real-time data acquisition (Paes et al., 2022; Pinto et al., 2021; Farooq et al., 2020). An algorithm was developed using the free software Arduino Integrated Development Environment (Arduino IDE; https://arduino.cc) to monitor the study variables via wireless internet (GPRS/GSM) on the ThingSpeak platform (www.thingspeak.com) and calculate the estimated daily global solar radiation by integrating the values acquired every 10 min.

The daily Qg_{obs} value was obtained from the weather station of the Department of Biosystems Engineering of ESALQ/USP, located 1.1 km away. The instantaneous estimated solar irradiance (ESR) was obtained using the power generated throughout the day by a photovoltaic solar panel installed on the horizontal plane.

The instruments for measuring the generated power comprised a 10 W and 12 V Sinosola SA10-36P (350 × 252 mm) solar panel (Table 1), with a 10 A PWM (pulse width modulation) charge controller, lead-acid battery (12 V and 7 Ah), circuit breakers, metal box to protect the system, INA219 sensor (Texas Instruments, Dallas, USA) for current, voltage, and power, wires, and connections. A load of approximately 5 W was connected to the system to prevent the battery from entering the full charge regime and the charge controller from limiting the generated power. The solar panel was placed 2 m above the ground. The surface of the solar panel was cleaned every 30 days due to the presence of dirt, which negatively impacted the acquired daily results.

An equation of the relationship that defines the rated power of a given solar panel and the 1000 W m^{-2} radiation was derived from converting the generated power into solar radiation (Eq. 1); that is, the generated power is proportional to the incident radiation, and the panel efficiency (Eq. 2), which can be expressed by:

$$ESR = \frac{1000 P_{inst}}{P_r \left(1 - E_{sp} - \alpha\right)} \quad (1)$$

$$E_a = \frac{P_{inst}}{X_n A_{sp}} \quad (2)$$

where:

ESR - estimated solar irradiance (W m^{-2});
P_{inst} - instantaneous power generated by the solar panel (W);
P_r - rated power of the solar panel (W);
E_{sp} - rated efficiency of the solar panel (decimal);
E_a - actual efficiency of the solar panel (decimal);
X_n - observed solar radiation (W m^{-2});
A_{sp} - useful area of the solar panel (m^2); and,
α - difference between the mean actual efficiency (E_a) and the rated efficiency (E_{sp}) of the solar panel (decimal).

The rated efficiency and the rated power are information available in the technical specifications of solar panels and are provided by the manufacturers.

The daily Qg_{estim} value was obtained by integrating the estimated solar radiation (ESR) values using Eq. 3 for the calculation at the 10 min time intervals.

Table 1. Solar panel specifications* provided by the manufacturer

Peak power (W)	V_{OC} (V)	I_{SC} (A)	I_{MP} (A)	V_{MP} (V)	η (%)
10	22.5	0.6	0.53	19	11.34

*V_{OC} - Open-circuit voltage; I_{SC} - Short-circuit current; I_{MP} - Current at maximum power V_{MP} - Voltage at maximum power; η - Efficiency

$$Qg_{estim} = \frac{h}{2}\{x_0 + 2x_1 + 2x_2 + 2x_3 + ... + x_n\} \quad (3)$$

where x_n is the estimated solar radiation (ESR) (W m^{-2}), and h is the interval between measurements (10/60 = 0.16666667).

The obtained Qg_{estim} values were compared with Qg_{obs} using the Pearson correlation coefficient (r), which measures the degree of correlation between the variables, the coefficient of determination (R^2), which measures how the data adequately adjusts the regression equation, and the index of agreement d, which indicates the performance of the proposed methodology, as suggested by Willmott et al. (1985).

The mean percentage error (MPE - which represents the percentage of deviation of the monthly radiation estimated by the model), the mean bias error (MBE - which represents the deviation from the means (systematic error), and negative values indicate underestimation) (Souza et al., 2011); the mean absolute error (MAE - which represents the mean deviation between observed and predicted values, showing how close the predictions are to the actual values) (Willmott & Matsuura, 2005), and the root mean square error (RMSE - which informs about the actual value of the error produced by the model) (Carvalho et al., 2015), were also calculated. All statistical tests were performed using a MS Excel spreadsheet (Table 2).

The values obtained for Qg_{obs} and Qg_{estim} were also compared with those calculated by the SunDATA software (CRESESB, 2017) and the NASA POWER database (Aboelkhair et al., 2019; Duarte & Sentelhas, 2020;) to reinforce the performance evaluation of the suggested methodology.

