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Full Length Research Paper

Solar radiation: Correlation between measured and predicted values in Mubi, Nigeria

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In this study, the correlation between measured and predicted values of solar radiation was made. A series of daily measurements of the global solar radiation on a horizontal surface was recorded in Mubi with the aid of a constructed pyranometer. The monthly average value was determined. The monthly average daily solar radiation on horizontal surface was also determined using sunshine duration. These parameters were input in some radiation models to compute the solar radiation. Finally, a prediction of the global solar radiation from climatological data has been attempted. The predicted values have been compared with the corresponding measured values. Predictions and measurements were found to be in rather good agreement. These results indicate that the pyranometer developed may be used satisfactorily for the measurement of solar radiation in the world.

Key words: Solar radiation, pyranometer, sunshine duration, climatological data.

INTRODUCTION

The growing populations of the world, the fast depleting reserves of fossil fuels, and the awareness of environmental impact have led the researchers to think of alternate sources of energy for a safer life on this earth. Therefore, the whole world is looking for non-exhaustible energy sources for their future. Among all the nonconventional energies, solar energy is the best option if it can be used in a cost effective manner because the technology is also environmentally sound. As the solar energy intercepted by the earth in one year is ten times greater than the total fossil resources including undiscovered and unexplored non-recoverable reserves (Palz, 1977), it is expected that the present worldwide research and development program on solar energy will help to solve the future energy crisis of the world.

Solar radiation is the radiant energy that is emitted by the sun from a nuclear fusion reaction that creates electromagnetic energy. The global radiation is an important parameter necessary for most ecological models and an input for different solar systems. It is the ultimate energy for all ecosystems. Solar radiation data are very important to architects, engineers and scientists for energy-efficient building designs; the development of active and passive solar energy applications; and climatology and pollution studies.

The best way of knowing the amount of global solar radiation at a site is to install pyranometers at different locations in the given region and look after their day-to day maintenance and recording but this method is very expensive. An alternative approach is to correlate the global solar radiation with the meteorological parameters at the place where the data is collected. The resultant correlation may then be used for locations of similar meteorological and geographical characteristics at which solar data are not available.

In many applications of solar energy, the most important parameters that are often needed are the average global solar irradiation and its components. Unfortunately, the measurements of this parameter are done only at a few places. For this reason, there have been attempts at estimating them from theoretical models. Such models include that of Sambo (1985), Awachie and Okeke (1990), Akpabio and Etuk (2004),

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Badmus and Momoh (2005), Hussaini et al. (2005), Iheonu (2001), Arinze and Obi (1983), Falayi and Rabiu (2005), El-Sebaii and Trabea (2005), Babatunde and Aro (1990), and Burari and Sambo (2001) to mention but a few. This correlations estimate the amounts of monthly average solar radiation from more readily available meteorological parameters such as the sunshine duration and extraterrestrial radiation.

Although solar radiation data are available at most meteorological stations, there are still stations in many regions in Nigeria - especially Mubi, in Adamawa State - that suffers from a shortage concerning the solar radiation records; therefore, we present the measurement of solar radiation from a developed reliable model pyranometer and correlated the values with one of the famous predicted model. In the present work, solar radiation measurement and estimation have been done for the first time for Mubi, to utilize solar energy for useful purpose.

The Mubi town has an area of 4728.77 km^2. It is located at latitude 10° 16' and longitude 13° 16'. It is one of the largest towns in Adamawa State, Nigeria. This work will help the energy strategist and planners to utilize solar energy potential to solve the energy deficit in this town of abundant sunshine, throughout the year.

