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Review Article

A Review of Solar Radiation Models—Part I

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Energy is considered as a key source for the future and plays a pivotal role in its socioeconomic development by raising the standard of living and the quality of life, not only for India but also for the world. In view of the scarce fossil fuel reserves, solar energy is one of the important sources of renewable energy used in India because of the suitable climate conditions. It receives about 5485.17 Wh/m^2 day of solar insolation with an annual total of about 19, 74, 661.2 Wh/m^2. Except for the monsoon months, solar radiation incidence is very encouraging, from the application point of view. For the efficient functioning and better performance of solar energy device, the information of solar radiation and its components at particular location is very essential for designing the solar energy devices. Therefore, over the years, several empirical correlations have been developed in order to estimate the more appropriate solar radiation in India as well as around the world. Here we present a review of different solar radiation models which predict global solar radiation and discussed the long-term plan to meet future energy demand with renewable energy due to economy growth.

1. Introduction

The growing demand in urban and rural areas for energy has necessitated the finding of alternative sources of energy. With the change in the rural scenario and agricultural practices, and the advent of gadgets like televisions, mobile phones, and computers, the demand of energy has increased by a multitude. In India, commercial energy consumption makes up about 65% of the total energy consumption. This includes coal with the largest share of 55%, followed by oil at 31%, natural gas at 11%, and hydroenergy at 3%. Noncommercial energy sources (like firewood, cow dung, agricultural wastes, etc.) make 30% over the total energy consumption [1]. Being a tropical country India has unlimited potential for producing renewable energy resources. During the past 25 years, there has a significant growth of the renewable energy technology, and today it considered by many countries as an important technology for the future. Many countries have already established or are in the process of establishing support programs to encourage the adoption of this new technology. The Government of India has also given a major fillip to the adoption of renewable energy by launching the JNNSM (Jawaharlal Nehru National Solar Mission), as one of the eight national missions on climate change, in November 2009. This mission aims to establish India as a global leader in solar energy, by creating the policy conditions for its diffusion across the country as quickly as possible. The immediate aim of the mission is to focus on setting up an enabling environment for solar technology penetration in the country, both at centralized and decentralized levels. The mission targets to set up 1100 MW (megawatt) of grid solar power, 7 million sq m of solar collectors, and 200 MW of off-grid solar applications in the first phase (by 2013). By the year 2022, it aims for establishing 20 000 MW of grid solar power, 20 million sq m of solar collectors, and 2000 MW of off-grid solar applications. However, the true success of this mission depends solely on the active participation of every member of the society. The Department of Energy and Climate Change of the UK (United Kingdom) has recently outlined a comprehensive long-term plan, which maps out the strategy for generating 30% of UK's electricity from renewable energy sources by 2020, up from 5.5% today. It also aims to generate 12% of heat and 10% of transport energy from renewable energy. In the US, California has proposed an enhanced RPS (renewable portfolio standards) target of 33% by 2020—up from the 2010 target of 20%. Mexico proposes to more than double the share of electricity generated from renewable from the existing 3.3% to 7.6% by 2012. Thus, a consensus is being developed that the utilization of renewable energy can be a tool for curbing carbon emissions.

To overcome the dependency on conventional fuels, researchers and many organizations are working on alternative fuels, which should be commercially viable, easy to use, less pollutant, and must be abundant in nature. In this direction, renewable energies, like Solar Energy, Tidal Energy, Wind Energy, Biofuels, and so forth, are suitable than conventional sources of energy. These nonconventional forms are not only renewable but also maintain ecology and environment as they are eco-friendly and do not contribute in global warming and production of green house gases, and so forth.

It is well known that solar energy is the source of life on earth. It heats its atmosphere and its lands, generates its winds, drives the water cycle, warms its oceans, grows its plants, feeds its animals, and even (over the long haul) produces its fossil fuels. This energy can be converted into heat and cold, driving force, and electricity. Since, solar radiation is vital to solar energy system design everywhere where adequate observations are missing [2]. Therefore, information on solar radiation and its components at a given location is very essential. The best database would be the long-term measured data at the site of the proposed solar system. However, the limited coverage of radiation measuring networks dictates the need for developing solar radiation models [3]. The main objective of the present study is to review solar radiation (global radiation) models for India and some of its provinces.

2. Review Models

It is generally accepted that models for solar radiation prediction are necessary, because in most cases the density and number of solar radiation measuring stations cannot describe the necessary variability [4]. It is understandable then that new models and improvements to existing modeling techniques are continually proposed which intend to improve estimates of solar radiation values with the use of more readily available meteorological variables [5–7].

2.1. Estimation of Global Solar Radiation Using Angstrom-Type Models. Angstrom [8] proposed the first theoretical model for estimating global solar radiation based on sunshine duration. Page [9] and Prescott [10] reconsidered this model in order to make it possible to calculate monthly average of the daily global radiation $\overline{H}$ (MJ/m^2 day) on a horizontal surface from monthly average daily total insolation on an extraterrestrial horizontal surface as per the following relation:

$$\frac{H}{H_0} = a + b\left(\frac{S}{S_0}\right), \tag{1}$$

where H is the monthly average global radiation on horizontal surface, S is the monthly average daily bright sunshine hours, S_0 is the maximum possible monthly average daily sunshine hours or the day length, a and b are constants, and H_0 is the monthly average daily extraterrestrial radiation (MJ/m^2 day) which can be expressed as [11]

