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Generation of typical solar radiation data for İstanbul, Turkey

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SUMMARY

Typical solar radiation data are very important as input in modelling, designing and performance evaluation of solar energy applications. In this study, typical solar radiation data were obtained for İstanbul, Turkey both from measured data and synthetic generation. Firstly, a test reference year for daily global solar radiation on a horizontal surface was generated using 19 years measured data. The daily global solar radiation as typical data for İstanbul was presented throughout a year in a tabular form. Secondly, the daily global solar radiation for İstanbul was expressed with a trigonometric equation using long-term measured data. It is expected that the typical data and the equation derived will be useful to the designers of solar energy systems as well as those who need to have fairly good estimates of daily global solar radiation for İstanbul. Copyright © 2003 John Wiley & Sons, Ltd.

KEY WORDS: global solar radiation; test reference year; solar radiation model; İstanbul (Turkey)

1. INTRODUCTION

Solar radiation data for applications of solar energy systems such as photovoltaics, solar thermal systems, and passive solar design should be readily available for particular settlement locations. Reliable solar radiation data is needed to provide input data in modelling, designing and performance evaluation of the solar energy applications (Shaltout and Tadros, 1994).

Solar energy is being seriously considered for satisfying significant part of energy demand in Turkey, as is in the world. In this respect, the importance of solar radiation data for design and efficient operation of solar energy systems has been acknowledged (Kaygusuz and Ayhan, 1999). Although, in recent years, many individual studies have been carried out on this subject for different locations of Turkey (Dincer *et al*., 1995; Kaygusuz and Ayhan, 1999; Şen and Tan, 2001; Ecevit *et al*., 2002; Oğulata and Oğulata, 2002; Üner and İleri,2000; Hepbaslı and Ulgen, 2002; Ulgen and Hepbaslı, 2002; Toğrul and Onat, 1999; Bulut *et al*., 1999), the studies have not been completed yet. In this study, typical solar radiation data for İstanbul (latitude = 40.58 N, longitude = 29.05 E and elevation = 39 m) were generated by using the daily global solar radiation measurements taken between the years 1983–2001. The global solar radiation data were taken from The State Meteorological Affairs General Directorate (DMİ) in computer diskettes for Göztepe weather station, İstanbul.

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2. DESCRIPTION OF METHODOLOGIES

The weather data such as outdoor temperature, relative humidity, wind velocity, and solar radiation are main inputs in the simulation and analysis of energy related systems. In the development of representative weather data, two approaches are generally used. One of which is the selection from real recorded data and the other is synthetic generation (Üner and İleri, 2000). In this study, both approaches were employed.

2.1. Generation of a test reference year

The real recorded data from past weather observations are selected for generation of representative weather data. A representative database for the one-year duration is known as test reference year (TRY) or typical meteorological year (TMY). TMY or TRY consists of the months selected from the individual years and concatenated to form a complete year (Marion and Urban, 1995; Said and Kadry, 1994; Petrakis *et al.*, 1998; Argiriou *et al.*, 1999; Gazela and Mathioulakis, 2001). Crow (1981) has developed representative weather data, so called the weather year for energy calculations (WYEC), for the American Society of Heating, Refrigeration and Air-Conditioning Inc. (ASHRAE). Many attempts have been made to produce such weather databases for different locations around the world (Shaltout and Tadros, 1994; Marion and Urban, 1995; Said and Kadry, 1994; Petrakis *et al.*, 1998; Argiriou *et al.*, 1999; Gazela and Mathioulakis, 2001; Crow,1981; Fagbenle, 1995).

Finkelstein–Schafer (FS) statistics (Finkelstein–Schafer, 1971) are the common methodology for generating typical weather data (Shaltout and Tadros, 1994; Marion and Urban, 1995; Said and Kadry, 1994; Petrakis *et al.*, 1998; Argiriou *et al.*, 1999; Gazela and Mathioulakis, 2001; Crow,1981; Fagbenle, 1995). According to these statistics (Finkelstein–Schafer, 1971), if a number, n, of observations of a variable X are available and have been sorted into an increasing order $X_1, X_2, \ldots, X_n$, the cumulative frequency distribution Function (CDF) of this variable is given by a function $S_n(X)$ which is defined as follows:

$$S_n(X) = \begin{cases} 0 & \text{for } X < X_1 \\ (k-0.5)/n & \text{for } X_k < X < X_{k+1} \\ 1 & \text{for } X > X_n \end{cases} \tag{1}$$

The FS by which comparison between the long-term CDF of each month and the CDF for each individual year of the month was done is given by the equation:

$$FS = (1/n)\sum_{i=1}^{n} \delta_i \tag{2}$$

where δ_i is the absolute difference between the long-term CDF of the month and one year CDF for the same month at X_i ($i = 1, 2, \ldots, n$), n being the number of daily readings of the month.

