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A Trial to Predict The Diurnal Global Solar Irradiance Received on A Horizontal Plane for Clear Days in Terms of The Solar Angles.

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Abstract

A general distribution function is suggested to predict both symmetrical and asymmetric diurnal global solar irradiance

q (t) W/m^2 received on a horizontal surface, where "t "is the local day time "h".

The distribution is given in terms of well-established parameters, namely:

t_d:- the length of the solar day expressed in term of the solar angles.

t_{max} :- the time of the day at which the irradiance reaches its maximum value q_{max} W/m^2 for symmetrical distribution $t_{max} = \frac{td}{2}$ i.e., it occurs at the midday time.

t_d, $t_{max,}$ and q_{max} are taken as parameters.

The suggested expression can be easily integrated along the length of the day time.

This gives the daily totals of the received solar energy per unit horizontal area.

This is of vital technical importance for solar energy exploitations and applications.

Comparison between computed according to the present model and published experimental meteorological data in Barcelona (Spain), Hong Kong (China), Jeddah, and Makah (Saudi Arabia) is given as illustrative examples. Comparison with the published trials for the same locations is also clarified. The introduced model itself gives good fitting for the intermediate interval points of the local day time, which is the more effective region.

Keywords

Prediction Formula, Global Solar Irradiance, Symmetrical and Asymmetrical Distributions, Comparative Study.

1. Introduction

The prediction of the diurnal global solar radiation q (t) W/m^2 incident on a horizontal surface is needed as one important input parameter to study theoretically the design and performance of solar systems for solar energy exploitation, for example, the performance and efficiency of a solar cells, flat plate collectors, water heating and treatment, pool heating, space heating, solar cookers, (Heating, Ventilation, and air conditioning) (HVAC) technological systems. It is also required to study the production of electricity using molten salt technologies in which the liquid salt is pumped through panels in a solar collector for further heating.

Analysis of solar radiation measurements has aroused the interest of many investigators [1-19]. The experimental measurements for the considered distribution q (t) W/m^2 for clear sky [2] [5] [8-9] [11] [16-20] show a symmetrical distribution that passes through a maximum value q_{max} at the midday time $t_0 = \frac{t_d}{2}$ between sunrise "t_r" and sunset "t_s" in hours. Trials to introduce governing formulae are given [3] [9] [13] [15].

The received solar energy is a function of several variables [2] such as the nature and extent of cloud cover, the aerosol and other atmospheric constituents such as O_2, N_2, CO_2, O_3, dust, etc.

Such a function depends also on other parameters such as the sunshine hours, the solar declination angle, the latitude, the altitude, and the relative humidity [2].

As a result of these challenges, it is not always possible to predict theoretically the actual shape of such a function to get accurate values of the received irradiance for a given location. Different trials are given by different authors with different degrees of fitting accuracy [2] [4] [5] [8] [10] [12] [14]. Most of such trials are either semi-empirical or incomplete to form a closed system, or they are difficult to be integrated.

The need for more accurate trials with better fitting degrees is still required. El-Adawi et al. [2] introduce a power expression for such a function, the parameters of which were determined through the least fitting technique. The given expression is not easy to be integrated.

Good fitting with published experimental meteorological data is obtained with maximum relative error 11%. Other trials expressed the required distribution in the form of a polynomial in $(t - t_{max})$ [8] with relative maximum error 16%, or in $\left(\frac{t-t_{max}}{t_{max}}\right)^2$ [10] with maximum relative error 15% or as polynomial in (t/t_d) with a correction factor $[\sin(\pi t/t_d)]$[6] with maximum relative error 15%.

The present trial represents a new approach to introduce a suggested formula based on well-established solar data such as

the length of the solar day "t_d" in hours, which is well defined in [13], and is also expressed through the maximum value of the daily solar irradiance q_{max} W/m^2. The expression for (t_d) is well defined in literature on meteorological basis [13].