METHODS OF PREDICTION

Various climatic parameters have been used in developing empirical relations for predicting the monthly average global radiation (Nguyen and Pryor, 1997). Among the existing correlations, the data of sunshine duration are widely available in many countries; various formulas based on them have been proposed to determine solar radiation from sunshine duration. The most generally used method was developed by Angstrőm, and later modified by Prescott. The modified version of Angstrőm–Prescott has been the most convenient and widely used correlation for estimating the global radiation. The formula is (Duffie and Beckman, 1994):

$$\frac{H}{H_0} = a + b\frac{S}{S_o} \quad (1)$$

where, H and H_0 are, respectively, the global radiation (MJm^{-2}day^{-1}) and the extraterrestrial solar radiation on a horizontal surface (MJm^{-2}day^{-1}); S and S_0 are, respectively, number of hours measured by the sunshine recorder and the maximum daily sunshine duration (or day length); and a, b are regression constants to be determined.

Regression equation (1) has been found to accurately predict global solar radiation in several locations (Akpabio, 1992). For monthly average, this formula holds (Duffie and Beckman, 1994):

$$\frac{\bar{H}}{\bar{H}_0} = a + b\frac{\bar{S}}{\bar{S}_o} \quad (2)$$

Here, $\bar{H}$ is the monthly average daily global radiation on a horizontal surface (MJm^{-2}day^{-1}), $\bar{H}_o$ is the monthly average daily extraterrestrial radiation on a horizontal surface (MJm^{-2}day^{-1}), $\bar{S}$ is the monthly average daily number of hours of bright sunshine, $\bar{S}_o$ is the monthly average daily maximum number of hours of possible sunshine.

Regression coefficient a and b have been obtained from the relationship given by Tiwari and Sangeeta (1977) and also confirmed by Frere (1980):

$$\begin{aligned} a &= -0.110 + 0.235\cos\phi + 0.323\,(S/S_o) \\ b &= 1.449 - 0.553\cos\phi - 0.694\,(S/S_o) \end{aligned} \quad (3)$$

There are also different methods in evaluating these constants. The extraterrestrial solar radiation on a horizontal surface can be calculated from the following equation (Duffie and Beckman, 1994):

$$H_o = \frac{24\times3600}{\pi} I_{sc}\left[1 + 0.033\cos\left(360\frac{dn}{365}\right)\right]\left[\left(\frac{2\pi\omega_s}{360}\right)\sin\phi\sin\delta + \cos\phi\cos\delta\sin\omega_s\right] \quad (4)$$

The value of 1367 Wm^{-2} has been recommended for solar constant I_{sc} (Frolich and Brusca, 1981). The hour angle ω_s for horizontal surface is given as (Duffie and Becman, 1994):

$$\omega_s = \cos^{-1}(-\tan\phi\tan\delta) \quad (5)$$

Declination is calculated as (Cooper, 1969):

$$\delta = 23.45\sin\left(360\frac{284 + dn}{365}\right) \quad (6)$$

Where *dn* is the day of the year from January 1 to December 31.

The day length S_0 is the number of hours of sunshine or darkness within the 24 h in a given day. For a horizontal surface, it is given by (Duffie and Becman, 1994):

$$S_o = \frac{2}{15}\cos^{-1}(-\tan\phi\tan\delta) = \frac{2}{15}\omega_s \quad (7)$$

(From Equation (5))

Instrumentation design for the measurement

The instrument used for the measurement of solar radiation is a reliable model pyranometer (RMP001) which we developed. The pyranometer is shown in Figure 1 as an outline in its housing and as a circuit diagram in Figure 2. The sensor element is a silicon diode, mounted on a plastic base, covered with a Teflon diffuser. The whole unit is placed on a base with a level control to ensure horizontality. The best detector was chosen based on the characteristics in the datasheets supplied by the manufacturers. The most suitable photodiode for this application was BPW21 with responsivity, sensitive area and noise equivalent power of 0.34 A/W, 7.34 × 10^{-6} m^2 and 7.2 × 10^{-14} W/Hz$^{1/2}$ respectively.

Construction of solar cell – based pyranometers are conceptually very simple and cheap. However, they require care design based on an understanding of the underlying physical principles. The

Figure 1. Picture of the constructed reliable model pyranometer (RMP001).

