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Review on mathematical models for the prediction of Solar radiation

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ABSTRACT

Global Solar Radiation (GSR) data is important for all solar energy based applications, mainly to forecast the output power of solar PV system in case of renewable energy integration in to the existing grid. The solar radiation components are measured using pyranometer, solarimeter and pyroheliometer and so on. It is not practically possible to install this radiation measuring instruments at all the locations due to the cost and difficulty in measurements. Hence the availability of solar radiation data is limited to few meteorological stations especially in the developing country like India. Therefore, it is necessary to develop mathematical models to predict the solar radiation to eliminate the costly pyranometer. In this paper, the review of mathematical models using trigonometric functions for the prediction of global solar radiation is presented. The mathematical models are applicable wherever the radiation data is unavailable. From the review results, it is concluded that mathematical model with both sine and cosine wave equation gives good prediction accuracy with correlation coefficient of 0.95.

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1. INTRODUCTION

Solar energy is one of the most important renewable energy sources for world's energy demand. Assessment of solar energy through the available solar radiation data is the first step towards the solar energy applications. Accurate knowledge of solar radiation is necessary for different solar energy applications. In, India, solar radiation data is not easily available due to the financial costs involved in the acquisition, installation and difficulties in measurement techniques and maintenance of measuring equipments. For all solar energy applications solar radiation is considered as the most important parameter. Solar radiation is the radiant energy emitted by the Sun in the form of electromagnetic waves. Figure 1 shows the instruments for measuring solar radiation components namely direct, diffuse and global solar radiation. Direct normal radiation is measured by a pyrheliometer and diffuse radiation by a shaded pyranometer. Global solar radiation is the sum of direct and diffuse radiation which is measured by a pyranometer. Solar radiation is measured only at a few locations due to the high cost involved in the purchase of these measuring equipments and maintenance thereof. Indian Meteorological Department (IMD), Pune provides data for quite a few stations in India, which is considered as the base data for the research purpose. Figure 2 shows the network of radiation stations of IMD, Pune. In 2011 MNRE has erected a network of 51 solar radiation measurement stations namely Solar Radiation Resource Assessment (SRRA) project at Centre for Wind Energy Technology(C-WET). In Tamil Nadu only seven solar radiation measuring stations are available. Table 1 presents the state wise SRRA stations established to measure the solar radiation components. These stations are measuring direct, diffuse and global irradiance. Indeed despite the continuous efforts to launch more solar radiation measurement stations in recent years, the number of stations measuring the solar radiation data is still restricted. In view of the above said factors, it is rather more economical to develop methods to estimate the GSR without using the costly measuring equipments.

Table 1. State Wise SRRA Stations Chart

S.No	State/UT	Number of stations established
1	Tamil Nadu	7
2	Karnataka	6
3	Andhra Pradesh	5
4	Maharashtra	3
5	Madhya Pradesh	3
6	Chhattisgarh	1
7	Gujarat	11
8	Rajasthan	12
9	Haryana	1
10	Jammu & Kashmir	1
11	Puducherry	1
	Total	51

Direct Normal Radiation Measured by **Pyrheliometer**

Diffuse Radiation Measured by **Shaded Pyranometer**

Global Solar Radiation Measured by **Pyranometer**

Figure 1. Instruments for Measuring Solar Radiation Components

Many Countries are increasing their renewable energy generation capacity as an alternative to conventional energy sources to avoid the dependence on the fossil fuels [1]. In addition, the use of renewable energy generation by solar PV will reduce CO2 emission to the environment [2]. Solar radiation data is essential for all solar energy based applications [3-4]. Several solar radiation prediction models are available in the literature to predict the solar radiation [5]. Various solar radiation models such as clear sky models [6-7], empirical models [8-9], solar radiation models using artificial intelligence techniques such as ANN [10-12], ANFIS [13-15], genetic algorithm [16], machine learning techniques [17-19] and other hybrid models [20] are reported in the literature. A comprehensive comparison of eight clear sky models against 16 independent data banks was published by Ineichen in 2006. Clear sky models are not suitable for radiation estimation under cloudy sky condition. Meteorological data based solar radiation models are the most commonly used models for radiation estimation which requires tedious data feeding work. GA technique is applied to estimate monthly average daily global solar radiation on horizontal surface [21-22]. Artificial neural network based models require large training time and it gives different results for each run.

The objective of this study is to review different mathematical models using trigonometric functions namely sine wave and cosine wave for the prediction of solar radiation to eliminate the costly pyranometer. The main advantage of mathematical model is radiation estimation can be determined even by using a simple calculator without any tedious data feeding work.

The paper has been organized as follows; Section 2 covers the mathematical models using trigonometric functions. Section 3 presents the performance metrics of solar radiation models. Section 4 contains the results and discussion. Section 5 covers the conclusion of this study.