The SunDATA software was initially based on data from the "Valores Medios de Irradiación Solar Sobre Suelo Horizontal" from the Centro de Estudos de la Energia Solar (CENSOLAR, 1993), containing data on monthly mean daily solar radiation on the horizontal plane for about 350 points in Brazil and neighboring countries. The software was updated in 2017 with satellite imagery and information from more than 72,000 points in the territory of Brazil. The SunDATA software is accessed on the website of the Sérgio S. de Brito Reference Center of Solar and Wind Energy (CRESESB, 2021). On this website, the coordinates (latitude and longitude) allow obtaining the location and mean daily values of global solar radiation on the horizontal and inclined plane in kWh m^{-2} per day for a given location.

The National Aeronautics and Space Administration - NASA has supported satellite systems and research through the Earth Science research program, providing important data for weather and climate processes studies. The NASA POWER database provides global meteorological data with a spatial resolution of 1° latitude-longitude for horizontal plane radiation data (NASA, 2021a). This system synthesizes and analyzes meteorological data on a global scale from various sources, being updated weekly, and all variables are available from 1983 to the present, except for rainfall data, which have been reported since 1997 (Duarte & Sentelhas, 2020). Solar radiation data are derived from the Global Energy and Water Exchanges Project Surface Radiation Budget (GEWEX SRB version 3.0), which currently estimates radiation at the top of the atmosphere (Monteiro et al., 2018; NASA, 2021b). This program integrates research, observations, and science activities with a mission to observe, understand, and model the hydrological cycles and energy fluxes in the Earth's atmosphere and on its surface. NASA POWER data can be obtained free of charge from the website of the National Aeronautics and Space Administration/Prediction of Worldwide Energy Resources (NASA, 2021c). Files in CSV format, with daily Qg values, were obtained for this database.

Table 2. Mathematical equations of the statistical indexes used to evaluate the performance of the estimated values of global solar radiation (Qg_{estim}) with the solar panel

	Index equation
Pearson correlation coefficient	$r = \frac{\sum_1^n (Qg_{estim} - Qg_{estimmean})(Qg_{obs} - Qg_{obs\ mean})}{\sqrt{\sum_1^n (Qg_{obs} - Qg_{obs\ mean})^2}\sqrt{\sum_1^n (Qg_{estim} - Qg_{estimmean})^2}}$
Coefficient of determination	$R^2 = \frac{\{\sum_{i=1}^n (Qg_{estim} - Qg_{estimmean})(Qg_{obs} - Qg_{obs\ mean})\}^2}{\sum_{i=1}^n (Qg_{estim} - Qg_{estimmean})^2 \sum_{i=1}^n (Qg_{obs} - Qg_{obs\ mean})^2}$
Willmott agreement index	$d = 1 - \{\frac{\sum (Qg_{estim} - Qg_{obs})^2}{\sum (\lvert Qg_{estim} - Qg_{obs\ mean}\rvert + \lvert Qg_{obs} - Qg_{obs\ mean}\rvert)^2}\}$
Mean absolute error	$MAE = \frac{1}{n}\sum_{i=1}^n \lvert Qg_{estim} - Qg_{obs}\rvert$
Mean bias error	$MBE = \frac{1}{n}\sum_{i=1}^n (Qg_{estim} - Qg_{obs})$
Mean percentage error	$MPE = \frac{1}{n}\sum 100 \frac{(Qg_{obs} - Qg_{estim})}{Qg_{obs}}$
Root mean square error	$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^n (Qg_{estim} - Qg_{obs})^2}$

$Qg_{obs\ mean}$ - Mean of observed values; $Qg_{estim\ mean}$ - Mean of estimated values; n - Number of observations and measurements (282)

Results and Discussion

The low-cost system, based on the Internet of Things (IoT), monitored the power generated on the 10 W solar panel and other parameters. It allowed real-time tracking of the variation in the estimate of global solar radiation, with visualization on the internet using the ThingSpeak platform. The system is entirely powered by solar energy, as also reported by Satheesan et al. (2021). Fahim et al. (2023) also implemented a low-cost IoT system as an alternative to traditional weather stations. They transmitted real-time air quality data from Hoceima (Morocco), demonstrating the feasibility of the system.

The mean value of the calculated α term in Eq. 1 was approximately 0.09, but the term could be adjusted in other studies. According to Pachali et al. (2022), Makade et al. (2019), and Sarkar & Sifat (2016), in the estimation of Qg using empirical models, the optimization of coefficients is of fundamental importance to minimize the difference between observed and estimated values.