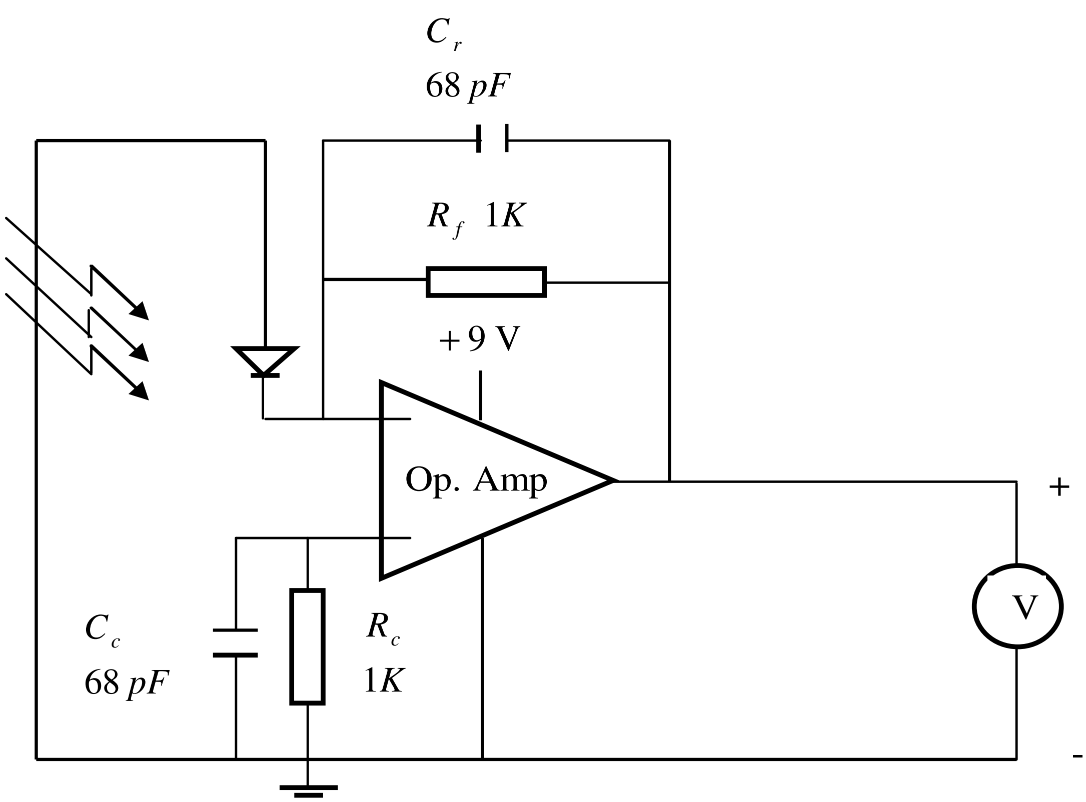

Figure 2. Pyranometer circuit diagram.