$$\begin{aligned} H_0 = {} & \frac{24}{\pi} I_{sc}\left[1 + 0.33\cos\left(\frac{360 D_n}{365}\right)\right] \\ & \times\left[\cos L \cos\delta \sin\omega_s + \frac{2\pi\omega_s}{360}\sin L \sin\delta\right], \end{aligned} \tag{2}$$

where ω_s is sunset hour angle in degree and defined as

$$\omega_s = \cos^{-1}(-\tan L \tan\delta). \tag{3}$$

I_{sc} is the solar constant. L is the latitude of location under consideration; D_n is the day of year starting from first January and δ is declination angle as given below

$$\delta = 23.45\sin\left[\frac{360(284 + D_n)}{365}\right]. \tag{4}$$

For a given month, the maximum possible sunshine duration can be computed by the following equation [12]:

$$S_0 = \frac{2}{15}\cos^{-1}(-\tan L \tan\delta). \tag{5}$$

The regression models that have been proposed in the literature are given below

Model 1. Page [9] has given the coefficients of modified Angstrom model as the following:

$$\frac{H}{H_0} = 0.23 + 0.48\frac{S}{S_0}. \tag{6}$$

Model 2. Kholagi et al. [13] obtained the following linear equations from the data measured at three different stations in Yemen:

$$\frac{H}{H_0} = 0.191 + 0.571\frac{S}{S_0}, \tag{7a}$$

$$\frac{H}{H_0} = 0.297 + 0.432\frac{S}{S_0}, \tag{7b}$$

$$\frac{H}{H_0} = 0.262 + 0.454\frac{S}{S_0}. \tag{7c}$$

Model 3. Benson et al. [14] have obtained regression constants in to two intervals of a year depending on the climatic parameters:

$$\frac{H}{H_0} = 0.18 + 0.60\frac{S}{S_0} \quad \text{for Jan–March and Oct–Dec}, \tag{8a}$$

$$\frac{H}{H_0} = 0.24 + 0.53\frac{S}{S_0} \quad \text{for rest of the month}. \tag{8b}$$

Model 4. H. P. Garg and S. N. Garg [15] obtained the following equations from the experimental data of eleven stations in India:

$$\frac{H}{H_0} = 0.3156 + 0.4520\frac{S}{S_0}. \quad (9)$$

Model 5. Bahel et al. [16] proposed the following relationship:

$$\frac{H}{H_0} = 0.175 + 0.552\frac{S}{S_0}. \quad (10)$$

Model 6. Jain [17] has proposed the following regression constants based on Angstrom-type correlation using the average daily global solar radiation and the sunshine data of 31 Italian locations:

$$\frac{H}{H_0} = 0.177 + 0.692\frac{S}{S_0}. \quad (11)$$

Model 7. Alsaad [18] suggested the following relation to estimate the global radiation for Amman, Jordan:

$$\frac{H}{H_0} = 0.174 + 0.615\frac{S}{S_0}. \quad (12)$$

Model 8. S. Jain and P. C. Jain [19] suggested the following correlation constants to estimate the global radiation over eight Zambian locations:

$$\frac{H}{H_0} = 0.240 + 0.513\frac{S}{S_0}. \quad (13)$$

Model 9. Luhanga and Andringa [20] proposed model as follows:

$$\frac{H}{H_0} = 0.241 + 0.488\frac{S}{S_0}. \quad (14)$$

Model 10. Raja and Twidell [21, 22] provided the following equations using the data from five main observatories in Pakistan and by taking into account the effect of latitude Φ:

$$\frac{H}{H_0} = 0.335 + 0.367\frac{S}{S_0}, \quad (15a)$$

$$\frac{H}{H_0} = 0.388\cos\Phi + 0.367\frac{S}{S_0}. \quad (15b)$$

Model 11. Jain [23] proposed the following relations for three locations (Salisbury, Bulawayo, and Macerata) on the measured data of Italy:

$$\frac{H}{H_0} = 0.313 + 0.474\frac{S}{S_0}, \quad (16a)$$

$$\frac{H}{H_0} = 0.307 + 0.488\frac{S}{S_0}, \quad (16b)$$

$$\frac{H}{H_0} = 0.309 + 0.599\frac{S}{S_0}. \quad (16c)$$

Model 12. Louche et al. [24] suggested the regression constants to estimate global solar radiation as a function of the ratio of sunshine duration:

$$\frac{H}{H_0} = 0.309 + 0.599\frac{S}{S_0}. \quad (17)$$

Model 13. Lewis [25] proposed the following linear equation to estimate global radiation for locations in the state of Tennessee, USA:

$$\frac{H}{H_0} = 0.14 + 0.57\frac{S}{S_0}. \quad (18)$$

Model 14. Gopinathan and Soler [26] suggested linear equation for locations with latitudes between 60 N and 70 N:

$$\frac{H}{H_0} = 0.1538 + 0.7874\frac{S}{S_0}, \quad (19a)$$

$$\frac{H}{H_0} = 0.1961 + 0.7212\frac{S}{S_0}. \quad (19b)$$

Model 15. Veeran and Kumar [27] proposed the following linear equation for two tropical locations in India:

$$\frac{H}{H_0} = 0.34 + 0.32\frac{S}{S_0}, \quad (20a)$$

$$\frac{H}{H_0} = 0.27 + 0.65\frac{S}{S_0}. \quad (20b)$$

Model 16. Tiris et al. [28] also proposed the regression constants using the five-year (1988–1992) data for Gebze:

