

RESEARCH ARTICLE

Engineering

Statistical Approach to select the Best Suitable Solar Model for Global Radiation: Case Study of Karachi, Pakistan

Enfoque Estadístico para la Selección de un modelo solar Adecuado de Radiación Global: Caso de Karachi, Pakistán

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Editors: Robert Paul Salazar

How to cite: Muhammad Uzair et al., Statistical Approach to select the Best Suitable Solar Model for Global Radiation: Case Study of Karachi, Pakistan, TECCIENCIA, Vol. 17, No. 32, 17-27, 2022
DOI:<http://dx.doi.org/10.18180/tecciencia.2022.32.2>

Abstract. Utilization of solar energy for the fulfillment of daily routine tasks has gained a lot of interest in the recent past. The complete utilization can be accomplished only if proper solar data is available for a particular site. The measurement of solar data is expensive and time consuming. Different empirical correlations are available for the estimation of solar radiations on a particular site. In this research, monthly average daily solar radiation on horizontal surface is compared with measured data available as typical metrological year, TMY2, and estimated from the different solar models available for Karachi. The models studied are Ahmad models, Raja Models, Hargreaves Model and Black model. The estimation of different empirical correlations and National Aeronautics and Space Administration (NASA) predictions are compared with the measured values. The comparison was done by using statistical techniques like MAPE, MBE, RMSE and t-stats. The results revealed that Hargreaves model is the best model to estimate global radiation for Karachi with minimum value of t-stats while Raja 3 model is the most inappropriate model with highest value of MAPE, RMSE, MBE and t-stat. Overall, the already established empirical correlations can be used for the estimation of solar energy for Karachi for complete utilization of solar energy with minimum errors.

Keywords: solar Energy, solar Models, horizontal surface, Karachi, statistical check.

1 | RESUMEN

La utilización de la energía solar dentro de las tareas rutinarias diarias ha ganado interés en el pasado reciente. La utilización completa se puede lograr solo si se dispone de datos solares adecuados para un sitio en particular.

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La medición de datos solares es costosa y requiere mucho tiempo. Están disponibles diferentes correlaciones empíricas para la estimación de las radiaciones solares en un sitio en particular. En este estudio, la radiación solar diaria promedio mensual en la superficie horizontal se compara con los datos medidos disponibles como año metrológico típico (*typical metrological year*) TMY2, y se estima a partir de los diferentes modelos solares disponibles para Karachi. Los modelos estudiados son los modelos Ahmad, Raja Models, Hargreaves Model y Black model. La estimación de diferentes correlaciones empíricas y las predicciones de la Administración Nacional de Aeronáutica y del Espacio (NASA) se comparan con los valores medidos. La comparación se realizó utilizando técnicas estadísticas como MAPE, MBE, RMSE y t-stats. Los resultados revelaron que el modelo de Hargreaves es el mejor entre ellos para estimar la radiación global para Karachi con un valor mínimo de t-stat. Por otro lado, se concluyó que el modelo Raja 3 es el más inapropiado con el valor más alto de MAPE, RMSE, MBE y t-stat. En general, las correlaciones empíricas establecidas se pueden utilizar para la estimación de la energía solar para Karachi para la utilización completa de la energía solar con errores mínimos.

Palabras clave: energía solar, modelos solares, superficie horizontal, Karachi, verificación estadística.

2 | INTRODUCTION

Energy scenario in Pakistan is substandard from the past few decades. The energy shortfall is around 4500 Megawatt since the last five years [1] which is considered to be the hindrance in economic, scientific and technical growth. In general, the energy requirement in Pakistan is fulfilled by importing 135,201 barrels of crude oil per day [2] which ultimately results in huge financial deficit. Also, Pakistan is located in a region which is greatly affected by global warming [3], [4]. In this scenario, the renewable energy systems have gained a lot of interest to overcome not only on the energy crisis but also to tackle the global warming effects.