To get a closed system, the value of q_{max} is suggested in terms of the extraterrestrial solar constant adjusted for the variation of the distance between the sun and the earth along the time of year [2] [4]. Thus the introduced distribution is not a semi-empirical one. This is an advantage of the present trial. Moreover, it can be easily integrated, and thus it is feasible for practical applications.

A comparative study is made between the experimental meteorological published data of the received global solar irradiance in different locations [14] [16] [18] [19] and that computed according to the present suggested model. The relative errors are indicated.

2. Theory

The experimental measured meteorological values of the global solar irradiance q (*t*), W/m^2 received on a horizontal surface as measured by different authors [2] [5] [14] revealed in a general symmetrical distribution about a maximum average value q_{max} acquired at midday time (t_{max} between sunrise t_r and sunset t_s)

$$i.e.\ t_{max} = \frac{t_s - t_r}{2} = \frac{t_d}{2}.$$

This symmetrical behavior is shown to be true for the whole solar year [14].

Moreover, the behavior of this function for different locations reveals its universal character [2] [5] [11-12] [17] [19].

In the present trial the suggested model to predict the function q (*t*) W/m^2 is given in the form:

$$q(t) = A\left(\frac{t}{t_{max}}\right)^m \left(\frac{t_d - t}{t_d - t_{max}}\right) \quad (1)$$

Shifted time scale is considered for which $t_r = 0$. This distribution satisfies the following conditions:

i) At $t = t_r = 0$ $\quad q(t_r) = 0$ (2)

ii) At $t = t_d$ $\quad q(t_d) = 0$ (3)

iii) At $t = t_{max}$ $\quad q(t) = q_{max}$ (4)

This gives: $A = q_{max}$ (5)

iv) At $t = t_{max}$ $\quad \left.\frac{\partial q(t)}{\partial t}\right|_{t=t_{max}} = 0$ (6)

This gives:

$$m = \frac{t_{max}}{t_d - t_{max}} \quad (7)$$

For symmetrical distribution, $t_{max} = \frac{t_d}{2}$

This gives:

$$m = 1 \quad (8)$$

Finally, one gets for symmetrical distribution the following expression:

$$q(t) = q_{max}\left(\frac{t}{t_{max}}\right)\left(\frac{t_d - t}{t_d - t_{max}}\right) \quad (9)$$

For asymmetrical distribution:

$$q(t) = q_{max}\left(\frac{t}{t_{max}}\right)\left(\frac{t_d - t}{t_d - t_{max}}\right)^{\left(\frac{t_d - tmax}{tmax}\right)} \quad (10)$$

For symmetrical distribution, the total daily solar energy received per unit area of a horizontal surface is given as:

$$\int_0^{t_d} q(t)dt = \left(\frac{q_{max}}{t_{max}}\right)\frac{1}{t_d - t_{max}}\int_0^{t_d} t(t_d - t)dt = 0.66\, q_{max} t_d \quad (11)$$

Expression (9) is used to fit the published experimental data on global solar radiation incident on a horizontal surface in [7-8] [14] [18-19].

The obtained computed values revealed that the suggested distribution (Eq.9) gives overestimated values:

Accordingly, the distribution (Eq.9) is modified to be in the form:

$$q(t) = q_{max}\left(\frac{t}{t_{max}}\right)\left(\frac{t_d - t}{t_d - t_{max}}\right) e^{\frac{-|t - tmax|}{t_d}} \quad (12)$$

The term $e^{\frac{-|t-tmax|}{t_d}}$ in equation (12) represents a correction function where, $e^{\frac{-|t-tmax|}{t_d}} \leq 1$

Finally, the following distributions are recommended:

For symmetrical distribution:

$$\left[\frac{t_{max}}{t_d} = \frac{1}{2}\right]$$

$$q\,(t) = q_{max}\left(\frac{t}{t_{max}}\right)\left(\frac{t_d - t}{t_d - t_{max}}\right) e^{\frac{-|t - tmax\,|}{t_d}} \quad (13)$$