δ_i and $F(X_i)$ are expressed with the following equations:

$$\delta_i = \max\left[\left|F(X_i) - (i-1)/n\right|, \left|F(X_i) - i/n\right|\right] \tag{3}$$

$$F(X_i) = 1 - \exp(-X_i/\bar{X}) \tag{4}$$

where X_i is an order sample value in a set of n observations sorted in an increasing order and $\bar{X}$ is the sample average.

Table I. The Test Reference Years with minimum (min) FS for monthly mean daily global solar radition for İstanbul.

Month	Year	Min FS
January	1998	0.035
February	1991	0.047
March	1987	0.027
April	1999	0.029
May	1999	0.034
June	1995	0.042
July	1991	0.045
August	2001	0.043
September	2000	0.035
October	1999	0.044
November	1992	0.037
December	1992	0.031

In this study, the function FS was computed for each month of every year of the data set. The representative year for each month was determined on the basis that the representative year is that of the smallest value of FS.

By applying the above methodology for all the months in the database, the TRY for solar radiation data was formed for İstanbul. Table I gives the test reference years with minimum FS for monthly mean global solar radiation for İstanbul. The value of minimum FS varies between 0.027 and 0.047.

The daily global solar radiation on a horizontal surface (I) obtained from the test reference years is given in Table II. As can be seen from the table, the minimum and maximum values of daily global solar radiation on a horizontal surface are, respectively, 0.68 MJ m^{-2} on 24 January and 26.76 MJ m^{-2} on 22 June, with an annual average value of 13.62 MJ m^{-2}.

Variation of TRY and the long-term all available measured data is shown in Figure 1. Both data fluctuate significantly and are very random throughout the year.

2.2. Expression of daily global solar radiation with a mathematical equation

The weather variables such as temperature and solar radiation are neither completely random nor deterministic; hence it is very difficult to present all variance mathematically. On the other hand, it is necessary to know the changes of weather data as well as possible throughout the year. Therefore, many attempts have been made to develop models for generation of typical weather variables, both daily and hourly (Knight *et al*., 1991). They range from simple empirical relations to complex models (Dincer *et al*., 1995; Ulgen and Hepbaslı, 2002; Sezai and Taşdemiroğlu, 1995; Mohandes *et al*., 2002; Alaruri and Amer, 1993; Dorvlo, 2000; Badescu, 1999; Gordon and Reddy, 1988; Jain and Lungu, 2002).

Time series, Fourier series, and regression analysis are mostly used techniques for synthetic generation of weather variables (Sezai and Taşdemiroğlu, 1995; Mohandes *et al*., 2002; Alaruri and Amer, 1993; Dorvlo, 2000; Badescu, 1999; Gordon and Reddy, 1988). The main advantage of the synthetic generation of weather variable is the readily usage of mathematical expressions in the computer programs and thus, not requiring tedious inputting work for the variables and database files for simulation.

Table II. Daily global solar radiation values obtained from test reference year data for İstanbul.

