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Review Article

Global Solar Radiation Models: A Review

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Abstract: The Sun is a larger planent which emits light and heat to the Earth for many applications such as solar heating, cooking, drying and interior illumination of buildings. Solar radiation data are required by solar engineers, architects, agriculturists and hydrologists for many applications. In the past, several empirical correlations have been developed in order to estimate the solar radiation around the world. The main objective of this study is to review the global solar radiation models available in the literature. There are several formulae which relate global radiation to other climatic parameters such as sunshine hours, relative humidity and maximum temperature. In this paper, the models are classified into three viz: models based on ratio (H/H_o), non-linear models and models based on empirical coefficients 'a' and 'b'.

Keywords: Empirical Coefficients, Maximum Temperature, Solar Radiation, Sunshine Hours

1. Introduction

Solar energy is the most important energy resource to man and indeed it is essential factor for human life. Solar energy is the clean, abundant, renewable and sustainable energy resource from the sun which reaches the earth in form of light and heat. Solar energy occupies one of the most important places among the various possible alternative energy sources for both urban and rural areas. An accurate knowledge of the solar radiation distribution at a particular geographical location is of vital importance for the development of many solar energy devices and for estimates of their performance [1].

Solar radiation data may be considered as an essential requirement to conduct feasibility studies for solar energy systems. The knowledge of solar energy preferably gained over a long period should be useful not only to the locality where the radiation data is collected but for the wider world community [2]. In some developing countries, the facility for global radiation measurement is available at a few places while bright sunshine hours are measured at many locations. Some cannot even afford the equipment and techniques involved.

Solar radiation data are important tools for many areas of research and applications in various engineering fields, in particular for arid and semi-arid regions, where the number of solar observation sites is poor. So far, a number of formulas and methods have been developed to estimate daily or monthly global radiation at different places in the world. The availability of meteorological parameters, which are used as the input of radiation models, is the important key to choose the proper radiation models at any location. Among all such meteorological parameters, cloud cover and bright sunshine hours are the most widely and commonly used ones to predict daily global solar radiation and its components at any location of interest [3]. Most of these models estimate monthly average daily global solar radiation and are based on the modified Angstrom-type equation.

Empirical models which have been used to calculate solar radiation are usually based on the following factors:

1. Astronomical and Geometrical factors (solar constant, earth-sun distance, solar declination, hour angle, azimuth angle of the surface, tilt angle of the surface, sun elevation angle, sun azimuth angle, latitude, longitude and elevation of the site). Physical factors (scattering of air molecules, water vapor content, scattering of dust and other atmospheric constituents such as O_2, N_2, CO_2, etc.).
2. Meteorological factors (extra-terrestrial solar radiation, sunshine duration, temperature, precipitation, relative humidity, effects of cloudiness, soil temperature, evaporation, etc.).

2. Factors Affecting Solar Radiations

The following are factors that affect the intensity of solar radiation absorbed at the Earth's surface:

a) *The effect of the atmosphere:* The effect of the atmosphere in modifying the sun's radiation before it arrives at earth surface is quite complex. When the sun rays get to within about 40kilometer at earth surface some of the energy is absorbed in band of zone and some is absorbed and scattered by an upper dust layer which is periodically recharged volcanic eruption or galactic dust clouds. A considerable amount of energy is absorbed and scattered by dry air molecules, water vapor lying close to earth surface and seasonally varying lower layer dust [4].

b) *The distance between the Earth and Sun:* The distance between the earth and sun at aphelion is equal to 152million kilometer and at perihelia equal to 146.2million kilometer. The distance between earth and sun varies from season to season according to the rotation of earth about the sun [5].

c) *The incident angle of solar radiation:* The earth receives maximum radiation when the radiation is incident at perpendicular to earth surface. When the incident angle of radiation increase the amount of radiation decrease. Also the amount of radiation decrease with increase of atmosphere thickness which cross it [6].

d) *The length of day and rotation of earth:* The earth rotated about the sun in 365.25days and rotated by itself in 24hours and the seasonal variation produce according to the inclined angle of earth axis rotation. The length of the days vary the amount of radiation received per days, then for long day the earth receive more radiation, more than short day [5].

3. Solar Radiation Models

Solar researchers have developed many empirical correlations which determine the relation between solar radiation and various meteorological parameters. As the availability of meteorological parameters, which are used as the input of radiation models is the most important key and output of radiation models (i.e. solar irradiance and solar irradiation).

Among the models, some of them are based on ratio of monthly average daily global radiation to the extra terrestrial radiation (H/H_o), non-linear and some are based on empirical coefficients 'a' and 'b'.