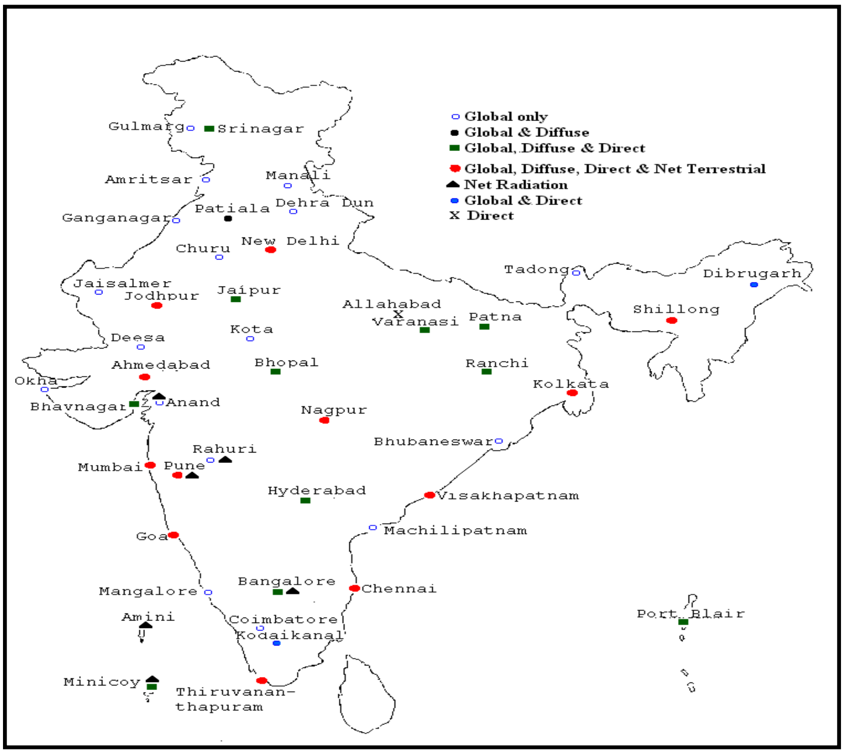

Figure 2. Network of 45 Radiation Stations of IMD

2. RESEARCH METHOD

Most of the radiation models examined for the estimation of global solar radiation are based on the commonly available meteorological parameters namely sunshine hours, relative humidity, and cloud cover, maximum and minimum temperature and so on. Simple mathematical models using trigonometric function for estimating daily GSR available in the literature to replicate the long term measured data are given as follows:

2.1. Sine Wave Model

Bulut (2007) established a solar radiation model with sine trigonometric function. This model has only one independent parameter, namely the day of the year [23]. The solar radiation model with sine wave trigonometric function to estimate the daily GSR (I) on horizontal surface in MJ/m2/ day is given by:

$$I = I_2(I_1 - I_2)\left|sin\left[\frac{\pi}{365}(d+5)\right]^{1.5}\right| \quad (1)$$

Where d is the number of the day starting from 1st January. The value of d is equal to one for the 1st January and d is equal to 365 for 31st December. I1 and I2 are the empirical coefficients. For each location these empirical coefficients should be determined separately by statistical tests.

2.2. Cosine Wave Model

Kaplanis (2006) developed a cosine wave mathematical model to predict daily GSR in six different climatic zones of Greece [24]. The correlation coefficient of the cosine wave model for all locations is greater than 0.99. The cosine wave equation is given by:

$$H = a_2 + a_1 * cos\left(\frac{2\pi}{364}n + a_2\right) \quad (2)$$

Where H is the daily mean global solar radiation, a0, a1 and a2 are the empirical coefficients and n is the day of the year starting from first January.

2.3. Sine and cosine wave Model

Huashan Li (2010) developed a trigonometric model using cosine and sine wave correlation is given by [25].

$$H = a_0 + a_1 * sin\left(\frac{2\pi a_2}{365} n + a_3\right) + a_4 * cos\left(\left(\frac{2\pi a_5}{365} n + a_6\right)\right) \tag{3}$$

Where a0, a1, a2, a3, a4, a5 and a6 are the empirical coefficients.

3. PERFORMANCE EVALUATION OF THE MODELS

The performance of the solar radiation models is evaluated on the basis of the following standard statistical metrics: the Mean Percentage Error (MPE), Mean Absolute Percentage Error (MAPE), Root Mean Square Error (RMSE), Mean Bias Error (MBE), Mean Absolute Bias Error (MABE) and Coefficient of determination (R2). The statistical study should be based on Hm - Hc (measured daily solar radiation vs. calculated daily solar radiation). MPE, MAPE, RMSE, MBE, MABE and R2 are defined by equations:

$$MPE = \{[\sum(H_m - H_c/H_m)] \tag{4}$$

$$MAPE = \{ [\sum|(\mathrm{H_m} - \mathrm{H_c})/\mathrm{H_m}|]100\}/\mathrm{N} \tag{5}$$

$$RMSE = \{[\sum(H_m - H_c)^2]/N\}^{1/2} \tag{6}$$

The Root Mean Square Error is constantly positive and ideal value is zero.

$$MBE = [\sum(H_m - H_c)]/N \tag{7}$$

MBE gives information on the long-term performance. A low MBE is preferred. Ideal value of zero MBE should be obtained.