Day	Global solar readiation on a horizontal surface (MJ m−2 day)											
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
1	6.45	6.51	14.31	3.34	19.21	25.12	18.52	17.86	18.83	12.72	10.90	4.07
2	6.99	9.49	8.77	9.00	19.11	23.89	18.36	8.74	20.46	10.10	8.50	2.29
3	5.48	8.54	5.74	11.80	20.66	25.20	21.50	24.23	20.62	14.12	10.30	8.29
4	5.74	11.67	4.96	7.95	21.47	24.66	25.24	25.37	20.60	15.09	10.25	9.14
5	6.57	10.36	5.32	18.02	19.34	23.33	11.59	24.01	19.21	12.86	3.49	2.87
6	6.05	9.23	16.71	17.53	2.69	21.60	4.92	25.33	11.62	14.29	10.77	7.12
7	7.35	4.75	9.69	17.79	21.95	23.71	17.93	23.43	20.15	11.35	5.55	3.19
8	7.48	5.73	5.53	19.55	24.86	20.39	22.49	23.21	22.02	2.59	11.23	7.48
9	7.59	4.87	16.41	17.68	24.90	7.51	22.94	22.89	17.83	3.79	2.96	7.23
10	5.49	3.91	7.01	18.61	20.39	22.72	23.38	23.27	18.06	14.63	6.58	3.97
11	5.50	8.41	13.71	10.19	22.78	26.28	26.03	20.93	18.42	9.80	9.82	5.02
12	7.18	8.41	5.54	19.55	20.42	25.37	26.07	20.24	4.73	16.48	10.58	2.08
13	8.32	6.84	14.12	20.04	18.36	20.83	23.12	5.02	16.04	15.67	1.41	1.88
14	7.12	6.98	16.49	6.05	21.42	24.39	25.04	19.58	18.51	15.12	3.44	3.57
15	7.01	3.64	11.59	21.15	21.75	19.19	25.91	23.81	18.54	5.30	9.95	5.55
16	7.42	9.57	16.73	17.94	21.80	25.25	21.93	20.48	12.59	12.13	10.25	1.41
17	7.01	1.59	9.21	9.54	11.90	25.57	26.71	22.38	18.38	5.39	8.54	1.11
18	7.42	8.41	5.26	20.52	22.68	21.08	22.77	22.53	18.26	14.09	6.44	2.29
19	4.24	5.74	18.39	22.00	16.56	17.79	20.49	3.33	17.66	2.39	5.58	1.02
20	4.24	13.86	18.98	22.18	24.78	18.54	23.18	4.66	15.63	3.67	1.76	2.22
21	2.47	13.02	19.54	15.57	21.75	23.78	23.86	23.48	17.43	5.55	3.04	8.49
22	1.81	6.56	16.14	21.73	22.40	26.76	23.07	19.94	16.25	6.46	4.18	1.05
23	1.23	4.60	6.78	18.81	22.18	23.97	19.13	19.97	15.62	2.38	5.20	6.35
24	0.68	6.68	2.27	20.11	18.64	22.39	24.35	19.15	5.43	9.20	6.66	4.57
25	2.41	2.29	2.98	19.29	15.14	26.05	24.63	17.83	16.34	10.20	8.79	1.76
26	0.70	7.89	17.97	12.13	19.64	26.40	26.20	20.41	18.31	12.89	4.35	3.84
27	3.33	5.94	18.96	22.20	22.99	24.14	24.34	20.79	7.76	12.58	3.49	6.78
28	1.13	12.23	13.25	13.69	25.28	18.93	23.99	17.82	11.70	11.43	6.23	2.96
29	7.40	—	17.47	20.90	25.02	12.82	25.35	18.53	13.50	11.29	4.07	7.38
30	6.13	—	20.04	18.95	22.28	26.16	23.76	20.83	16.73	4.89	1.71	7.75
31	9.03	—	14.98	—	23.92	—	20.22	20.07	—	10.27	—	6.00

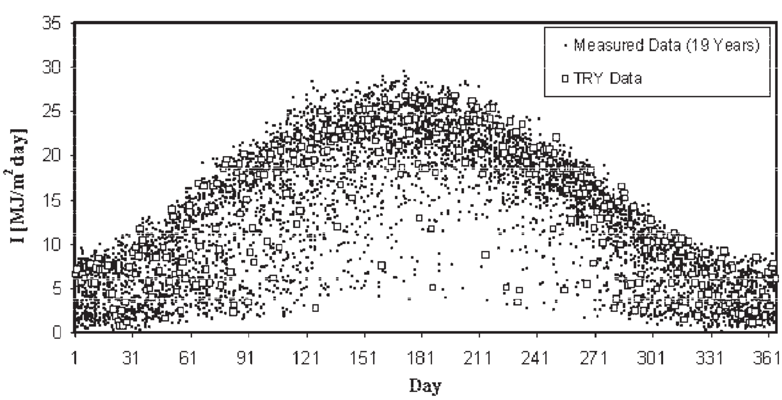

Figure 1. Variation of TRY and the long-term measured daily global solar radiation data for İstanbul.

Table III. The coefficients and statistical values for Equation (5).

I_1	I_2	± MAE (MJ m^{-2}day)	MRE (MJ m^{-2}day)	RMSE (MJ m^{-2}day)	r
21.41	2.57	3.24	0.33	4.20	0.84

In the present study, a simple mathematical model for daily global solar radiation based on a trigonometric function was attempted to simulate the long-term measured data. The function has only one parameter: the day of the year. The daily global solar radiation on a horizontal surface (I) in MJ m^{-2}day is

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

where d is the number of the day starting from 1 January. For the 1 January $d=1$, and for 31 December $d=365$. I_1 and I_2 are the coefficients determined by means of statistical analysis for which the details are given below.

The coefficients and the values for mean absolute error (MAE), mean relative error (MRE), root-mean-square error (RMSE), and correlation coefficient (r) of the equation obtained are given in Table III. For better data modelling, the RMSE, MAE and MRE should be minimum and the correlation coefficient r should approach to unity as closely as possible. In the current study, the coefficients of Equation (5) were determined by considering RMSE, MAE and MRE which are defined as (Daniel *et al*., 1971; Johnson and Bhattacharyya, 1996):

Root mean square error (RMSE):

$$\mathrm{RMSE} = \left(\frac{\sum_{i=1}^{m}(\mathrm{CV}_i - \mathrm{MV}_i)^2}{m - m_\mathrm{p}}\right)^{1/2} \tag{6}$$

where CV denotes the value calculated from Equation (5), MV denotes the measured value, m is the number of values, and m_p is the number of the parameters in the particular model. m_p is 2 for the model used in this study.