For asymmetrical distribution:

$$\left[\frac{t_{max}}{t_d} \neq \frac{1}{2}\right]$$

$$q\,(t) = q_{max}\left(\frac{t}{t_{max}}\right)\left(\frac{t_d - t}{t_d - t_{max}}\right)^{\left(\frac{t_d - tmax}{tmax}\right)} e^{\frac{-|t - tmax\,|}{t_d}} \quad (14)$$

It is worth to note that the length of the day "t_d" can be expressed in terms of the latitude L and the solar declination "δ" [15] as follows:

$$t_d = \frac{24h}{180^0} \cos^{-1}(\tan \delta \tan L) \quad (15)$$

Where,

$$\delta = 23.45 \sin 360 \left(\frac{284+n}{365}\right) \quad (16)$$

and "n" is the day number of the year starting from 1 January i.e,

(1 ≤ n ≤ 365).

To get a closed system of equations, the physical quantity q_{max} is suggested on the theoretical basis to be in the form [2-4] [9] [15]:

$$q_{max} = \alpha \bar{s} \quad (17)$$

Where, $\bar{s}$ is the extraterrestrial solar constant adjusted for the variation of the distance between the sun and the earth and along the time of the year [9]:

$$\bar{s} = s\left(1 + 0.033 \cos\left(\frac{360+n}{365}\right)\right) \quad (18)$$

And, $s = 1353 W/m^2$ [15] is the solar constant.

It is worth to note that q_{max} is computed [4] according to equation(17) for Barcelona (Spain), Hong Kong (China), Jeddah, and Makah (Saudi Arabia).

3. Computations

The function q (t) is computed according to Equation (12) for different locations.

The obtained results are compared with the corresponding meteorological published data as illustrative examples.

The measure of the fitting is taken as

$$\varepsilon = \left|\frac{q_{exp} - q_{cal}}{q_{exp}}\right| * \frac{100}{100}$$

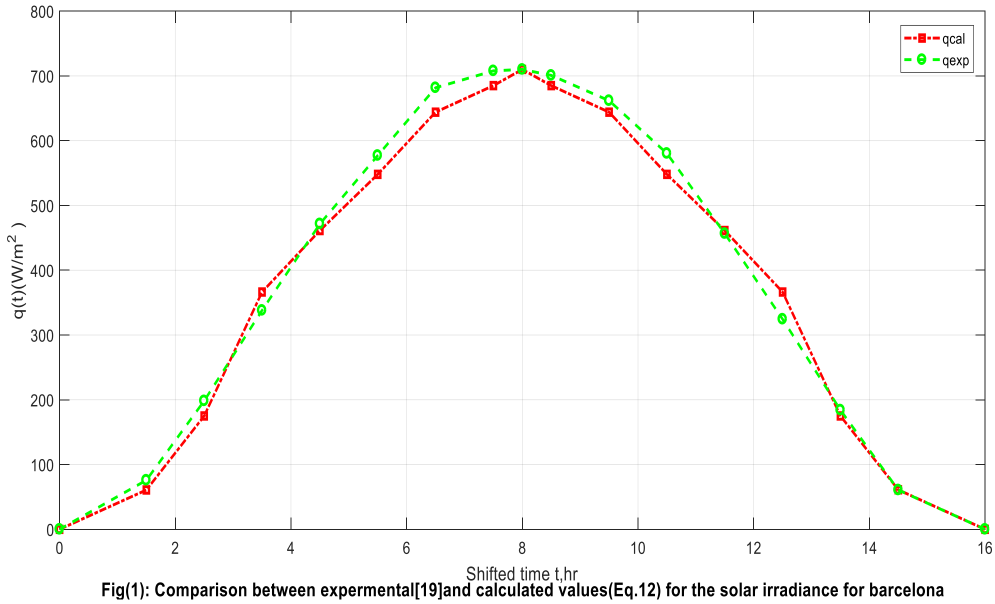
This step is summarized as follows:

1) The considered data for Barcelona (Spain) (Latitude41˚23'N, Longitude2˚7'E) January 1973 [11] are given in Table 1 and are illustrated graphically (as shown in Figure 1).
2) The data for Hong Kong (China) (Latitude 22˚19'N, Longitude 114˚10'E) December 1978 [20] are given in Table 2 and are illustrated graphically (as shown in Figure 2).