$$\frac{H}{H_0} = 0.2262 + 0.418\frac{S}{S_0}. \quad (21)$$

Model 17. Said et al. [29] obtained the following equation to estimate monthly average daily global solar radiation:

$$\frac{H}{H_0} = 0.215 + 0.527\frac{S}{S_0}. \quad (22)$$

Model 18. Ulgen and Ozbalta [30] suggested the following regression constants for Bornova, Izmir, Turkey:

$$\frac{H}{H_0} = 0.2424 + 0.5014\frac{S}{S_0}. \quad (23)$$

Model 19. Chegaar and Chibani [31] have proposed the following linear relationship between H/H_0 and S/S_0 for estimating global solar radiation on horizontal surface:

$$\frac{H}{H_0} = 0.2424 + 0.5014\frac{S}{S_0}, \quad (24a)$$

$$\frac{H}{H_0} = 0.2424 + 0.5014\frac{S}{S_0}, \quad (24b)$$

$$\frac{H}{H_0} = 0.2424 + 0.5014\frac{S}{S_0}. \quad (24c)$$

Model 20. I. T. Toğural and H. Toğural [32] suggested the relation for the estimation of global solar radiation in Turkey:

$$\frac{H}{H_0} = 0.318 + 0.449\frac{S}{S_0}. \quad (25a)$$

The results of regression analyses applied for winter (January–March and October–December intervals) and summer (April–September) are given below:

$$\frac{H}{H_0} = 0.2947 + 0.4669\frac{S}{S_0} \quad \text{for winter}, \quad (25b)$$

$$\frac{H}{H_0} = 0.5103 + 0.1628\frac{S}{S_0} \quad \text{for summer}, \quad (25c)$$

$$\frac{H}{H_0} = 0.2948 + 0.5342\frac{S}{S_{nh}} \quad \text{for winter}, \quad (25d)$$

$$\frac{H}{H_0} = 0.5067 + 0.1937\frac{S}{S_{nh}} \quad \text{for summer}, \quad (25e)$$

$$\frac{H}{H_0} = 0.1739\ln\frac{S}{S_{nh}} + 0.6782 \quad \text{for winter}, \quad (25f)$$

$$\frac{H}{H_0} = 0.1124\ln\frac{S}{S_{nh}} + 0.6822 \quad \text{for winter}. \quad (25g)$$

Model 21. Ulgen and Hepbasli [33] proposed the linear relation equation for Ankara, Istanbul, and Izmir in Turkey:

$$\frac{H}{H_0} = 0.2671 + 0.4754\frac{S}{S_0}. \quad (26)$$

Model 22. Ahmad and Ulfat [34] also suggested the linear regression constants for Karachi, Pakistan:

$$\frac{H}{H_0} = 0.324 + 0.405\frac{S}{S_0}. \quad (27)$$

Model 23. Jin et al. [35] proposed the following relation:

$$\frac{H}{H_0} = 0.1332 + 0.6471\frac{S}{S_0}. \quad (28)$$

Model 24. El-Sabaii and Trabea [36] reported the following first-order Angstrom-type correlations for Egypt using the measured data for five Egyptian locations (Al-Arish, Rafah, Matruh, Tanta, and Aswan):

$$\frac{H}{H_0} = 0.3647 + 0.3505\frac{S}{S_0}. \quad (29)$$

Model 25. Aras et al. [37] proposed the following linear equation for twelve provinces in the Central Anatolia Region of Turkey:

$$\frac{H}{H_0} = 0.3078 + 0.4166\frac{S}{S_0}. \quad (30)$$

Model 26. Rensheng et al. [38] suggested the linear equation to estimate global solar radiation as follows:

$$\frac{H}{H_0} = 0.176 + 0.563\frac{S}{S_0}. \quad (31)$$

Model 27. Katiyar and Pandey [39] reported the following first-order Angstrom-type correlations for four locations (Jodhpur, Calcutta, Bombay, and Pune, India), respectively, for the estimation of global solar radiation using the long-range measured data of five years (2001–2005):

$$\frac{H}{H_0} = 0.2276 + 0.5105\frac{S}{S_0}, \quad (32a)$$

$$\frac{H}{H_0} = 0.2623 + 0.3952\frac{S}{S_0}, \quad (32b)$$

$$\frac{H}{H_0} = 0.2229 + 0.5123\frac{S}{S_0}, \quad (32c)$$

$$\frac{H}{H_0} = 0.2286 + 0.5309\frac{S}{S_0}. \quad (32d)$$

Further, in order to develop the first-order correlation applicable to all Indian locations, the authors combined the entire measured data of all the four locations together and analyze to obtain the following correlation:

$$\frac{H}{H_0} = 0.2281 + 0.5093\frac{S}{S_0}. \quad (32e)$$

Over the years, the following authors study the constants of Angstrom equation.