Fig. 1 shows the electricity production techniques in Pakistan. It is evident that major portion of the energy is fulfilled by thermal energy sources, although the share of hydro is appreciable but still there is a very little share of other renewable energy techniques. A lot of research to determine the potential, challenges and opportunities of wind, solar, biomass, hydro and biomass in Pakistan has been conducted [5, 6, 7, 8, 9, 10, 11]. Solar energy among all other renewable energy technologies is widely acceptable and adaptable by the local community due to its availability, simplicity and low operation expenditures [12, 13, 14, 15]. One of the major problems associated with the solar energy is to determine the amount of energy available on particular site for proper designing and assessment of conversion devices [16]. Solar radiation can be classified as extra-terrestrial and terrestrial radiation. Extra-terrestrial radiations are received without the presence of the atmosphere. On the other hand, the radiation received on earth's surface after passing it through the atmosphere are known as terrestrial radiation. Extra-terrestrial radiation can be calculated by using the formula presented by Klein [17] while terrestrial radiation cannot be calculated, but measured or estimated by using the different statistical models. The measurement of solar radiation includes the installation of solar radiation measuring setup on the particular site then data recording and then analysis for installation of solar energy conversion process but the process is expensive and is time consuming [18] while solar radiation can be estimated for a particular site by using the already available data [19]. Different empirical correlations are available for estimating the solar radiation on the horizontal surface. These empirical correlations provide the estimated amount of radiation on any particular site by already available data measured by weather station on that particular site. These empirical correlations can be based on the following parameters [20]:

- Solar geometry of that particular site.
- Geographical placement of that particular site (latitude, longitude etc.).
- Environment and ambient conditions.

A lot of researchers have presented different types of empirical correlations for estimating the amount of terrestrial radiation on a particular site and is difficult to select the best suitable model for that particular location [21]. The empirical correlations used to estimate the monthly average daily solar radiation on the

horizontal surface are based on the Angstrom model [22]. The model is linear regression model and is based on extra-terrestrial monthly average daily global radiation on horizontal surface, day length and sun shine hours. Paulescu [23] has reviewed Angstrom model for 59 different locations of Europe and found that Angstrom model can predict approximately 90% of the changeability of clearness index in European territory. Ahmad and Ulfat [24] proposed the first order and second order Angstrom model for Karachi and revealed that percentage error for the equations found is below 5% which clearly shows that Angstrom model can be provide a good approximation for Karachi. Raja and Tiwari [25] have also developed the model for Pakistan. The model is based on extra-terrestrial radiations, sun shine hours, day length and latitude of the location. From the literature, one can conclude that there are numerous empirical available to estimate the global radiation on horizontal surface at a particular site [21] but is difficult to select the best correlation. This study deals with the comparative study to select the best suitable model to estimate the radiation on horizontal surface. The results obtained from the correlations are compared with measured data and with the data available on NASA website.

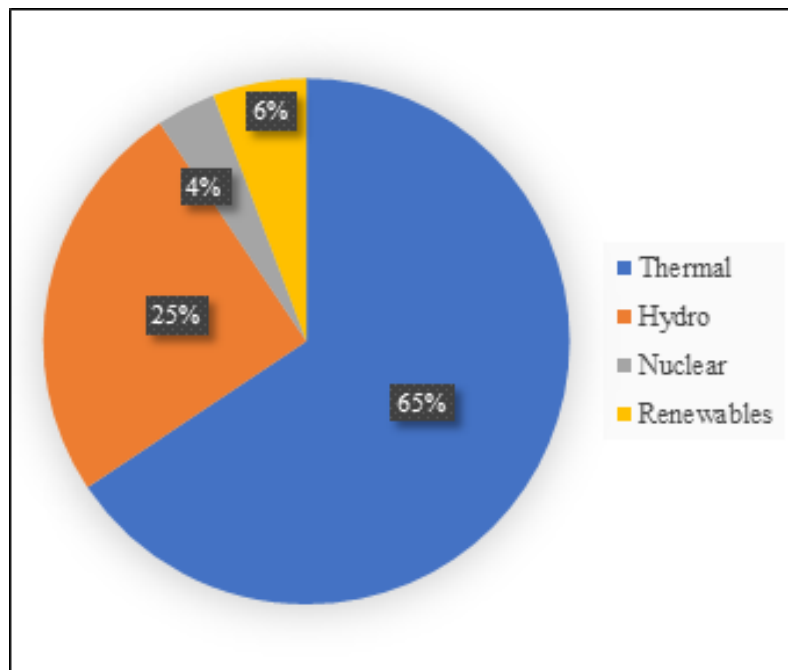


FIG. 1 Energy Mix of Pakistan in 2019 [26].