Table 1: Comparison between experimental [19] and calculated values (Eq. (12)) for solar irradiance for

Barcelona (Spain)

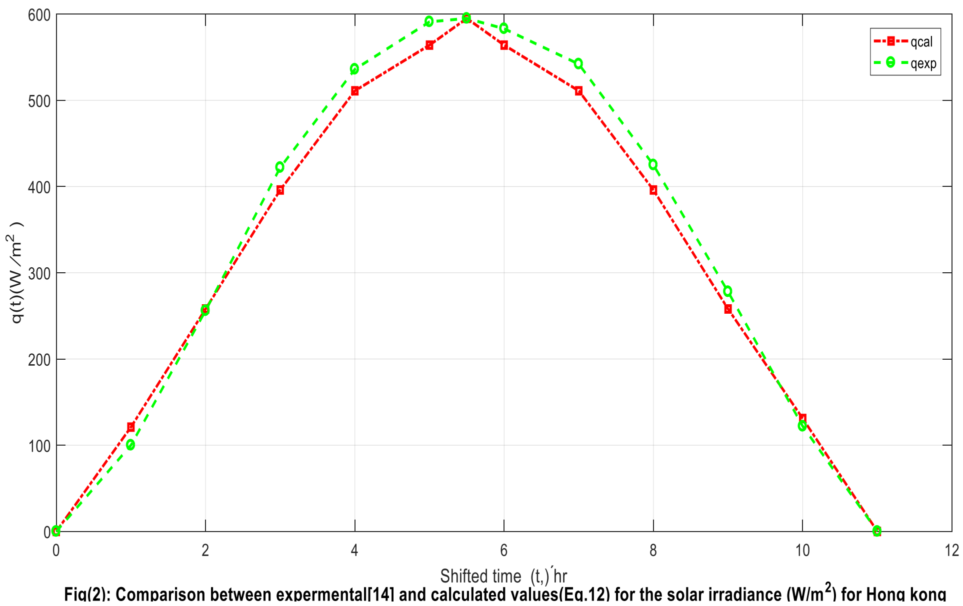
Local time,hr	**Shifted time** $\acute{t}, hr.$	$q_{exp}(W/m^2)$	$q_{cal}(W/m^2)$	**ε%**
4	0	0	0	0
5.5	1.5	75.8	60.73	20.84
6.5	2.5	198.3	175.49	11.75
7.5	3.5	338	366.36	8.39
8.5	4.5	471.5	461.30	2.16
9.5	5.5	577.1	547.99	5.04
10.5	6.5	681.7	643.73	8.50
11.5	7.5	707.8	685.47	3.15
12	8	710	710	0
12.5	8.5	700.8	685.47	2.19
13.5	9.5	661.8	643.73	5.75
14.5	10.5	580.3	547.99	5.57
15.5	11.5	456.6	461.30	1.030
16.5	12.5	324.4	366.36	12.93
17.5	13.5	184.1	175.46	4.67
18.5	14.5	60.7	60.73	0
20	16	0	0	0



Fig(1): Comparison between expermental[19]and calculated values(Eq.12) for the solar irradiance for barcelona

Table 2: Comparison between experimental [14] and calculated values (Eq. (12)) for solar irradiance for Hong Kong (China)

Local time, hr	Shifted time $\acute{t}, hr.$	$q_{exp}(W/m^2)$	$q_{cal}(W/m^2)$	ε %
6.5	0	0	0	0
7.5	1	100	130.65	30.65
8.5	2	255.58	257.56	0.77
9.5	3	422.26	376.09	10.93
10.5	4	536.15	511.54	4.59
11.5	5	590.5	563.86	4.51
12	5.5	594.5	595	0.08
12.5	6	583.38	563.86	3.34
13.5	7	541.71	511.54	4.59
14.5	8	425.03	376.09	11.52
15.5	9	277.8	257.56	7.28
16.5	10	122.23	130.65	6.89
17.5	11	0	0	0