Coefficient of determination R2 shows the linearity between the calculated GSR and measured GSR values and can be obtained by using the relation.

$$R^2 = 1 - \left[\sum(H_m - H_c)^2/\sum\left(H_m - H_{avgm}\right)^2\right] \tag{8}$$

where Hm is the measured value, Hc is the calculated value of solar radiation, N is the total number of observations and Havgm is the mean measured radiation.

4. RESULTS AND DISCUSSION

The trigonometric model developed by Huashan Li is validated by comparing with sine wave and cosine wave equation using the statistical error tests [23-24]. Table 2 shows the error statistics of sine wave, cosine wave mathematical model and trigonometric model with both sine and cosine wave correlation. The trigonometric model is very easy, quick, efficient and reliable and can be used for predicting the daily GSR in locations where the radiation data is unavailable. But the percentage error of these mathematical models is high when compared with regression and artificial intelligence based models. The major advantage of these models is the ready usage of mathematical equations and radiation estimations can be determined even by a simple small calculator.

Table 2. Comparison of Mathematical Models using Trigonometric Functions

Author	Year	Model	MAPE	MABE	RMSE	R^2
S.N. Kaplanis	2006	Trigonometric model with cosine wave equation	9.625	1.344	1.795	0.927
Hu¨samettin Bulut	2007	Trigonometric model with sine wave equation	9.512	1.263	1.650	0.939
Huashan Li	2010	Trigonometric model with both sine and cosine wave equation	7.630	1.069	1.418	0.955

5. CONCLUSION

Accurate prediction of global solar radiation is very important for all solar energy applications. Various Solar radiation models are available for the estimation of global solar radiation. In this paper a comprehensive study on papers using mathematical models utilizing trigonometric functions are reviewed. It is observed that mathematical model with both sine and cosine wave functions give good prediction accuracy with correlation coefficient of 0.95. These models do not need tedious data feeding work for the estimation of solar radiation. This helps in assessing the long-term performances of solar energy systems. From the detailed review, it can be concluded that mathematical model using trigonometric functions can be used to estimate solar radiation wherever the radiation data is unavailable.

NOMENCLATURE

AI	Artificial Intelligence
ANN	Artificial Neural Network
H_c	Calculated Value
H_m	Measured Value
C-WET	Centre for Wind Energy Technology
R	Correlation Coefficient
DHI	Diffuse Horizontal Irradiance
DNI	Direct Normal Irradiance
GA	Genetic Algorithm
GHI	Global Horizontal Irradiance
GSR	Global Solar Radiation
IMD	India Meteorological Department
L	latitude of location under consideration
LMS	Least Mean Square
ML	Machine Learning
MABE	Mean Absolute Bias Error
MAE	Mean Absolute Error
MAPE	Mean Absolute Percentage Error
MBE	Mean Bias Error
MPE	Mean Percentage Error
MNRE	Ministry for New and Renewable Energy
S	Monthly mean daily bright sunshine hours
H	Monthly mean daily global solar radiation on horizontal surface (MJ/m^2 /day)
D_n	Number of day of year starting from the first of January
a-d	Regression coefficients
RMSE	Root Mean Square Error
SRRA	Solar Radiation Resource Assessment
SVM	Support Vector Machine

REFERENCES

[1] T. M. N. T. Mansur, *et al.*, "Performance Analysis of Self-Consumed Solar PV System for A Fully DC Residential House," *Indones. J. Electr. Eng. Comput. Sci.*, vol/issue: 8(2), pp. 391–398, 2017.

[2] T.M.N.T.Mansur, *et al.*, "A Comparative Study for Different Sizing of Solar PV System under Net Energy Metering Scheme at University Buildings," *Bulletin of Electrical Engineering and Informatics (BEEI)*, Vol. 7, No. 3, pp. 450~457, 2018.

[3] Salwa Assahout, *et al.*, "A Neural Network and Fuzzy Logic based MPPT Algorithm for Photovoltaic Pumping System," *Indonesian Journal of Power Electronics and Drive Systems(IJPEDS)*, Vol 9, No 4, pp.1823-1833, 2018.

[4] A.Mellit, et al., "Methodology for predicting sequences of mean monthly clearness index and daily solar radiation data in remote areas: Application for sizing a stand-alone PV system," *Renewable Energy*, 33, pp.1570-1590, 2008.