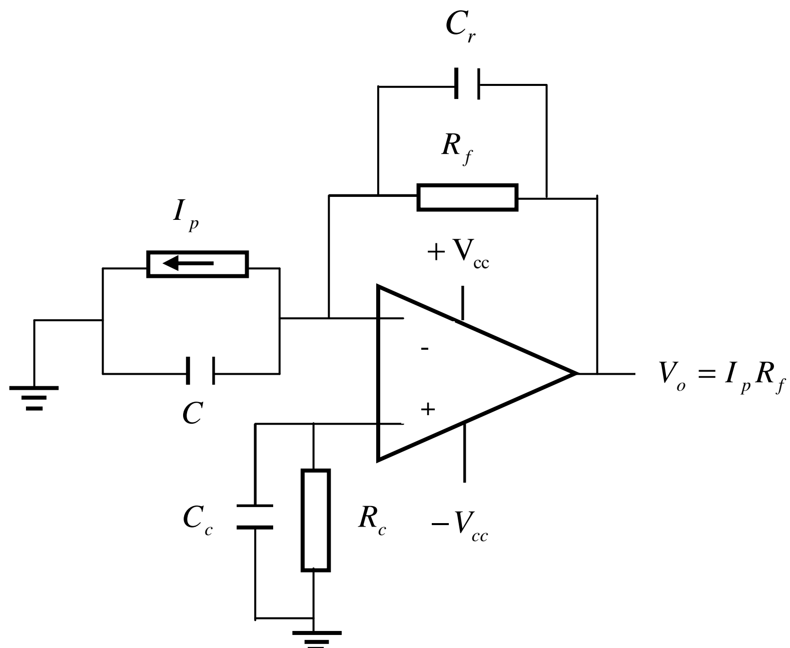

Figure 3. Transimpedance amplifier circuitry.

developed pyranometer generates an electrical signal proportional to the irradiance received and converts the small current received from the detector to a voltage and amplifies it to a voltmeter.

The transimpedance amplifier shown in Figure 3 is configured around the LTC1051 operational amplifier (OPAM) in order to condition signal from the photodiode as shown in Figure 2. In this circuit, I_p is the photocurrent from the diode and *C* its parasitic capacitor. C_c, R_c *Cr* are compensation capacitor, correction resistor and stabilization capacitor respectively. The feedback resistor R_f fixes the DC gain in the circuit in order to obtain an output from $V_0 = I_p R_f$.

An irradiance of 1,200 W/m^2 obtained from a 200-W quartz tungsten halogen lamp is used to calculate the value of R_f. For this, the BPW21 photodiode produces the photocurrent $Ip = 3.0 \times 10^{-3}$ A (that is, *Ip*.= irradiance × sensitive area × responsivity). In order to carry out precise adjustment for maximum analogue-to-digital converter of 3 V, the value of *Rf* implemented is 1 KΩ (from $R_f = V_o/I_p$).*Rc* with value of 1 KΩ is connected to the non-inverting input of the OPAM for correcting the DC error due to polarization currents. This resistor has a detrimental effect in terms of noise which is amplified (Graeme, 1996); hence, a 68 *pF* compensation capacitor *Cc* is connected in parallel with it. The parasitic capacitor on the photodiode BPW21, *C*, is 580 *pF* which influence the stability of the assembly. Finally, a 68 *pF* capacitor *Cr* is connected in parallel with the feedback resistor R_f to perfect the stability of the amplifier (Figure 2).

The reliable model pyranometer (RMP001) was then calibrated against a reference high quality pyranometer, Kipp and Zonen CMP 3 whose calibration was trusted (14.71± 0.36 µV^{-1} Wm^{-2}). The conversion of the output from RMP001 from volts to Wm^{-2} was done to obtain a calibration constant of 5230±0.02 Wm^{-2} (Figure 4).

Materials and measurement procedures

The daily sunshine hour data were collected for a period of one year (from 1st November, 2008 to 31st October, 2009) from Adamawa State University's meteorological station at Mubi. The relevant meteorological and solar radiation data like H, H_o, S/S_o, ω, δ, a and b calculated from equations (1) to (7) are presented. The measurement of solar radiation at 1 min intervals with the aid of the reliable model pyranometer was recorded for Mubi, Adamawa State, Nigeria, using a data logger. The logger has a USB interface with proprietary software for communicating with a computer. The data was stored in a propriety binary format and later saved as a text file that was imported into excel. Daily average value of solar radiation was then determined in Wm^{-2}. The global solar radiation data measured in (MJm^{-2} day^{-1}) was converted to (Wm^{-2}) using a factor of 11.6 Wm^{-2} (http://www.fao.org/docrep). This is presented in Table 1.

The comparison methods

In this study, two statistical tests, mean bias error (MBE) and root mean bias error (RMSE), and t-statistic were used to evaluate the accuracy of the constructed reliable model pyranometer.