3 | METHODOLOGY

Karachi is considered for this study with latitude 24.86° N and longitude 67.00° E. The average temperature of Karachi is 30°C [27]. On the map of Pakistan, Karachi is located in southern part at the sea shore (Fig. 2). Karachi covers an area of 3780 square kilometer and the weather is hot and humid.

Monthly average daily, terrestrial radiation on the horizontal surface can be estimated by using the following regression correlation as proposed by Angstrom [22] as follows

$$\frac{\bar{H}}{\bar{H}_o} = a + b \left(\frac{S}{S_{max}} \right) \quad (1)$$

here, \bar{H}_o , is known as monthly average daily extra-terrestrial radiation on horizontal surface and can be

calculated by Klein's formula [17] and S_{max} is the average day length. Parameters a and b are known as regression coefficient and have some physical meaning. Here a is the ratio of diffuse radiation to that of extra-terrestrial radiation and b is the ratio of direct radiation to that of extra-terrestrial radiation [28]

$$\bar{H}_o = \frac{24}{\pi} \times G_{sc} \left[1 + 0.033 \cos \left(\frac{360N}{365} \right) \right] \times \left(\frac{\pi\omega_s}{180} \sin \delta \sin \phi + \cos \phi \cos \delta \sin \omega_s \right) \quad (2)$$

where $G_{sc} = 1367W/m^2$ is the solar constant, N is the number of the year, ω_s is the sunset hour angle for the average day of the month, ϕ is the location's latitude and δ is the solar declination angle.

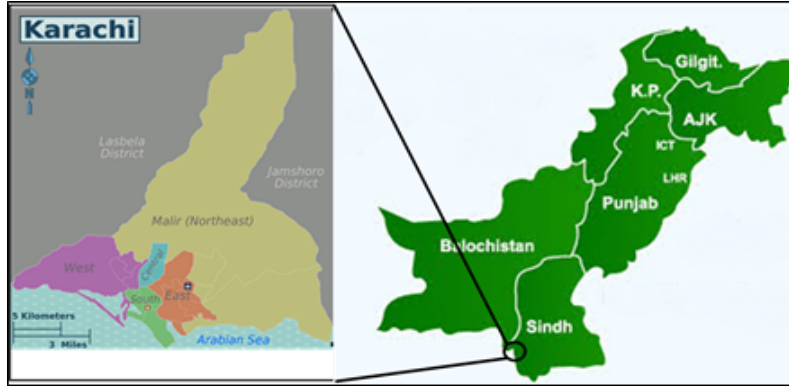


FIG. 2 Study location of Karachi [29].

The solar declination angle can be calculated using Coopers' equation [30]

$$\delta = 23.34 \sin \left(\frac{360}{365} (284 + N) \right). \quad (3)$$

The sunset hour angle can be calculated by using the knowledge of latitude and declination angle [31]

$$\omega_s = \arccos(-\tan \phi \tan \delta). \quad (4)$$

The average day length can be calculated as

$$S_{max} = \frac{2}{15} \omega_s. \quad (5)$$

For Karachi, first order and second order Regression based Angstrom model was solved by Ahmad and Ulfat [24] as:

$$\frac{\bar{H}_g}{\bar{H}_o} = 0.324 + 0.405 \left(\frac{S}{S_{max}} \right), \quad \text{and} \quad (6)$$

$$\frac{\bar{H}_g}{\bar{H}_o} = 0.348 + 0.320 \left(\frac{S}{S_{max}} \right) + 0.07 \left(\frac{S}{S_{max}} \right)^2. \quad (7)$$

The ratio S/S_{max} for Karachi is shown in Fig. 3. Raja and Tiwari [25] have also presented the empirical correlation for Pakistan for the estimation of terrestrial radiations on horizontal surface

$$\frac{\bar{H}_g}{\bar{H}_o} = 0.335 + 0.367 \left(\frac{S}{S_{max}} \right), \quad (8)$$

$$\frac{\bar{H}_g}{\bar{H}_o} = 0.388 \cos \phi + 0.367 \left(\frac{S}{S_{max}} \right), \quad \text{and} \quad (9)$$

$$\frac{\bar{H}_g}{\bar{H}_o} = 0.388 \cos \phi + 0.407 \left(\frac{S}{S_{max}} \right). \quad (10)$$