A sharp reduction in rainfall was observed at the site during April, May, and June (autumn in the southern hemisphere), according to rainfall data obtained from the weather station, located 1.1 km away, with a decrease from a mean of 30.2 to 12.7 mm per month in April, May and June (Figure 1). Rainfall also reduced from 23.4 to 3.6 mm per month in July, August, and September (winter), which is normal in the region, as it has a dry winter. October presented a reduction in Qg (Figure 2) due to the rainfall of 132.1 mm, distributed in 15 days. Although November and December had the highest rainfall,

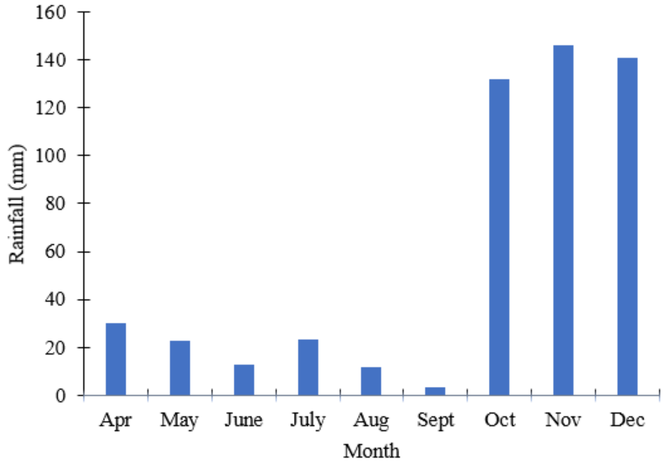


Figure 1. Monthly variations in the observed rainfall between April 01 and December 31, 2021

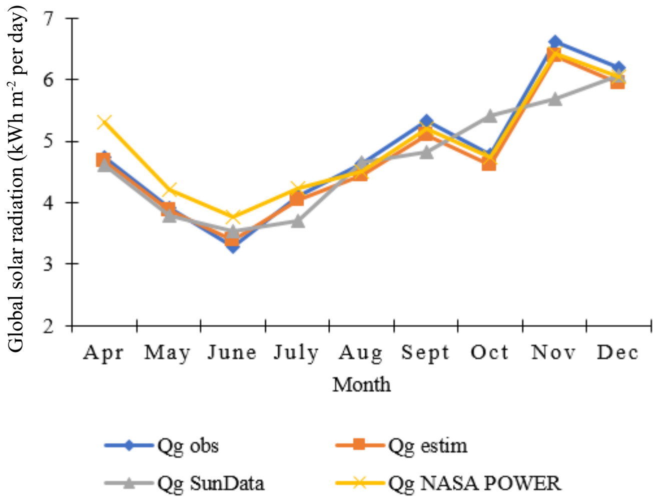


Figure 2. Comparison between the observed (Qg obs) and estimated (Qg estim) global solar radiation and calculated radiation provided by the Sun DATA software (Qg SunData) and NASA POWER database (Qg NASA POWER) between April 01 and December 31, 2021

the Qg was higher because of the beginning of the summer and the days with less rain.

Liu & Scott (2001) found that the model with the best R^2 also included rainfall data as a parameter for predicting Qg. These data typically contribute to the understanding of Qg results. In a study to estimate maize yield, Duarte & Sentelhas (2020) observed that rainfall data from the National Water Agency - ANA allows for a satisfactory estimation of yield potential.

Figure 2 shows the monthly Qg values for the site where the study was conducted, i.e., values calculated by the SunDATA software, obtained by the NASA POWER database, and observed and estimated by the proposed methodology.

The observed variation in Qg (Figure 2), lower in June and higher in November/December, is attributed to the perihelion and aphelion when the Earth is closest or farthest from the Sun. Samanta et al. (2019) obtained maximum values in estimating global solar radiation using the Angstrom-Prescott equation between March and April, with lower values in December. Similar results were obtained by Acharya et al. (2021) in predicting Qg using different empirical models in Nepal. This is due to their location in the northern hemisphere. The comparison with the data from the SunDATA software shows that the highest difference (14.2%) occurred in November (Figure 2), as this month presented a high number of days with rainfall (9 days), which probably affected the local global solar radiation values. Usually, data obtained locally are more accurate (CRESESB, 2017; Samanta et al., 2019). Moreira Júnior et al. (2020) found that the values of the SunDATA software for their location presented an overvalue of 10.85% compared to the experimental data. The data obtained by NASA POWER showed an overvalue in April, May, and June of this study (Figure 2). Samanta et al. (2020) conducted a study in the northern hemisphere (India) and observed, in many cases, higher mean measured and calculated Qg values than those obtained by NASA POWER. The variation found in this study can be explained by the possible presence of clouds, mainly in June, and the presence of particulate matter in the air, which obstructs the passage of solar radiation. The obtained results are an indication of the assertiveness of the proposed methodology.