Mean bias error

The mean bias error is defined as:

$$MBE = \frac{1}{n}\sum_{i=1}^{n} d_i \tag{8}$$

where n is the number of data pairs and d_i is the difference between the measured and predicted values. This test provides information on the long-term performance. A low MBE is desired. A positive value gives the average amount of over-insolation in the measured value and vice-versa. A drawback of this test is that over-insolation of an individual observation will cancel under-insolation in a

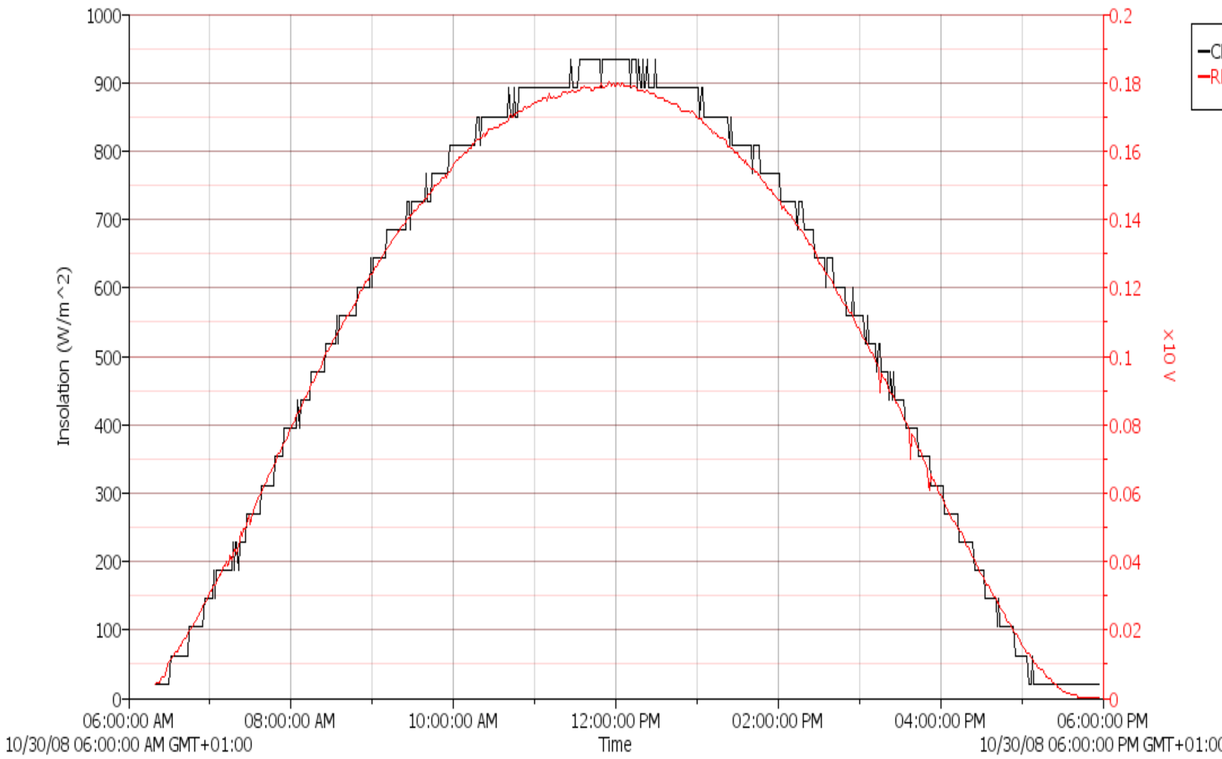

Figure 4. Graph of solar radiation measured with CMP3 and RMP001verses time on 30th October, 2008.

Table 1. Correlation between predicted and measured values of monthly average daily global radiation.