Model 28. Rietveld [40] examined several published values of a and b and noted that a is related linearly and b hyperbolically to the appropriate yearly average value of S/S_0 such that

$$a = 0.10 + 0.24\frac{S}{S_0}, \quad (33a)$$

$$b = 0.38 + 0.08\frac{S}{S_0}. \quad (33b)$$

The Rietveld model [40] can be simplified to a constant-coefficient Angstrom-Prescott equation:

$$\frac{H}{H_0} = 0.18 + 0.62\frac{S}{S_0}. \quad (34)$$

Model 29. Gariepty [41] has reported that the empirical coefficients a and b are dependent on mean air temperature (T) and the precipitation (P):

$$a = 0.3791 - 0.0041T - 0.0176P, \quad (35a)$$

$$b = 0.4810 - 0.0043T - 0.0097P. \quad (35b)$$

Model 30. Kilic and Ozturk [42] determined that the coefficients a and b are functions of the solar declination (δ) with ϕ and Z given by the following equations:

$$a = 0.103 - 0.000017Z - 0.198\cos(\phi - \delta), \quad (36a)$$

$$b = 0.533 - 0.165\cos(\phi - \delta). \quad (36b)$$

2.2. Estimation of Global Solar Radiation Using Higher Order Correlations. Page [9] pointed out that linear-type equation based on climatologically means cannot necessarily be expected to be applicable extreme values for a particular day, as it overestimates the total radiation on cloudless days, that is, when $S/S_0 = 1$ and on overcast days that is, when $S/S_0 = 0$. This fact was later confirmed by Benson et al. [14] and Michalsky [43] who considered the relationship on the basis of individual daily records. The former study shows a significant downward curvature of the data points with discontinuity of H/H_0 at $S/S_0 = 0$; hence, a quadratic form for the relationship between daily global/extraterrestrial radiation and actual/maximum possible hours of sunshine greater than zero was employed as

$$\frac{H}{H_0} = a + b\left(\frac{S}{S_0}\right) + c\left(\frac{S}{S_0}\right)^2. \quad (37)$$

Higher order correlations (higher than quadratic) also have the same property as quadratic correlations. In general, a higher order correlation is written as

$$\frac{H}{H_0} = a + b\left(\frac{S}{S_0}\right) + c\left(\frac{S}{S_0}\right)^2 + d\left(\frac{S}{S_0}\right)^3, \quad (38)$$

where a to d are regression coefficients.

Model 31. Öelman et al. [44] have developed second-order polynomial equation to estimate global solar radiation:

$$\frac{H}{H_0} = 0.195 + 0.676\left(\frac{S}{S_0}\right) - 0.083\left(\frac{S}{S_0}\right)^2. \quad (39)$$

Model 32. Bahel et al. [45] also developed the following third-order correlation based on the measured data of global and bright sunshine hours for 48 stations around the world:

$$\frac{H}{H_0} = 0.16 + 0.87\left(\frac{S}{S_0}\right) - 0.61\left(\frac{S}{S_0}\right)^2 + 0.34\left(\frac{S}{S_0}\right)^3. \quad (40)$$

Model 33. Akinoğlu and Ecevit [46] suggested the second-order polynomials to estimate the global solar radiation for Turkey:

$$\frac{H}{H_0} = 0.145 + 0.845\left(\frac{S}{S_0}\right) - 0.280\left(\frac{S}{S_0}\right)^2. \quad (41)$$

Model 34. Samuel [47] proposed the ratio of global to extraterrestrial radiation as a function of the ratio of sunshine hours for third-order polynomials:

$$\frac{H}{H_0} = -0.14 + 2.52\left(\frac{S}{S_0}\right) - 3.71\left(\frac{S}{S_0}\right)^2 + 2.24\left(\frac{S}{S_0}\right)^3. \quad (42)$$

Model 35. Taşdemiroğlu and Sever [48] also developed the following second-order polynomials to estimate global solar radiation for six locations of Turkey, as follows:

$$\frac{H}{H_0} = 0.225 + 0.014\left(\frac{S}{S_0}\right) + 0.001\left(\frac{S}{S_0}\right)^2. \quad (43)$$

Model 36. Lewis [25] also proposed the following third-order equation to estimate global radiation for locations in the state of Tennessee, USA, as follows:

$$\frac{H}{H_0} = 0.81 - 3.34\left(\frac{S}{S_0}\right) + 7.38\left(\frac{S}{S_0}\right)^2 - 4.51\left(\frac{S}{S_0}\right)^3. \quad (44)$$

Model 37. Yildiz and Oz [49] developed the following second-order polynomials using the measured data of five stations located in different places of Turkey:

$$\frac{H}{H_0} = 0.2038 + 0.9236\left(\frac{S}{S_0}\right) - 0.3911\left(\frac{S}{S_0}\right)^2. \quad (45)$$

Model 38. Aksoy [50] developed the quadratic equation to estimate global solar radiation for Turkey, as follows:

$$\frac{H}{H_0} = 0.148 + 0.668\left(\frac{S}{S_0}\right) - 0.079\left(\frac{S}{S_0}\right)^2. \quad (46)$$

Model 39. Said et al. [29] obtained the following second-order equation to estimate monthly average daily global solar radiation on a horizontal surface at Tripoli, Libya:

$$\frac{H}{H_0} = 0.1 + 0.874\left(\frac{S}{S_0}\right) - 0.255\left(\frac{S}{S_0}\right)^2. \quad (47)$$

Model 40. Ulgen and Ozbalta [30] suggested the following second-order regression constants for Bornova, Izmir, Turkey:

$$\frac{H}{H_0} = 0.0959 + 0.9958\left(\frac{S}{S_0}\right) - 0.3922\left(\frac{S}{S_0}\right)^2. \quad (48)$$