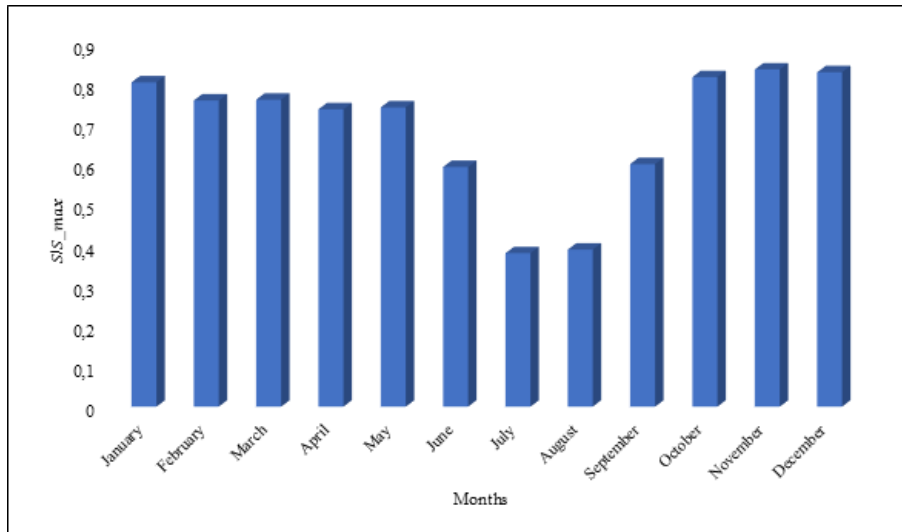


FIG. 3 Ratio of S/S_{max} for all months in Karachi.

Hargreaves and Samani [32] have proposed solar model for estimation of terrestrial radiations on horizontal surface based on maximum and minimum temperature

$$\frac{\bar{H}_g}{\bar{H}_o} = a \sqrt{T_{max} - T_{min}}. \quad (11)$$

Black [33] has developed a model for estimation of terrestrial radiations on horizontal surface based on mean total cloud cover during day time

$$\frac{\bar{H}_g}{\bar{H}_o} = 0.803 - 0.34C - 0.458C^2 \quad (12)$$

where C is known as the mean cloud cover during the sunshine time. The study is conducted to evaluate the solar radiation on horizontal surface for Karachi using different models available and then compared with the TMY2 data. The comparison is done by using the statistical techniques (Mean Absolute Percentage Error

(MAPE); Mean Bias Error (MBE); Root Mean Square Error (RMSE) and t-statistics). MAPE is an indicator which shows the accuracy of the data as a percentage of error and is given by

$$MAPE = \frac{1}{n} \sum \left| \frac{\bar{H} - \bar{H}_p}{\bar{H}} \right| \times 100 \quad (13)$$

Here \bar{H} is the TMY2 value, \bar{H}_p is the value obtained from the empirical correlation and n is the number of observations. The ideal value for MAPE is zero. MBE provides the comparison of the actual deviation between TMY2 and predicted values. It provides information on long-term performance and is given by

$$MBE = \frac{1}{n} \sum \left(\frac{\bar{H} - \bar{H}_p}{\bar{H}} \right). \quad (14)$$

Here \bar{H} is the TMY2 value, \bar{H}_p is the value obtained from the empirical correlation and n is the number of observations. The ideal value for MBE is zero. RMSE provides the comparison of the actual deviation between TMY2 and predicted values. It provides information on short-term performance and is given by

$$RMSE = \sqrt{\frac{1}{n} \sum \left(\frac{\bar{H} - \bar{H}_p}{\bar{H}} \right)^2}. \quad (15)$$

It might be possible that MBE and RMSE can provide false direction to select the solar model. These errors do not provide the information about the statistical significance of the correlations. The t-statistics provides a comparison of models as well specifies the significance of the output of the model. The t-statistics can be performed using

$$t - Stat = \sqrt{\frac{(n-1)MBE^2}{RMSE^2 - MBE^2}}. \quad (16)$$

The smaller values of above-mentioned errors and tests (MAPE, MBE, RMSE and t-statistics test provide accurate output from the model [19], [21].