The observed and estimated global solar radiation values were highly correlated, as shown in Figure 3. The accuracy of the proposed methodology was confirmed with the determination of performance indexes (Table 3).

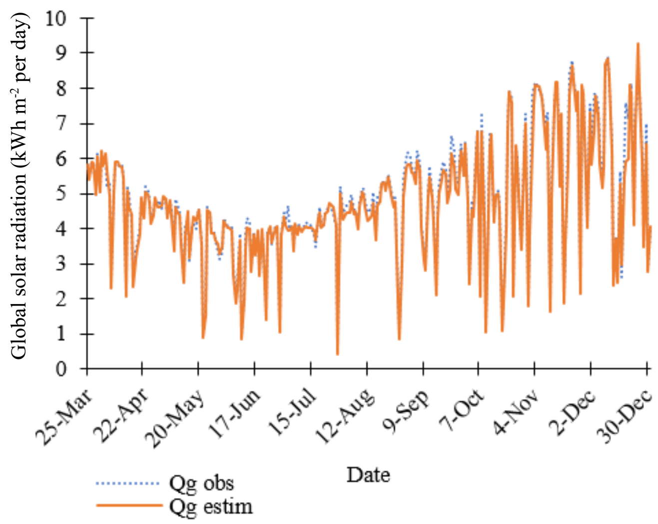


Figure 3. Comparison between observed (Qg obs) and estimated (Qg estim) daily global solar radiation by the proposed methodology between March 25 and December 31, 2021

Table 3. Performance indexes calculated for the validation of the proposed methodology for estimating global solar radiation (Qg_{estim}) and comparison with NASA POWER (NP) indexes. Total number of data = 282

Q_g*	d	r	R^2	Statistical tests			
				MAE (kWh m^{-2} per day)	MBE (kWh m^{-2} per day)	MPE (%)	RMSE (kWh m^{-2} per day)
Qg_{estim}	0.999	0.989	0.977	0.202	-0.146	3.25	0.292
NP	0.999	0.953	0.908	0.409	0.089	-3.87	0.517

*Daily scale; d - Willmott agreement index; r - Pearson correlation coefficient; R^2 - Coefficient of determination; MAE - Mean absolute error; MBE - Mean bias error; MPE - Mean percentage error; RMSE - Root mean square error

A simple linear regression equation (Figure 4) was fitted Eq. 4:

$$Qg_{estim} = 0.9744Qg_{obs} - 0.0213\left[\text{kWh m}^{-2}\text{ per day}\right] \quad (4)$$

The high r and R^2 values can also prove the data precision and accuracy, that is, 0.989 and 0.977, respectively. Generally, the estimated Qg data tend to be slightly underestimated, but with low MBE and MAE values of −0.146 kWh m^{-2} per day and 0.202 kWh m^{-2} per day, respectively (Table 3). According to Menges et al. (2006), the ideal range of MPE is between −10% and +10%, with the value obtained being 3.25%, indicating the excellent performance of the methodology. Statistical errors (MAE, MBE, and RSME) are all close to zero.

Figure 4 shows the dispersion of the measurements around the (1:1) 45° straight line, proving the validity of the proposed methodology. All statistical indicators confirm this conclusion.

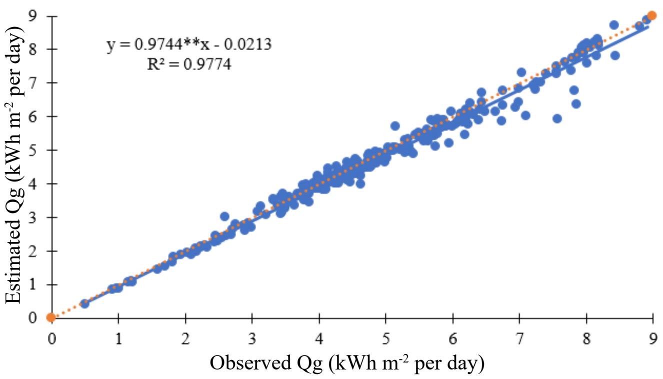
Table 3 shows the statistical indexes and errors of the comparison between the observed Qg data (Qg_{obs}) and the NASA POWER Qg data (Qg_{NP}) on a daily scale.