Model 41. Ertekin and Yaldiz [51] have proposed the following third-order polynomial equations for Antalya, Turkey:

$$\frac{H}{H_0} = -2.4275 + 11.946\left(\frac{S}{S_0}\right) - 16.745\left(\frac{S}{S_0}\right)^2 + 7.9575\left(\frac{S}{S_0}\right)^3. \quad (49)$$

Model 42. Ulgen and Hepbasli [52] proposed the third-order relation for Izmir in Turkey, as follows:

$$\frac{H}{H_0} = 0.2408 + 0.3625\left(\frac{S}{S_0}\right) + 0.4597\left(\frac{S}{S_0}\right)^2 - 0.3708\left(\frac{S}{S_0}\right)^3. \quad (50)$$

Model 43. I. T. Toğural and H. Toğural [32] suggested the third-order relation for the estimation of global solar radiation in Turkey, as follows:

$$\frac{H}{H_0} = 0.1796 + 0.9813\left(\frac{S}{S_0}\right) - 0.2958\left(\frac{S}{S_0}\right)^2 - 0.2657\left(\frac{S}{S_0}\right)^3, \quad (51a)$$

$$\frac{H}{H_0} = 0.1587 + 1.3652\left(\frac{S}{S_{nh}}\right) - 0.1175\left(\frac{S}{S_{nh}}\right)^2 \quad \text{for winter}, \quad (51b)$$

$$\frac{H}{H_0} = 0.288 + 0.9874\left(\frac{S}{S_{nh}}\right) - 0.6967\left(\frac{S}{S_{nh}}\right)^2 \quad \text{for summer}. \quad (51c)$$

Model 44. Ulgen and Hepbasli [33] also proposed the third-order polynomial relation for Ankara, Istanbul, and Izmir in Turkey, as follows:

$$\frac{H}{H_0} = 0.2854 + 0.2591\left(\frac{S}{S_0}\right) + 0.6171\left(\frac{S}{S_0}\right)^2 - 0.4834\left(\frac{S}{S_0}\right)^3. \quad (52)$$

Model 45. Ahmad and Ulfat [34] also suggested the quadratic equation for Karachi, Pakistan:

$$\frac{H}{H_0} = 0.348 + 0.320\left(\frac{S}{S_0}\right) + 0.070\left(\frac{S}{S_0}\right)^2. \quad (53)$$

Model 46. Tarhan and Sari [53] have proposed second and third-order polynomial models to predict solar radiation over the Central Black Sea Region of Turkey, as follows:

$$\frac{H}{H_0} = 0.1874 + 0.8592\left(\frac{S}{S_0}\right) - 0.4764\left(\frac{S}{S_0}\right)^2,$$
$$\frac{H}{H_0} = 0.1520 + 1.1334\left(\frac{S}{S_0}\right) - 1.1126\left(\frac{S}{S_0}\right)^2 + 0.4516\left(\frac{S}{S_0}\right)^3. \quad (54)$$

Model 47. Aras et al. [37] also proposed the following second- and third-order equations for twelve provinces in the Central Anatolia Region of Turkey:

$$\frac{H}{H_0} = 0.3398 + 0.2868\left(\frac{S}{S_0}\right) + 0.1187\left(\frac{S}{S_0}\right)^2,$$
$$\frac{H}{H_0} = 0.4832 - 0.6161\left(\frac{S}{S_0}\right) + 1.8932\left(\frac{S}{S_0}\right)^2 - 1.0975\left(\frac{S}{S_0}\right)^3. \quad (55)$$

Model 48. Bakirchi [54] proposed third-order polynomial equation for Erzurum, Turkey:

$$\frac{H}{H_0} = 0.6307 - 0.7251\left(\frac{S}{S_0}\right) + 1.2089\left(\frac{S}{S_0}\right)^2 - 0.4633\left(\frac{S}{S_0}\right)^3. \quad (56)$$

Model 49. Besides, all the above empirical correlations discussed, a sixth order polynomial could also be fitted by Katiyar et al. [55] for sixteen Indian locations:

$$\frac{H}{H_0} = a_6 + b_6\left(\frac{S}{S_0}\right) + c_6\left(\frac{S}{S_0}\right)^2 + d_6\left(\frac{S}{S_0}\right)^3 + e_6\left(\frac{S}{S_0}\right)^4 + f_6\left(\frac{S}{S_0}\right)^5 + g_6\left(\frac{S}{S_0}\right)^6, \quad (57)$$

where a_6, b_6, c_6, d_6, e_6, f_6, and g_6 are constants, which are presented in Table 1.

Instead of polynomials regression analysis, several investigators reported the following multilinear regression equation to predict global solar radiation.

Model 50. Falayi et al. [56] developed a number of multi linear regression equations to predict the relationship between global solar radiations with one or more combinations of the following weather parameters: clearness index (H/H_0), mean of daily temperature (T), ratio of maximum and minimum daily temperature (θ), relative humidity (RH), and relative sunshine duration (S/S_0) for Iseyin Nigeria for five years (1995–1999), using the Angstrom model as base:

$$\frac{H}{H_0} = 0.1874 + 0.8592\left(\frac{S}{S_0}\right) - 1.567\,(\theta) + 0.0033\,(\text{RH}) - 0.00806\,(T). \quad (58)$$

Model 51. Al-Salihi et al. [57] also developed multi linear regression equations for Baghdad, Mosul, and Rutba, Iraq, to predict the relationship between the ratio of global to extraterrestrial solar radiations with the combinations of the following weather parameters: maximum temperatures

Table 1: Regression coefficients of sixth order polynomial (57) for different cities of India.