Month	$\bar{S}/\bar{S}_o$	a	b	$\bar{H}_o$ MJm^{-2} d^{-1}	$\bar{H}$ Predicted MJm^{-2} d^{-1}	$\bar{H}$ Predicted Wm^{-2}	$\bar{H}$ Measured Wm^{-2}
Nov. 2008	0.63	0.33	0.47	32.31	19.91	230.96	237.78
Dec. 2008	0.62	0.32	0.47	30.94	18.92	219.47	211.68
Jan. 2009	0.62	0.32	0.47	31.78	19.43	225.39	218.04
Feb. 2009	0.65	0.33	0.45	34.24	21.31	247.20	241.84
Mar. 2009	0.67	0.34	0.44	36.69	23.29	270.16	262.99
Apr. 2009	0.48	0.28	0.57	37.87	20.96	243.19	229.51
May. 2009	0.47	0.27	0.58	37.60	20.40	236.66	217.40
Jun. 2009	0.51	0.29	0.55	37.06	21.14	245.22	234.45
Jul. 2009	0.48	0.28	0.57	37.14	20.56	238.50	212.83
Aug. 2009	0.39	0.25	0.63	37.51	18.59	215.64	196.73
Sept,2009	0.41	0.25	0.62	36.95	18.63	216.11	204.04
Oct, 2009	0.47	0.27	0.58	34.89	18.93	219.59	206.00

separate observation.

Root mean square error

The root mean square error is defined as:

$$RMSE = \left(\frac{1}{n} \sum_{i=1}^{n} d_i^2 \right)^{1/2} \tag{9}$$

This test provides information on the short-term performance of the correlations by allowing a term-by-term comparison of the actual

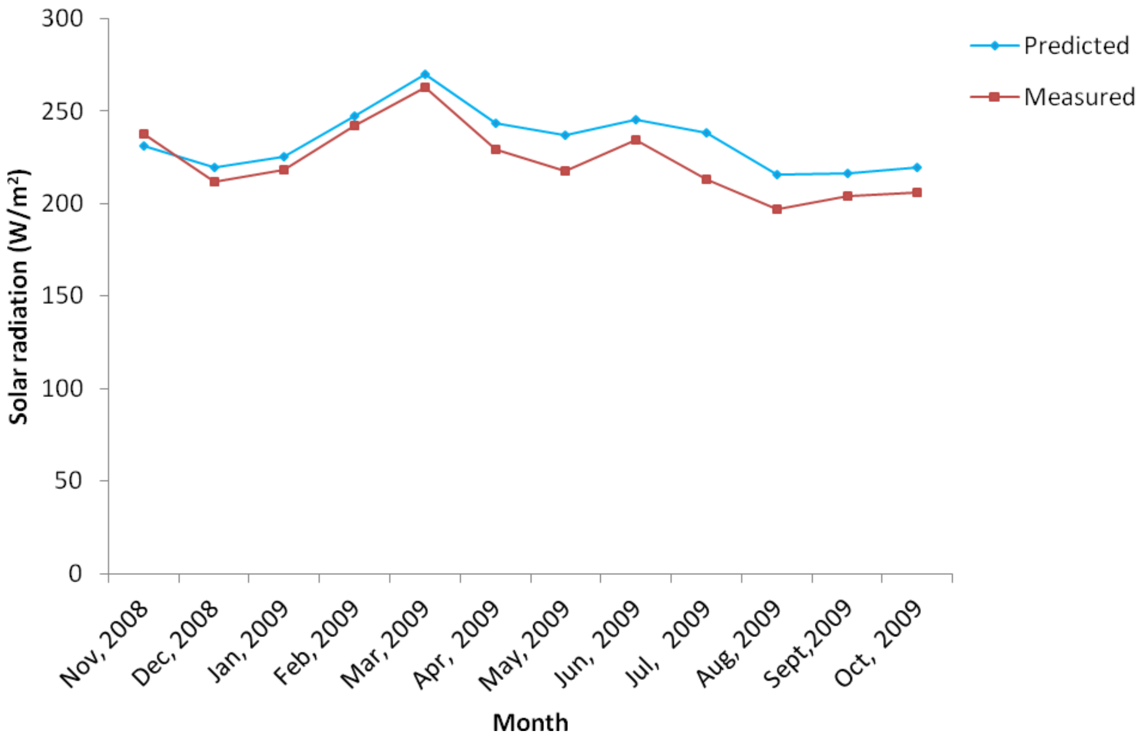

Figure 5. The predicted and measured values of solar radiation.

deviation between the measured value and the predicted value; the smaller the value, the better the pyranometer's performance. However, a few large errors in the sum can produce a significant increase in RMSE.