Figures 5 and 6 show the relationship between Qg_{obs} and Qg_{NP} for the period under study. A simple linear regression equation (Eq. 5) was also fitted, explaining 90.8% of the data variation:

$$Qg_{NP} = 0.89Qg_{obs} + 0.6247\left[\text{kWh m}^{-2}\text{ per day}\right] \quad (5)$$

The Pearson correlation coefficient (r) and the coefficient of determination (R^2) indicated a precision, with values of 0.953 and 0.908, respectively. According to Beruski et al. (2015), the coefficients of determination and correlation give an idea of the data precision. The accuracy can be obtained by the index of agreement (d) proposed by Willmott et al. (1985). The d value equal to 0.999 obtained for Eq. 4 and Eq. 5 indicates a high accuracy.

The values of the performance indexes of the proposed methodology for Qg_{estim} are better than those presented by NASA POWER on a daily scale (Table 3). Most NASA POWER error estimations were higher, and the coefficients of determination and correlation were slightly smaller; however, it can be useful and employed as a source of climatic data for agricultural activities, correlating reasonably well with the obtained data (Monteiro et al., 2018; Rodrigues & Braga, 2021).



** - Significant at $p \leq 0.01$ by F test

Figure 4. Scatter plot between the daily global solar radiation (Qg) observed in the weather station and the daily global solar radiation estimated by the proposed methodology between March 25 and December 31, 2021

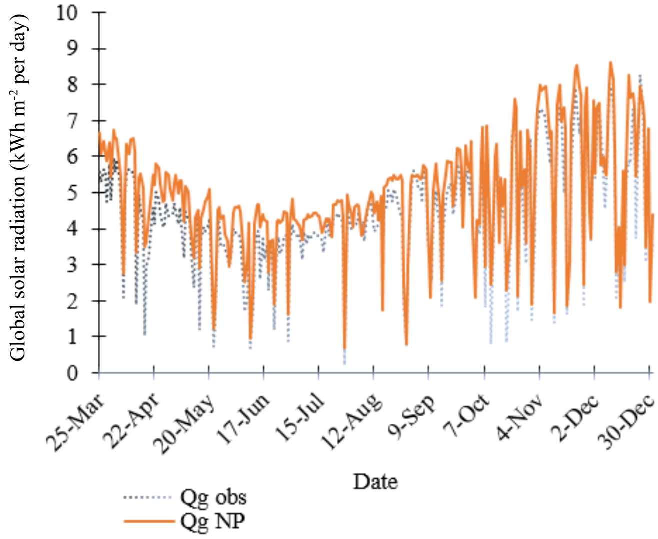
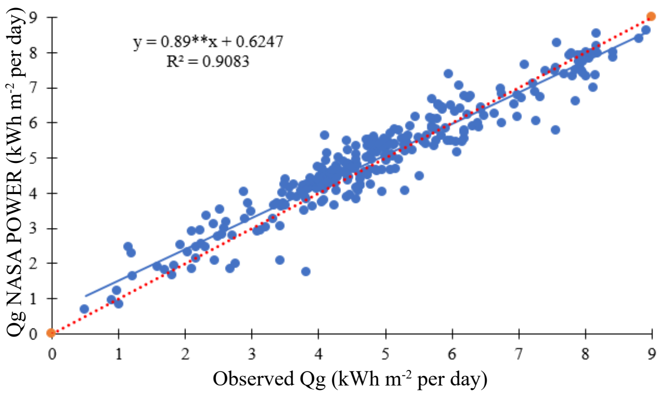


Figure 5. Comparison between the observed daily global solar radiation (Qg obs) of the weather station and that obtained by NASA POWER (Qg NP) between March 25 and December 31, 2021



** - Significant at $p \leq 0.01$ by F test

Figure 6. Scatter plot between the daily global solar radiation observed (Qg obs) in the weather station and the daily global solar radiation obtained by NASA POWER (Qg NP) between March 25 and December 31, 2021

Conclusions

1. The methodology developed in this study can be used to estimate the daily and monthly global solar radiation (Qg) values with high accuracy and precision.

2. The SunDATA software and the NASA POWER database presented similar values relative to the observed data over the study period.

3. Periodic solar panel cleaning is important to avoid significant losses in system efficiency.

4. Qg estimates by the proposed technique can be improved by calibrating the α term in Eq. 1.

5. This study may assist people or entities in obtaining mean data of local estimated global solar radiation at a very low cost.

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