3.1. Models Based on Ratio (H/Ho)

In this section, models which are based on ratio of monthly average daily global radiation to the extra terrestrial radiation (H/H_o) and some of models are estimated monthly or daily are presented:

3.1.1. Angstrom–Prescott Model

Angstrom was the first researcher that proposed a correlation for estimating monthly average daily global solar radiation in 1924 [7], who derived a linear relationship between the ratio of average daily global radiation to the corresponding value on a completely clear day (H/H_c) at a given location and the ratio of average daily sunshine duration to the maximum possible sunshine duration as:

$$\frac{H}{H_c} = a + b\left(\frac{S}{S_0}\right) \quad (1)$$

Where:

H is the monthly average daily global radiation,

H_c is the monthly average clear sky daily global radiation,

S is the monthly average daily hours of bright sunshine (h),

So is the monthly average day length (h),

a and b are empirical coefficients.

The above equation was most widely used correlation but there is some basic difficulty which lies in the definition of the term H_c [8] and the others have modified the method that replace the term H_c with extra-terrestrial radiation on a horizontal surface H_o rather than on clear day radiation and therefore proposed the following relation:

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

H_o is the monthly average daily extra-terrestrial radiation,

The values of the monthly average daily extra-terrestrial irradiation (H_o) can be calculated from the equation given below as [5].

$$H_0 = \frac{24}{\pi} I_{sc}\left[1 + 0.033\cos\left(\frac{360n}{365}\right)\right]\left[cos\varphi cos\delta sin\omega_s + \frac{\pi}{180}\omega_s sin\varphi sin\delta\right] \quad (3)$$

Where:

I_{sc} is the solar constant (1367Wm^{-2}),

φ is the latitude of the site,

δ is the solar declination,

ω_s is the mean sunrise hour angle for the given month

n is the number of days of the year starting from first January.

The solar declination (δ) and the mean sunrise hour angle (ω_s) can be calculated by following equations:

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

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

For a given month, the maximum possible sun-shine duration (monthly average day length, S_0) can be computed by using the following equation:

$$S_0 = \frac{2}{15}\omega_s \quad (6)$$

Although the Angstrom–Prescott equation can be improved to produce more accurate results, it is used as such for many applications. Some of the regression models based on the Angstrom–Prescott model which proposed in literature are given as follows:

a) Akpabio and Etuk model for Onne region (within the rain forest climatic zone of southern Nigeria) [9].

$$\frac{H}{H_0} = 0.23 + 0.38\left(\frac{S}{S_0}\right) \quad (7)$$

b) Lewis model for state of Tennessee, U.S.A. [10].

$$\frac{H}{H_0} = 0.14 + 0.57\left(\frac{S}{S_0}\right) \quad (8)$$

c) Rensheng *et al.,* model for 86stations in China [11].

$$\frac{H}{H_0} = 0.176 + 0.563\left(\frac{S}{S_0}\right) \quad (9)$$

d) After many years, the coefficients of the modified Angstrom-type model was provided by Page [12], and the coefficients was claimed to be applicable anywhere in the world:

$$\frac{H}{H_0} = 0.23 + 0.48\left(\frac{S}{S_0}\right) \quad (10)$$

e) Al-saad in 1990 derived the Angstrom-type equation to estimate the monthly average daily global radiatio n for Amman, Jordan [13]:

$$\frac{H}{H_0} = 0.174 + 0.615\left(\frac{S}{S_0}\right) \quad (11)$$

f) The following correlation, where the regression coefficients of the Angstrom–Prescott model seem to be as a function of the latitude of the site to estimate monthly average daily global solar radiation was proposed by Dogniaux and Lemoine (14):

$$\frac{H}{H_0} = 0.37022 + \left[0.00506\left(\frac{S}{S_0}\right) - 0.00313\right]\varphi + 0.32029\left(\frac{S}{S_0}\right) \quad (12)$$

g) This model is an Angstrom type model with a third parameter appears as the power of the sunshine duration ratio. A proposed non-linear model for the estimation of global solar radiation from available sunshine duration data was developed by Sen [15]:

$$\frac{H}{H_0} = a + b\left(\frac{S}{S_0}\right)^c \quad (13)$$

El-Sebaii *et al.,* [16] calibrated this model for Jeddah, Saudi Arabia in 2009 as:

$$\frac{H}{H_0} = -0.864 + 1.862\left(\frac{S}{S_0}\right)^{2.344} \quad (14)$$

3.1.2. Rietveld Model

By analysis of measured data collected from 42stations located in different countries, Rietveld [17] proposed an unified correlation to compute the horizontal global solar radiation. The Rietveld model, which is claimed to be applicable anywhere in the world, is given in the following equation:

$$\frac{H}{H_0} = 0.18 + 0.62\left(\frac{S}{S_0}\right) \quad (15)$$

The author also examined several published values of 'a' and 'b' coefficients of the Angstrom–Prescott model and noted that constants 'a' and 'b' are related linearly to the appropriate mean value of S/S_0 as follows:

$$a = 0.10 + 0.24\left(\frac{S}{S_0}\right) \quad (16)$$

$$b = 0.38 + 0.08\left(\frac{S}{S_0}\right) \quad (17)$$

Benson et al., Model

Benson *et al.,* (1984) proposed two different correlations for estimating monthly average daily global radiation for two intervals of a year depending on the climatic parameters [18]:

For January–March and October–December, the estimation formula was:

$$\frac{H}{H_0} = 0.18 + 0.6\left(\frac{S}{S_0}\right) \quad (18)$$

For April–September, the estimation formula was:

$$\frac{H}{H_0} = 0.24 + 0.53\left(\frac{S}{S_0}\right) \quad (19)$$

3.1.3. Luhanga and Andringa Model

In 1990, Luhanga and Andringa [19] developed their own model for estimating monthly average daily global solar radiation as follow:

$$\frac{H}{H_0} = 0.241 + 0.488\left(\frac{S}{S_0}\right) \quad (20)$$

3.1.4. Louche et al., Model

The model presented below was proposed by Louche *et al.,* [20] to predict monthly average daily global solar radiation:

$$\frac{H}{H_0} = 0.206 + 0.546\left(\frac{S}{S_0}\right) \quad (21)$$

Moreover, the Angstrom–Prescott model has been modified by using the ratio of (S/Snh) instead of (S/S0) by the same authors as presented below:

$$\frac{H}{H_0} = a + b\left(\frac{S}{S_{nh}}\right) \quad (22)$$

$$\frac{1}{S_{nh}} = \frac{0.8706}{S_0} + 0.0003 \quad (23)$$

Where

S_{nh} is sunshine duration that taking into account the natural horizontal of the site (hour).

3.1.5. Hargreaves and Samani Model

Maximum and minimum temperatures can also be used for estimation of monthly daily average solar radiation as recommended in 1982 by Hargreaves and Samani in the equation given below [21]:

$$\frac{H}{H_0} = a(T_{max} - T_{min})^{0.5} \quad (24)$$

Where:

T_{max} and T_{min} are mean maximum and mean minimum daily temperatures respectively (°C).

Initially, coefficient 'a' was set to 0.17 for arid and semi-arid regions. Hargreaves later recommended using a=0.16 for interior regions and a=0.19 for coastal regions [22].

By reviewing the work of Hargreaves and Samani, Allen in 1997 suggested employing a self-calibrating model to estimate mean monthly global solar radiation as in the equation below [23]:

$$\frac{H}{H_0} = K_r(T_{max} - T_{min})^{0.5} \quad (25)$$

Previously, Allen had expressed the empirical coefficient K_r as a function of the ratio of atmospheric pressure at the site (P_s, kPa) and at sea level (P_0, 101.3kPa) as follows [24]:

$$K_r = K_{ra}(\frac{P_s}{P_0})^{0.5} \quad (26)$$

For the empirical coefficient K_{ra}, Allen suggested values of 0.17 for interior regions and 0.20 for coastal regions.

Hunt *et al.,* in 1998, proposed a model by adding another coefficient 'b' to Hargreaves and Samani model [25]:

$$H = a(T_{max} - T_{min})^{0.5} H_0 + b \quad (27)$$

Annandale *et al.,* [26] modified Hargreaves and Samani model by introducing a correction factor for parameter 'a' to account the effects of reduced altitude and atmospheric thickness on H as:

$$\frac{H}{H_0} = a(1 + 2.7 \times 10^{-5} Z)(T_{max} - T_{min})^{0.5} \quad (28)$$

Bayat and Mirlatifi [27] used this model with a=0.15 to estimate the daily global solar radiation in Shiraz, Iran:

$$\frac{H}{H_0} = 0.15(1 + 2.7 \times 10^{-5} Z)(T_{max} - T_{min})^{0.5} \quad (29)$$

3.1.6. Garg and Garg Model

Garg and Garg [28] proposed a double linear relation for obtaining monthly mean daily global solar radiation as follows:

$$\frac{H}{H_0} = a + b\left(\frac{S}{S_0}\right) + cW \quad (30)$$

Where:

W(cm) is the atmospheric precipitable water vapor per unit volume of air and is computed according to Leckner [29]:

$$W = 0.0049RH\left[\frac{e^{\left(26.23 - 5416/T_k\right)}}{T_k}\right] \quad (31)$$

Where:

T_k is the mean air temperature in Kelvin (K)

El-Metwally model for Egypt [43].

$$\frac{H}{H_0} = 0.219 + 0.526\left(\frac{S}{S_0}\right) + 0.004W \quad (32)$$

3.1.7. Bristow and Campbell Model

Bristow and Campbell [30] developed a simple model for daily global solar radiation with a different structure in which H is an exponential function of ΔT in 1984:

$$\frac{H}{H_0} = a\left[1 - e^{(-b\Delta T^C)}\right] \quad (33)$$

Where:

ΔT is the temperature term difference (°C).