City	a_6	b_6	c_6	d_6	e_6	f_6	g_6
Trivandrum	−14.2	202.1	−1103.2	3075.6	−4645.1	3626	−1148.8
Kodaikanal	3.3	−54.9	391.6	−1379.2	2579.4	−2439.1	914.9
Madras	−57.9	607.9	−2594.1	5803.9	−7179.9	4659.6	−1240.3
Goa/Panji	−5.9	99.6	−591.9	1725.5	−2637.4	2031	−621.6
Vishakhapatnam	3.2	−31.6	132.4	−260.3	258.1	−121.6	20.6
Pune	7.5	−126.5	830.6	−2587.1	4131.4	−3270.5	1017.9
Mumbai	−0.6	17.1	−107.6	336	−543.7	437.4	−138.3
Nagpur	8.7	−126.8	744.1	−2175.1	3376.3	−2660.9	838.3
Bhaunagar	4.5	−72.3	460.6	−1403.9	2217.9	−1748.3	542.9
Ahmedabad	−40.7	557	−2913.5	7548.4	−10314.9	7127	−1963.6
Kolkata	120.2	−1615.5	8855.7	−25284.5	39698.8	−32525	10871.3
Shilong	4.41	−93.3	786.7	−3160.2	6534.3	−6692.6	2685.3
Jodhpur	−9548.5	83762.7	−304722	588492.5	−636355	36533.9	−86994.9
Kanpur	−4403.9	45088.2	−188221.5	411457.7	−497959	316921.4	−82990.2
Lucknow	−788	6597.75	−22837.6	41857.6	−42847.4	23230.5	−5212.8
New Delhi	−6326.6	66694.4	−290381.6	668728.9	−859459.2	584685.8	−164539.1

(T_{max}), sunshine duration (S/S_0), and relative humidity (RH) as follows:

$$\frac{H}{H_0} = 10.78 + 0.071\left(\frac{S}{S_0}\right) + 0.0026\left(T_{max}\right) - 0.00078\,(\mathrm{RH}) \quad \text{for Baghdad,} \tag{59a}$$

$$\frac{H}{H_0} = 8.86 + 0.301\left(\frac{S}{S_0}\right) + 0.0035\left(T_{max}\right) + 0.00157\,(\mathrm{RH}) \quad \text{for Mosul,} \tag{59b}$$

$$\frac{H}{H_0} = 15.07 + 0.104\left(\frac{S}{S_0}\right) + 0.00139\left(T_{max}\right) - 0.00112\,(\mathrm{RH}) \quad \text{for Rutba.} \tag{59c}$$

2.3. Estimation of Global Solar Radiation Based on Ambient Temperature

Model 52. Bristow and Campbell [58] suggested the following relationship for daily values of global solar radiation (H) as a function of daily extraterrestrial solar radiation (H_0) and temperature difference (ΔT) as

$$\frac{H}{H_0} = A\left[1 - \exp\left(-B\Delta T^{C}\right)\right], \tag{60}$$

where $\Delta T = T_{max} - T_{min}$ and A, B, and C are the empirical coefficients. The values of A, B, and C in Bristow and Campbell's model were taken to be 0.7, 0.004–0.01, and 2.4, respectively.

Model 53. Allen [59] estimated mean monthly global solar radiation as a function of H_0, mean monthly maximum temperature (T_M), and mean monthly minimum (T_m) as

$$\frac{H}{H_0} = K_r\left(T_M - T_m\right)^{0.5}, \tag{61a}$$

where K_r is defined as

$$K_r = K_{ra}\left(\frac{P}{P_0}\right)^{0.5}. \tag{61b}$$

Following Lunde [60], $K_{ra} = 0.17$ and P/P_0 may be defined as

$$\frac{P}{P_0} = \exp\left(-0.0001184\,h\right), \tag{61c}$$

where P and P_0 are the values of local and standard atmospheric pressure, respectively, and h is the altitude of the place in meters.

Model 54. Pandey and Katiyar [61] proposed the following first- to third-order equations for the pairs of (H/H_0) and (θ/θ_0) at Jodhpur, Ahmedabad, Calcutta, Bombay, and Pune stations, India:

$$\begin{aligned} \frac{H}{H_0} &= 0.2889 + 0.1562 * \left(\frac{\theta}{\theta_0}\right), \\ \frac{H}{H_0} &= -1.148 + 1.901 * \left(\frac{\theta}{\theta_0}\right) - 0.5109 * \left(\frac{\theta}{\theta_0}\right)^2, \\ \frac{H}{H_0} &= -5.159 + 9.126 * \left(\frac{\theta}{\theta_0}\right) - 4.766 * \left(\frac{\theta}{\theta_0}\right)^2 + 0.8201 * \left(\frac{\theta}{\theta_0}\right)^3, \end{aligned} \tag{62}$$

where θ and θ_0 are the maximum and minimum air temperatures, respectively.

Inspite of these, Ertekin et al. estimated monthly average daily global radiation on horizontal surface for Antalya and turkey [62–64]. Further, his group compared all the existing solar radiation models with their results [65]. They have further given spatial and temporal modeling of global solar radiation dynamics as a function of sunshine duration for

Turkey [66] and thereafter they have produced good results by assessing regional spatial-temporal dynamics of global solar radiation models over Turkey [67].