4 | RESULTS AND DISCUSSION

The solar declination angle was calculated by Eq. (3) whose results are well defined in the literature [31]. The declination angle varies day by day but on a particular day, it has fixed value for all the locations. The amount of extra-terrestrial radiations incident in Karachi was calculated by Eq. (2) and is shown in Fig. 4. The maximum radiations received was observed in the month of June with maximum value around $11000kWh/m^2$ -day. While, the minimum value was found to be in the month of December and is around $6300kWh/m^2$ -day.

The monthly average daily global terrestrial radiations on horizontal surface in Karachi obtained from Eqs. 6-12 and NASA values were compared against the data available as typical metrological year (TMY2) file. The performance of different models varied throughout the year. The values obtained from empirical correlations, and TMY2 are shown in Fig. ???. Comparing all these models, it was obvious that these models were providing over-estimated values with the percentage error of up to 12% (Fig. 7) except the models of Black and Raja 3. Also, the irregular patterns were observed in the month of July and August. These errors occurred due to the cloud cover in those months and a smaller number of sun shine hours. During these months, only Black's model performed better than any other selected models. Except July and August, for remaining months, all models estimated the results within 15% error compared with measured data. The monthly average daily terrestrial

radiations obtained in all the months have presented in Fig. 7. The estimation from 3rd correlation of Raja has shown the highest value while minimum is received from Hargreaves. The estimation shows slightly over value than the recorded values at weather station.

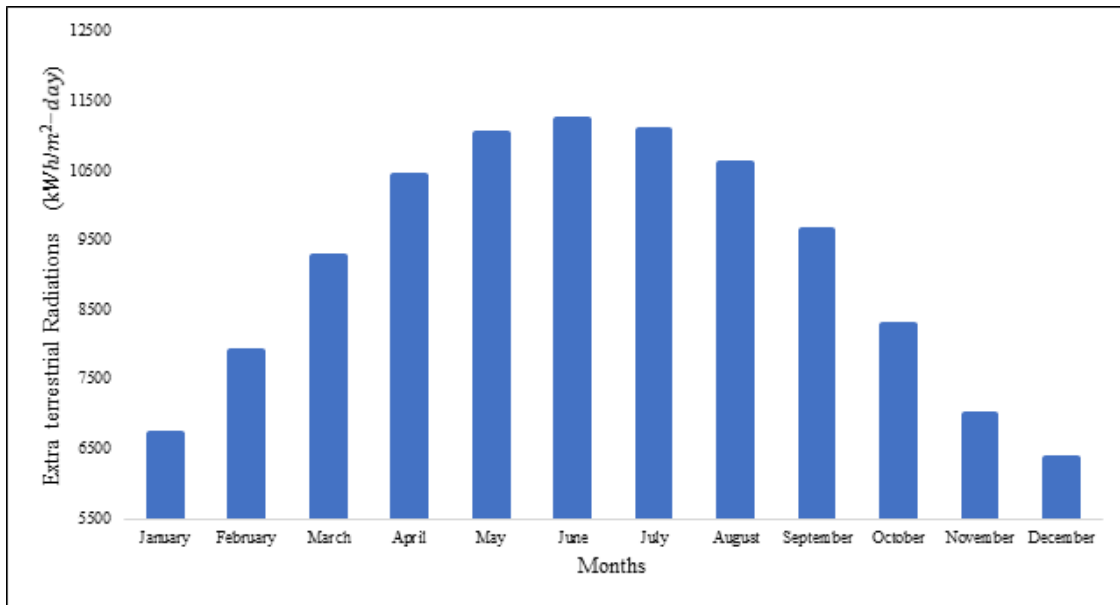


FIG. 4 Extra-terrestrial radiations incident in Karachi throughout the year.