[5] Rich Inman. H., *et al.*, "Review of Solar forecasting methods for renewable energy integration," *Progress in Energy and Combustion Science*, vol. 39, pp. 535 -576, 2013.

[6] Pierre Ineichen, "Comparison of eight clear sky broadband models against 16 independent data banks," *Solar Energy*, vol.80, pp. 468 -478, 2006.

[7] C.A. Gueymard, "REST2: High performance solar radiation model for cloudless sky irradiance, illuminance and photosynthetically active radiation—Validation with benchmark dataset," *Solar Energy*, 82, pp.272- 285, 2008.

[8] Mohammad Arif Sobhan Bhuiyan, *et al.*, "Emperical Computation of Solar Radiation and Determination of Regression Coefficients for Khulna City," *TELKOMNIKA Indonesian Journal of Electrical Engineering*, vol. 12, pp. 8015-8021, 2014.

[9] R.Meenal and A.Immanuel Selvakumar, "Temperature based Radiation Models for the Estimation of Global Solar Radiation at Horizontal Surface in India," *Indian Journal of Science and Technology* 9(46) /101922, 2016.

[10] R.Meenal and A.Immanuel Selvakumar, "Review on Artificial Neural Network based solar radiation prediction," *International Conference Communication and Electronics Systems (ICCES 2017)*

[11] Hatice Citakoglu,"Comparison of artificial intelligence techniques via empirical equations for prediction of solar radiation," *Computers and Electronics in Agriculture,* 115, pp.28-37, 2015.
[12] Amit Kumar Yadav, Hasmat Malik, S.S. Chandel, "Selection of most relevant input parameters using WEKA for artificial neural network based solar radiation prediction models," *Renewable and Sustainable Energy Reviews*, 31, pp.509–519, 2014.
[13] Sani Salisu, *et al.*, "A Wavelet Based Solar Radiation Prediction in Nigeria Using Adaptive Neuro-Fuzzy Approach," *Indonesian Journal of Electrical Engineering and Computer Science(IJEECS),* Vol. 12, No. 3, pp. 907~915, December 2018.
[14] Kasra Mohammadi, *et al.*, "Potential of adaptive neuro-fuzzy system for prediction of daily global solar radiation by day of the year", *Energy Conversion and Management*, 93, pp.406 – 413, 2015.
[15] H.Victor Quej, *et al.*, "ANFIS, SVM and ANN soft-computing techniques to estimate daily global solar radiation in a warm sub-humid environment," *Journal of Atmospheric and Solar-terresrial physics*, 155, pp.62-70, 2017.
[16] R.Meenal and A.Immanuel Selvakumar, "Temperature based model for predicting global solar radiation using Genetic Algorithm [GA]," *International Conference on Innovations in Electrical, Electronics, Instrumentation and Media Technology - ICIEEIMT17*.
[17] R.Meenal and A.Immanuel Selvakumar, "Solar Radiation Resource Assessment using WEKA," 2nd *International Conference on Inventive Systems and Control*, ICISC-2018.
[18] R.Meenal and A.Immanuel Selvakumar, "Assessment of Solar Energy Potential of Smart Cities of Tamil Nadu Using Machine Learning with Big Data," *In: Peter J., Alavi A., Javadi B. (eds) Advances in Big Data and Cloud Computing. Advances in Intelligent Systems and Computing*, vol 750. Springer, Singapore, 2019.
[19] R Meenal, *et al*., "Solar Mapping of India using Support Vector Machine," J. *Phys.: Conf. Ser. 1142 012010,* 2018.
[20] Rizwan Majid Jamil and Kothari DP., "Generalized Neural Network Approach for Global Solar Energy Estimation in India," *IEEE Transactions on Sustainable Energy*, 2, 3(3), pp.576-84, 2012.
[21] R.Meenal and A.Immanuel Selvakumar, "Global Solar Radiation prediction using Genetic Algorithm," *Journal of Electrical Engineering*, vol.17, pp. 632-639, 2017.
[22] Farzad Fathian, "Predicting global solar radiation using Genetic algorithm [GA]," *Bull. Env. Pharmacol. Life Sci*. 2 (6), pp. 54-63, 2013.
[23] Hu¨samettin Bulut, "Simple Model for the generation of daily Global Solar-Radiation data in Turkey," *Applied Energy*, vol. 84, pp. 477–491, 2007.
[24] Kaplanis. SN, "New methodologies to estimate the hourly global solar radiation; Comparisons with existing models," *Renewable Energy,* vol. 31, pp. 781–790, 2006.
[25] Huashan Li, *et al.*, "Estimating daily global solar radiation by day of year in China," *Applied Energy*, vol.87, pp.3011–3017, 2010.

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