3. Result and Discussion

Being a clean, eco-friendly, domestic energy source, renewable energy will be the essential components of future sustainable energy sources. For development of suitable theoretical model the information of solar radiation at a given location is needed. Therefore, we have studied the 61 models from 1960 to 2010 for the ratio of global to extraterrestrial radiation as a function of the ratio of sunshine duration (linear model), higher order relationship between H/H_0 and S/S_0 (second-, third-, and six-order relation) and based on ambient air temperature. There are 30 models derived from the Angstrom-type regression equation. These models are also known as linear models because the empirical coefficients a and b were obtained from the results of the first-order regression analysis. Angstrom [8] recommended values of 0.25 and 0.75, respectively, for the constants a and b based on data from Stockholm. It is obvious that $a + b = 1$, because on clear days $\bar{s}/\bar{s}_0$ is supposed to be equal to 1. However, because of the inherence in sunshine recorders, measurements of $\bar{s}/\bar{s}_0$ will never be equal to 1. So the constant a usually has values in the interval 0.1–0.3 and the sum $a + b$ ranges from 0.6 to 0.9. Tiris et al. [28] tested the (21) on the basis of statistical error tests and recommended (21) to estimate the monthly average daily global radiation for the Gebze location in Turkey. Said et al. [29] compared seven models (Rietveld [40], Dogniaux and Lemoine [68], H. F. Garg and S. N. Garg [69], Gariepty [41], Glover and McCulloch [70], Hay [71], and Black [72]) for Tripoli and observed that the Dogniaux and Rietveld results follow the measured data closely over the whole year period. Garg and Garg model has an excellent fit for the experimental data for the months: June, July, August, and September, but it deviates considerably for the period January to May. Black model was found the least accurate of all of these models with noted overestimation of global radiation for all the months of the years. Glover and Hey results follow closely those of Dogniaux and Rietveld, respectively. I. T. Toğural and H. Toğural [32] developed many equations using the ratios of S/S_0 and S/S_{nh} to estimate the global radiation in Turkey. It was seen that the equations which include the summer and winter periods gave better than the others in all the developed equations. It is predictable results that the performances of the equations are different for the whole Turkey and for the cities. Equations (25a), (25b), (25c), (25d), (25e), (25f), (51a), (51b), and (51c) gave the best results in all of the developed equations. Finally, these results clearly indicate that reliance on the RMSE and MBE used separately can lead to a wrong decision in selecting the best model from a suited of candidate models and that the use of the RMSE and MBE in isolation is not an adequate indicator of model performance. Therefore, the t-statistic should be used in conjunction with these two indicators to better evaluate a model's performance. Ahmad and Ulfat [34] suggested that (27) and (53) can be used with confidence for Karachi, Pakistan, with the percentage error for all the months being below 5%. El-Sabaii and Trabea [36] reported the first-order Angstrom-type correlations using the measured data for five Egyptian locations (Al-Arish, Rafah, Matruh, Tanta, and Aswan) for Egypt, (29), can be used for estimating global radiation for any location of Egypt with absolute values of the MPE less than 6%.

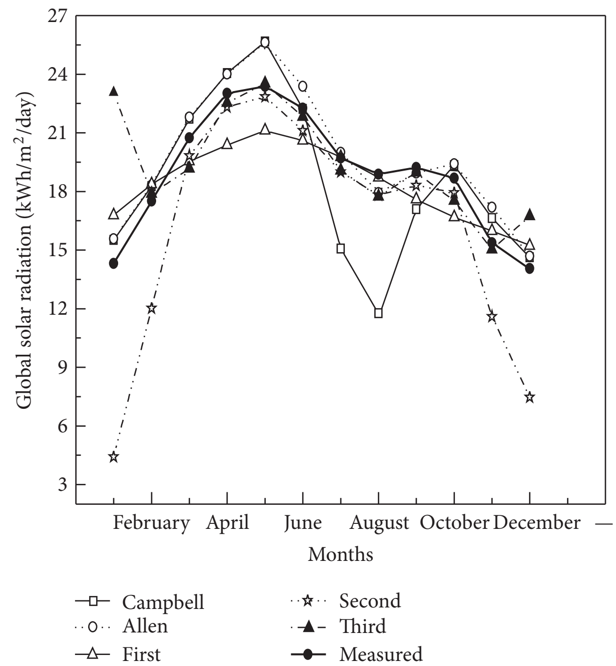

Figure 1: Measured and estimated global solar radiation for Jodhpur, India.

Katiyar and Pandey [39] compared our own model [39] with the theoretical estimates of Angstrom [8], Bahel et al. [16], and El-Sabaii and Trabea [36] models along with the measured data for Jodhpur, Calcutta, Bombay, and Pune. Comparison of all stations shows that equation (32e) predicts more accurate results than Angstrom [8], Bahel et al. [16], and El-Sabaii and Trabea [36] models. For further validation Katiyar and Pandey model is compared with the measured data for Matrough, Arish, and Cairo cities of Egypt. Katiyar and Pandey [39] also observed that the second- and third-order Angstrom-type correlations do not significantly improve the accuracy of the estimated global solar radiation over first order.

Using multi linear regression analysis Falayi et al. [56] reported that (58) has the highest value of correlation coefficient and correlation determination, which gives good results.