It is obvious that each test by itself may not be an adequate indicator of a pyranometer's performance. It is possible to have a large RMSE value and at the same time a small MBE (a large scatter about the line of perfect measurement).It is also possible to have a relatively small RMSE and a relatively large MBE (consistently small over- or under measurement).

Although these statistical indictors generally provide a reasonable procedure to compare models, they do not objectively indicate whether a model's measures are statistically significant, that is, not significantly different from their predicted counterparts. In this article, an additional statistical indicator, the t-statistic, was used. The statistical indicator allows models to be compared and at the same time, indicate whether or not a model's measures are statistically significant at a particular confidence level (Stone, 1993). It was seen that the t-statistic used in addition to the RMSE and MBE gave more reliable and explanatory results (Togrul, 1998).

t-statistic

t-statistic is defined as (Walpole and Myers, 1989):

$$t = \left[\frac{(n-1)MBE^2}{RMSE^2 - MBE^2} \right]^{1/2} \tag{10}$$

The smaller the value of t, the better is the model's performance. To determine whether a model's predicts are statistically significant, one simply has to determine a critical t value obtainable from standard statistical tables, that is, $t_{\alpha/2}$ at the α level of significance and (n-1) degrees- of- freedom. For the model's predicts to be judged statistically significant at the $1-\alpha$ confidence level, the calculated t value must be less than the critical t value.

RESULTS AND DISCUSSION

Table 1 shows the values of possible fraction of sunshine $\bar{S}/\bar{S}_o$, monthly average daily extraterrestrial radiation on a horizontal surface $\bar{H}_o$, predicted and measured monthly average daily global radiation on a horizontal surface $\bar{H}$. The regression coefficient a and b are also presented in Table 1.

A close examination of Figure 5 shows that the maximum predicted and measured values are 270.16 and 262.99 Wm^{-2}, respectively, occurred in the month of March during winter. The minimum values predicted and measured are 215.64 and 196.73 Wm^{-2} respectively. They occurred in August during summer period.

It is possible to observe that the regression coefficients show variations during the course of the year as shown in Table 1. Variations in a and b values are explained as a consequence of periodic climatological variations in the atmosphere. The a estimates varies from 0.34 to 0.25

Table 2. Statistical test results.

MBE Wm^{-2}	RMSE Wm^{-2}	*t*
-11.23	38.91	1.0

which is maximum in March and minimum in August; while the b coefficient ranges from 0.44 to 0.63, being highest in August and lowest in March. It is clearly observed that a is inversely proportional to b.

According to the statistical test results, the values of RMSE and MBE are in the acceptable ranges. As shown in Table 2, the values of RMSE and MBE are 38.91 and -11.23 Wm^{-2}, respectively.

The comparison between the measurement and estimation was carried out according to the t value, because this statistic is more effective for determining the statistical properties. For all the whole period, the calculated t value is 1.0 which is less than the critical t value (1.96).

Conclusion

The correlations between measured and predicted values of solar radiation at Mubi were carried out in this work. The average RMSE and MBE for the comparison between measured and predicted global radiation are 38.91 and -11.23 Wm^{-2}, respectively. These values are in the acceptable ranges. The t-statistic depends on both, the RMSE and MBE, and it was recommended that it should be used in conjunction with these indicators in order to help to assess a model's performance more reliably. These results indicate that the pyranometer developed in this paper may be used satisfactorily for the measurement of solar radiation in the world.

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