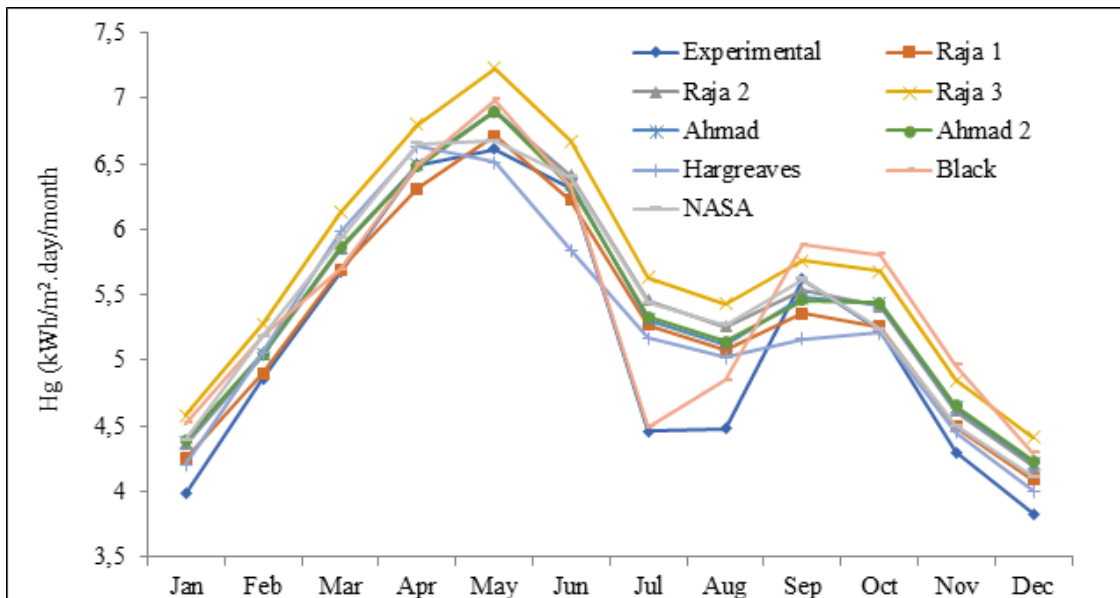


FIG. 5 Variation of terrestrial radiations.

To evaluate the accuracy of empirical correlations, statistical techniques have used. The MAPE, and MBE of different models and NASA values have calculated with respect to the TMY2 values as shown in Figures 8 -9. While the RMSE of the models and NASA values are calculated with respect to the measured values and provide information on the long-term performance (Figure 10) MAPE, MBE and RMSE are not adequate indicator in order to judge the accuracy of the models, it might be possible that at a same time there is small

value of MBE but large value of RMSE or vice versa which may lead towards the wrong decision [27].

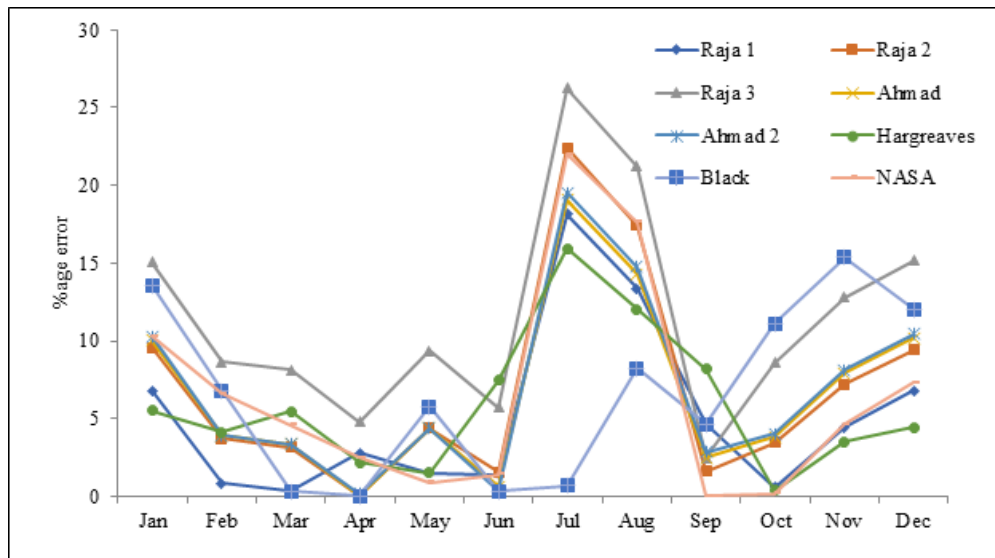


FIG. 6 Month-wise Percentage Error.