Coefficient 'a' represents the maximum radiation that can be expected on a clear day, and coefficients 'b' and 'c' control the rate at which 'a' is approached as the temperature difference increases.

In 1999, Goodin *et al.,* [31] refined the Bristow and Campbell model by adding H_0 term which act as a scaling factor allowing ΔT to accommodate a greater range of H values as shown below:

$$\frac{H}{H_0} = a\left[1 - e^{\left(-b\frac{\Delta T^C}{H_0}\right)}\right] \quad (34)$$

The results proved that this model provides reasonably accurate estimates of irradiance at non-instrumented sites and that the model can successfully be used at sites away from the calibration site [32].

Meza and Varas [33] assumed that 'a' and 'c' coefficients of Bristow–Campbell model are fixed and the only 'b' coefficient was adjusted to minimize the square errors as follows:

$$\frac{H}{H_0} = 0.75\left[1 - e^{(-b\Delta T^2)}\right] \quad (35)$$

3.1.8. Mahmood and Hubbard Model

Mahmood and Hubbard [34] estimated daily solar radiation based on maximum and minimum daily air temperatures and proposed the following model:

$$H = a(T_{max} - T_{min})^{0.69} {H_0}^{0.91} \quad (36)$$

$$H_{mod} = \frac{H - 2.4999}{0.8023} \quad (37)$$

Where:

H_{mod} is the estimated global solar radiation corrected for systematic bias, in MJ/m^2 day.

3.1.9. Swartman and Ogunlade Model

The global solar radiation can be expressed as a function of the (S/S_0) ratio and mean relative humidity (RH). In 1967, Swartman and Ogunlade [35] developed the following models:

$$H = a\left(\frac{S}{S_0}\right)^b RH^c \quad (38)$$

$$\frac{H}{H_0} = a + b\left(\frac{S}{S_0}\right) + cRH \quad (39)$$

Where

RH is the mean relative humidity (%).

3.1.10. Gopinathan Model

Gopinathan [36] introduced a multiple linear regression equation of the form:

$$\frac{H}{H_0} = a + b\cos\varphi + cZ + d\left(\frac{S}{S_0}\right) + eT + fRH \quad (40)$$

Abdallah [37] modified the Gopinathan model for Bahrain in 1994 as:

$$\frac{H}{H_0} = a + b\left(\frac{S}{S_0}\right) + cT + dRH \quad (41)$$

$$\frac{H}{H_0} = a + b\left(\frac{S}{S_0}\right) + cT + dRH + ePS \quad (42)$$

Where:

PS is the ratio between mean sea level pressure and mean daily vapor pressure.

Maghrabi [38] estimated in 2009, the ability of this model for estimating monthly mean global solar radiation in kWh/m^2 for Tabouk, Saudi Arabia:

$$\frac{H}{H_0} = -0107 + 0.70\left(\frac{S}{S_0}\right) - 0.0025T + 0.004RH \quad (43)$$

3.2 Non Linear Models

There are some models used to estimated monthly, weekly or daily solar radiations and these models are as follows:

3.2.1. Bahel Models

The world wide correlation for estimating monthly average daily global radiation based on bright sunshine hours and global radiation data of 48stations around the world, with varied meteorological conditions and a wide distribution of geographic locations was developed by Bahel [39]:

$$\frac{H}{H_0} = 0.16 - 0.87\left(\frac{S}{S_0}\right) - 0.61\left(\frac{S}{S_0}\right)^2 + 0.34\left(\frac{S}{S_0}\right)^3 \quad (44)$$

3.2.2. Black Model

By applying a data from many parts of the world, a quadratic equation for estimating global radiation was proposed by Black [40]:

$$\frac{H}{H_0} = 0.803 - 0.340C - 0.458C^2 (C \le 0.8) \quad (45)$$

Where:

C is mean total cloud cover during day time observations in octa.