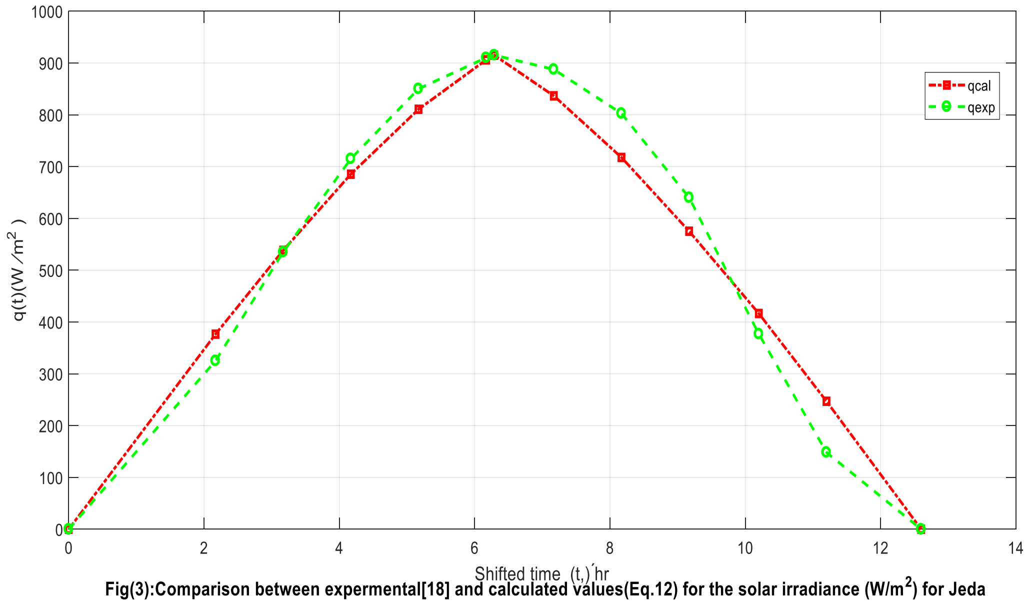
Fig(2): Comparison between expermental[14] and calculated values(Eq.12) for the solar irradiance (W/m^2) for Hong kong

3) The data for Jeddah (Saudi Arabia)(Latitude 21˚37'N, Longitude 40˚25'E) April 1982 [18] are given in Table 3 and are illustrated graphically (as shown in Figure 3).

4) The data for Makah (Saudi Arabia) (Latitude 38.5˚E, Longitude 21.5˚N) March 1983 [16] is given in Table 4 and is illustrated graphically (as shown in Figure 4).

Table (3): Comparison between experimental [18] and calculated values (Eq. (12)) for solar irradiance for Jeddah