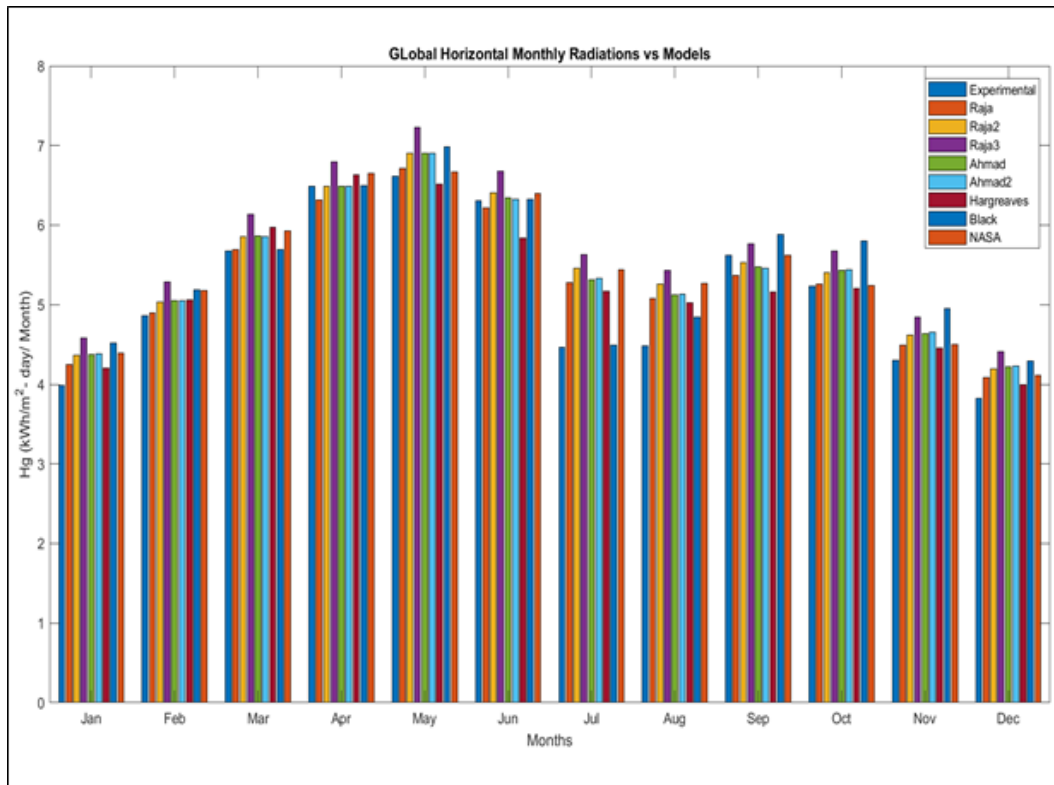


FIG. 7 Variation of terrestrial radiations obtained from models, NASA and TMY2 data in all the months.

So, t-Statistics is more reliable and accurate tool to check the accuracy of the model in comparison of RMSE and MBE. The smallest value of t-stats shows the highest accuracy of the model. From Fig. 11, for Raja 1, Raja 2, Raja 3, Ahmad 1, Ahmad 2, Hargreaves, Black and NASA are 1.68, 3.4, 6.86, 3.56, 3.45, 1.13, 4.42

and 3.36 respectively.

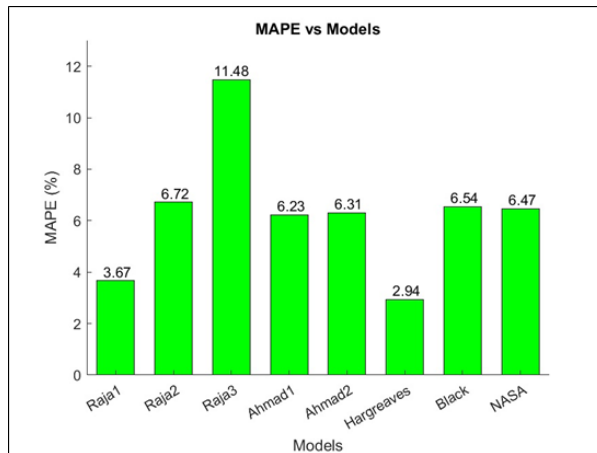


FIG. 8 MAPE of models and NASA with respect to TMY2 values.