3.2.3. DeJong and Stewart Model

In 1993, DeJong and Stewart [41] introduced the effect of precipitation in a multiplicative form as follow:

$$\frac{H}{H_0} = a(T_{max} - T_{min})^b (1 + cP + dP^2) \quad (46)$$

3.2.4. Hunt et al., Model

Hunt *et al.,* [42] introduced precipitation (P, mm) and (T_{max}, °C) in an additive form that have had the highest accuracy at eight sites in Canada:

$$H = a(T_{max} - T_{min})^{0.5} H_0 + bT_{max} + cP + dP^2 + e \quad (47)$$

3.2.5. El-Metwally Model

A non-linear correlation between clear index (H/H_0) and relative sunshine (S/S_0) for predicting global solar radiation was proposed in 2005 by El-metwally [43] as follows:

$$\frac{H}{H_0} = a^{\left(1/ S/S_0\right)} \quad (48)$$

The model used to estimate global radiation for Egypt was presented [43] as:

$$\frac{H}{H_0} = 0.713^{\left(1/ S/S_0\right)} \quad (49)$$

3.3. Models Based on Empirical Coefficients 'a' and 'b'

In this section, models which are based on empirical coefficients 'a' and 'b' and some of models are estimated monthly or daily are presented:

3.3.1. Kilic and Ozturk Model

In 1983, Kilic and Ozturk [44] calculated the 'a' and 'b' regression coefficients of Angstrom model for Turkey as:

$$a = 0.103 + 0.000017Z + 0.198\cos(\varphi - \delta) \quad (50)$$

$$b = 0.533 - 0.165\cos(\varphi - \delta) \quad (51)$$

3.3.2. Zabara Model

The correlated monthly 'a' and 'b' values of the Angstrom–Prescott model with monthly relative sunshine duration (S/S_0) as a third order function was derived by Zabara in 1986 as follows [45]:

$$a = 0.395 - 1.247\left(\frac{S}{S_0}\right) + 2.680\left(\frac{S}{S_0}\right)^2 - 1.674\left(\frac{S}{S_0}\right)^3 \quad (52)$$

$$b = 0.395 - 1.384\left(\frac{S}{S_0}\right) - 3.249\left(\frac{S}{S_0}\right)^2 + 2.055\left(\frac{S}{S_0}\right)^3 \quad (53)$$

3.3.3. Gopinathan Model

Another author, Gopinathan [46] in 1988 suggested 'a' and 'b' regression coefficients of Angstrom–Prescott model as a function of elevation (Z) and sunshine ratio (S/S_0) for estimation of the global solar radiation as given below:

$$a = 0.265 + 0.07Z - 0.135\left(\frac{S}{S_0}\right) \quad (54)$$

$$b = 0.401 - 0.108Z + 0.325\left(\frac{S}{S_0}\right) \quad (55)$$

Gopinathan [36] reported the following correlation for estimation of the global solar radiation:

$$\frac{H}{H_0} = \left[-0.309 + 0.539cos\varphi - 0.0693Z + 0.290\left(\frac{S}{S_0}\right)\right] + \left[1.527 - 1.027cos\varphi + 0.0926Z - 0.359\left(\frac{S}{S_0}\right)\right]\left(\frac{S}{S_0}\right) \quad (56)$$

Where:
Z is the altitude of the site (Km),
φ is the latitude of the site, and
S/S_o is sunshine ratio.

3.3.4. Gariepy's Model

Gariepy [47] has reported that the empirical coefficients 'a' and 'b' in the Angstrom–Prescott model are dependent on mean air temperature (T, °C) and the amount of mean precipitation (P, cm) and finally proposed the empirical coefficients as:

$$a = 0.3791 - 0.0041T - 0.0176P \quad (57)$$

$$b = 0.4810 + 0.0043T + 0.0097P \quad (58)$$

Where:
T is the mean air temperature (°C)
P is the mean precipitation in cm.

4. Conclusions

In this study, are view of available solar radiation models was conducted to assist in the selection of most appropriate and accurate model based on the available measured meteorological data. And finally, the following conclusions may be drawn from the present study:

A. Most of solar radiation models given to estimate the monthly average daily global solar radiation are of the modified Angstrom-type equation.
B. It may be concluded that the models presented in this study may be used reasonably well for estimating the solar radiation at a given location and possibly in anyplace with similar climatic conditions.
C. Solar radiation models are to measure amount of solar radiation hourly or daily.
D. It can also concluded that solar radiation can be affected due to some parameters such as atmospheric layer, distance between the Earth and Sun, incident angle of solar radiation, length of the day and rotation of Earth, e.t.c
E. The regression constants of some collected solar models have been generally presented to calculate the global solar radiation with high accuracy in a given location.

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