Since the air temperature is a worldwide measured meteorological parameter, it rarely used in solar radiation techniques. Therefore, we have compared the results with the theoretical estimates of Pandey and Katiyar [61], Bristow and Campbell [58], and Allen [59] as well as with measured data through Figure 1.

Comparison shows that Bristow and Campbell's [58] model for Ahmedabad, Calcutta, and Pune shows higher values of global radiation due to higher values of temperature deference, while Allen [59] model gives satisfactory results. However, Pandey and Katiyar [61] model with their third-order correlation provide more accurate estimates than Bristow and Campbell and Allen models.

4. Conclusions

In the absence and scarcity of trustworthy solar radiation data, the need for empirical model to predict and estimate global solar radiation seems inevitable. Sunshine-based models are employed for estimation of global solar radiation for a location. These models given in this study will enable the solar energy researcher to use the estimated data due to fine agreement with the observed data. Most of the models given to estimate the monthly average daily global solar radiation are of the modified Angstrom-type relation. It is also concluded that the first-order Angstrom-type correlation supercedes over second and third orders not only for the accuracy of estimated monthly average daily global radiation on horizontal surface but also requires less computational work. Katiyar and Pandey model (32e) was found as the most accurate model for the estimation of monthly average daily global radiation on horizontal surface for Indian location. Equation (32e) may also be extended for other locations which have the same values of the maximum clearness index. The temperature base model also indicates that Pandey and Katiyar model (Model 54) has good potential for use in estimating values of monthly average global solar radiation on horizontal surface for the locations where measurements of the sunshine duration are not available.

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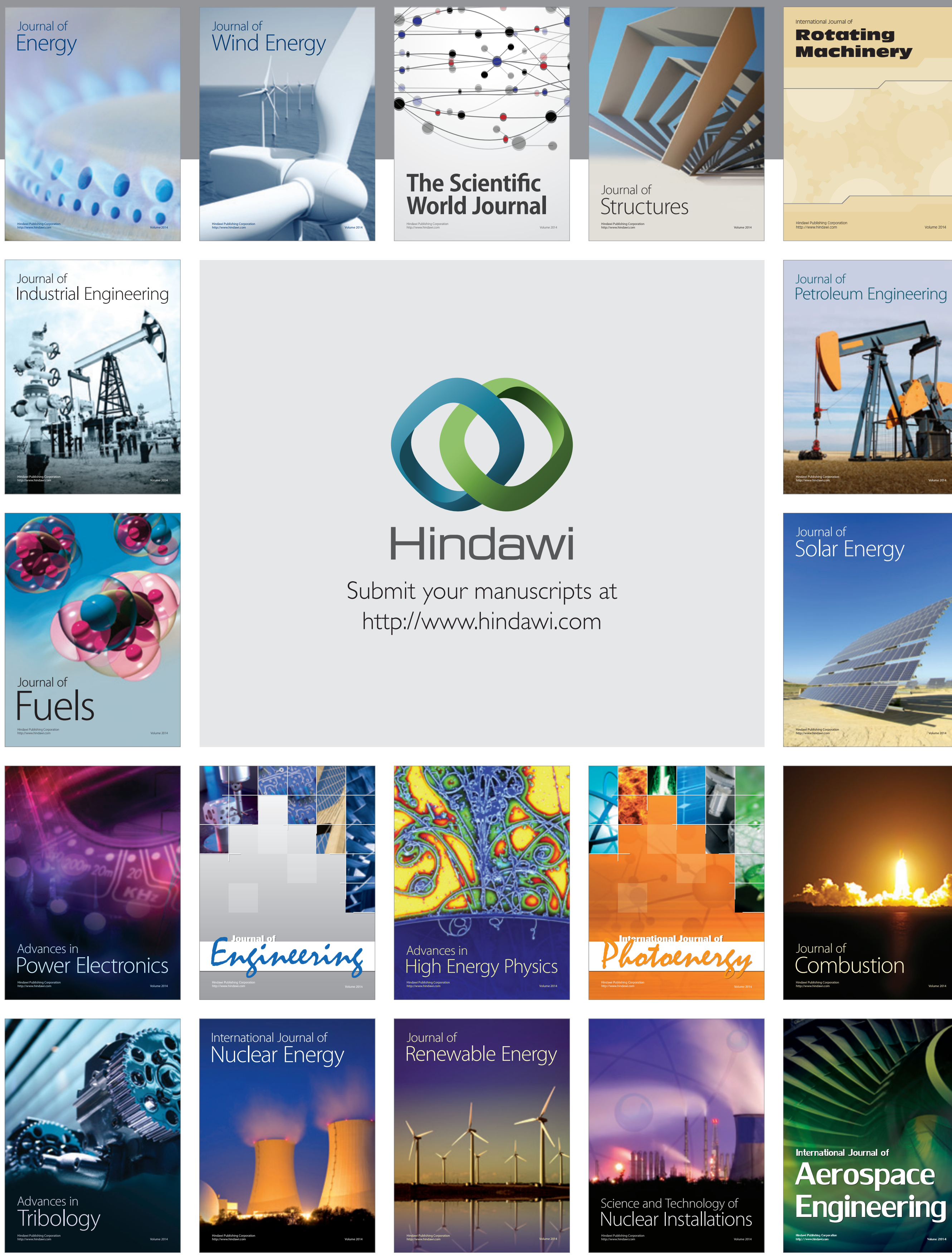

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