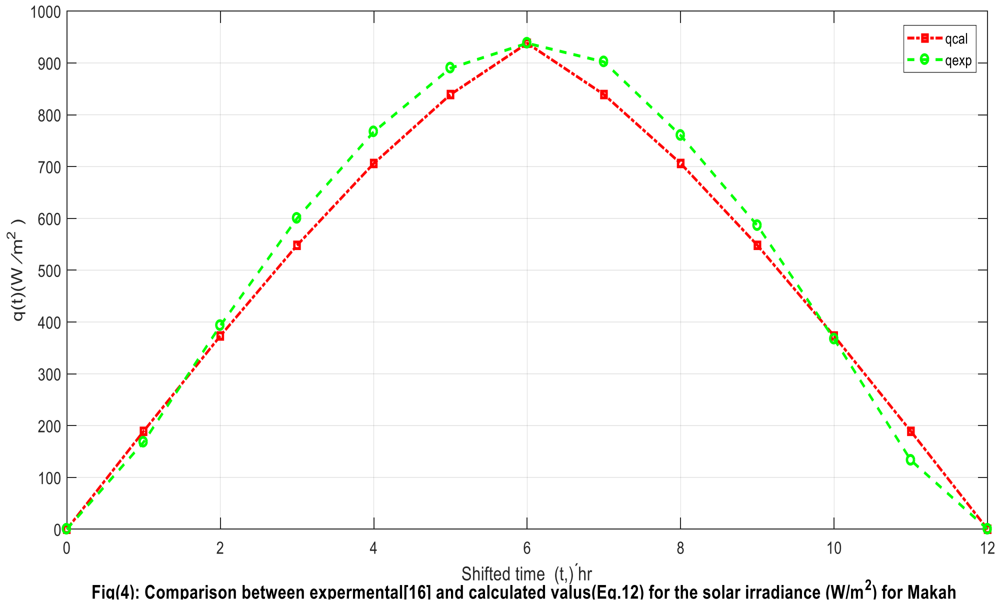
Local time, hr	**Shifted time** $\acute{t}, hr.$	$q_{exp}(W/m^2)$	$q_{cal}(W/m^2)$	**ε %**
6.08	0	0	0	0
8.25	2.17	325	376.53	15.85
9.25	3.17	535	538.34	0.62
10.25	4.17	715	685.27	4.16
11.25	5.17	850	810.52	4.64
12.25	6.17	910	905.98	0.44
12.37	6.29	915	915	0
13.25	7.17	887.5	836.48	5.75
14.25	8.17	802.5	717.59	10.58
15.25	9.17	640	575.20	10.12
16.25	10.17	376.8	416.40	10.51
17.66	11.17	148.3	247.13	66.64
18.66	12.58	0	0	0



Fig(3):Comparison between expermental[18] and calculated values(Eq.12) for the solar irradiance (W/m^2) for Jeda

Table (4): Comparison between experimental [16] and calculated values (Eq. (12)) for solar irradiance for Makah

Local time, hr	**Shifted time** $\acute{t}, hr.$	$q_{exp}(W/m^2)$	$q_{cal}(W/m^2)$	**ε %**
6.5	0	0	0	0
7.5	1	168	188.94	12.46
8.5	2	393	373.39	4.98
9.5	3	600	547.89	8.68
10.5	4	767	705.78	7.98
11.5	5	890	839.03	5.72
12.5	6	938	938	0
13.5	7	902	839.03	6.98
14.5	8	760	705.78	7.13
15.5	9	586	547.89	6.50
16.5	10	367	373.39	1.74
17.5	11	133	188.94	42.06
18.5	12	0	0	0



Fig(4): Comparison between expermental[16] and calculated valus(Eq.12) for the solar irradiance (W/m^2) for Makah

The relative errors obtained according to the present model are compared with the corresponding published meteorological values obtained for the same locations and at the same local day time, as shown in the corresponding tables.

It is revealed that the introduced model is promising and gives better fitting relative to some other trials as [6] and [12] irrespective of the extreme points. The model itself gives good fitting for the intermediate points. These points are the more effective one. The obtained relative errors are 11% for Hong Kong and 12% for Barcelona, Jeddah, and Makah respectively.

4. Conclusions

1) The introduced trial to predict the daily global solar irradiance for clear days is promising. It gives good fitting (≅ 12%) when compared with the corresponding measured data.
2) The introduced formula can easily be integrated along the local day time to get the total energy received per day per unit area.
3) This is of vital importance for technological applications.
4) The symmetrical and asymmetrical distributions are considered.
5) The given distribution is expressed in terms of a well-defined parameters, which is the length of the solar day t_d [15]. It is also expressed in term of the maximum value of the solar irradiance qmax attained during the considered day.
6) The latter is suggested in the present study to be expressed in terms of a modified solar constant. Thus the formula is based totally on pure theoretical arguments and consideration.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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Nomenclatures

t, Time variable (hr.).

t_r , sunrise time (hr.).

t_s , sunset time (hr.).

$t_d = (t_s - t_r)$, The length of the day (hr.).

t_{max}, The midtime between sunrise and sunset.

$q(t)$, W/m^2 Solar irradiance.

L, latitude.

Greek Symbols:

δ, Solar declination (defined in the text).