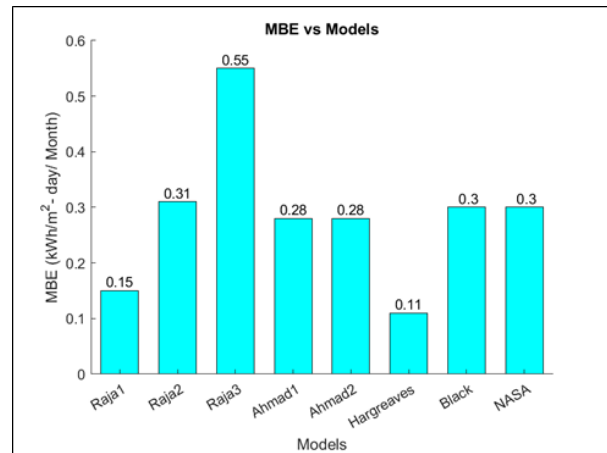


FIG. 9 MBE of models and NASA with respect to TMY2 values.

In order to statistically significant estimation from the model, the t-value should be less the critical value associated with confidence level. With a significance level of 0.05, only two models (Raja1 and Hargreaves) showed the values less than the critical value of 2.09, providing the statistically significant results over the whole year. By relaxing the confidence level, other models will also provide the acceptable results.

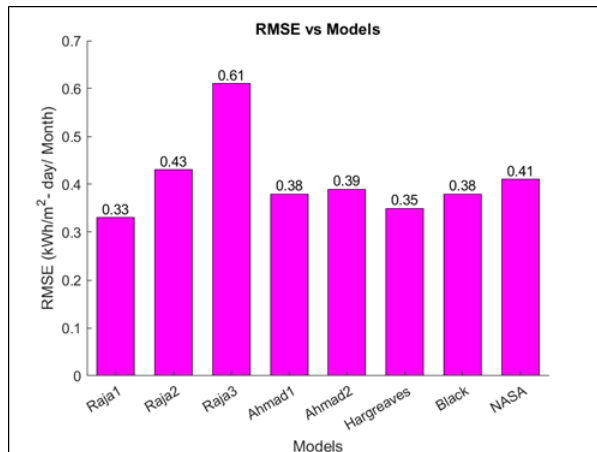


FIG. 10 RMSE of models and NASA with respect to TMY2 values.

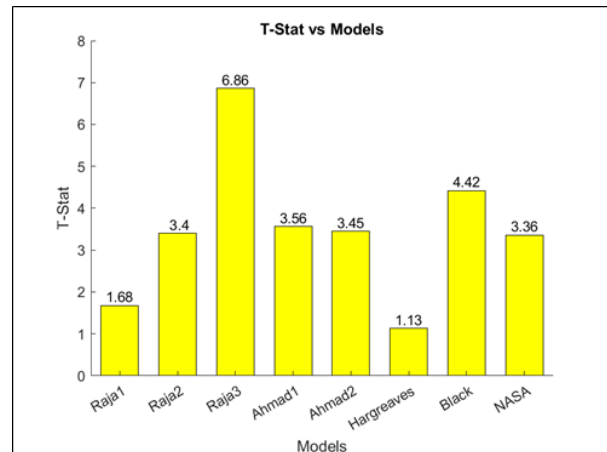


FIG. 11 t-stats of models and NASA with respect to TMY2 values.

Conclusion

The monthly average daily global radiation on horizontal surface in Karachi is TMY2ly measured and estimated from the different empirical correlations. The estimated values of models and NASA are compared via statistical techniques like MAPE, MBE, RMSE and t-stats. The lowest value of MAPE is occurred for Hargreaves model with 2.94 % while maximum is occurred for Raja 3 with 11.48%. The lowest value of MBE is occurred for Hargreaves model with 0.11kWh/m²-day while maximum is occurred for Raja 3 with 0.55h/m² - day. The lowest value of RMSE is occurred for Raja1 model with 0.33kWh/m²-day while maximum is occurred for Raja 3 with 0.61kWh/m²-day. Alone MAPE, MBE and RMSE are not sufficient for determination of accuracy of the model. t-stat value was used for determination of accuracy of the model, the lowest value has achieved for

Hargreaves with 1.33 while maximum has achieved for Raja 3 with 6.86. On the basis of results obtained, one can conclude that Hargreaves is the best model for estimation of monthly average daily global radiations on the horizontal surface with minimum error while Raja 3 can lead towards the wrong estimation with maximum error. Overall, the available models can be used for the prediction of global radiations with minimum errors.

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