Absolute error (AE):

$$\mathrm{AE} = |\mathrm{CV} - \mathrm{MV}| \tag{7}$$

Relative error (RE):

$$\mathrm{RE} = \frac{|\mathrm{CV} - \mathrm{MV}|}{\mathrm{MV}} \tag{8}$$

Correlation coefficient (r):

$$r \equiv \sqrt{\frac{S_\mathrm{t} - S_\mathrm{r}}{S_\mathrm{t}}} \tag{9}$$

where S_t and S_r are defined as follows:

$$S_\mathrm{t} = \sum_{i=1}^{m}(\mathrm{MMV} - \mathrm{MV}_i)^2 \tag{10}$$

$$S_\mathrm{r} = \sum_{i=1}^{m}(\mathrm{MV}_i - \mathrm{CV}_i)^2 \tag{11}$$

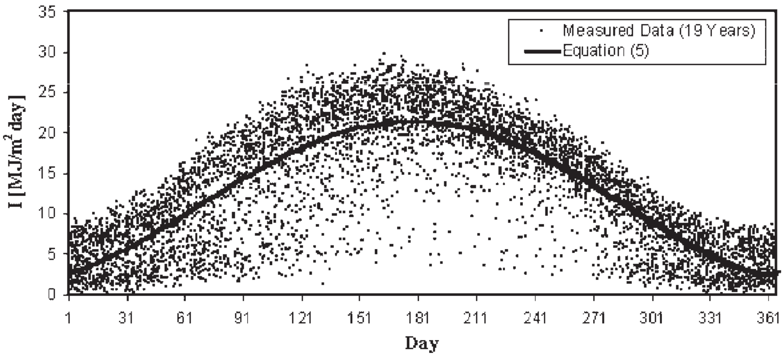

Figure 2. Variation of daily global solar radiation throughout the year for İstanbul.

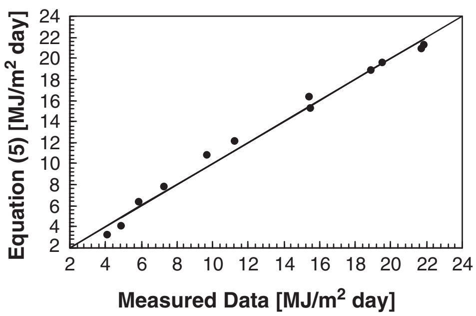

Figure 3. The long-term measured monthly mean solar radiation versus the monthly mean solar radiation obtained from Equation (5).

where MMV is the average of measured values (MV) and it is simply given by

$$\mathrm{MMV} = \frac{\sum_{i=1}^{m} \mathrm{MV}_i}{m} \tag{12}$$

It can be seen from Table III that the values of statistical indicators are at an acceptable level. This means that the equation obtained represent the measured data with acceptable errors.

Variation of the long-term measured data and the data obtained from Equation (5) in a year is depicted in Figure 2. As shown in Figure 2, although the long-term measured solar radiation data fluctuate and are very random, the values obtained from Equation (5) follow this variation throughout the year.

The monthly mean values of the daily solar radiation obtained from Equation (5) and the long-term measured data are compared in Figure 3. It can be seen that the accuracy of the equation is very good on monthly bases.

Figure 4 shows variation of the monthly mean values of the daily solar radiation obtained from Equation (5), TRY and the long-term measured data. As can be seen from the figure, both the TRY data and the data obtained from Equation (5) represent the long-term recorded solar radiation data with a good accuracy. The agreement among three data sets is reasonably good.

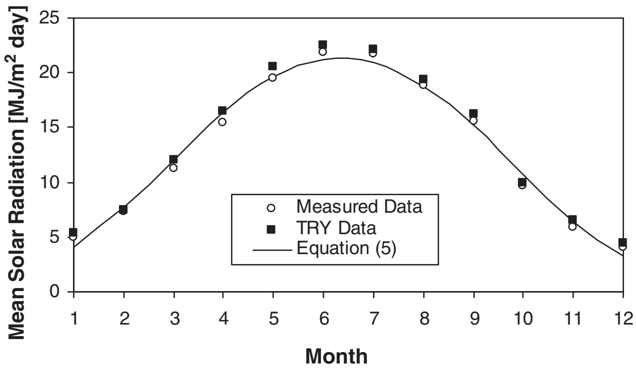

Figure 4. Variation of monthly mean of the daily solar radiation for İstanbul.

3. CONCLUSIONS

Generation of typical solar radiation is very important for the calculations concerning many solar applications. In this study, a test reference year for global solar radiation for İstanbul, Turkey was produced using 19 years measured data. The daily global solar radiation on a horizontal surface for İstanbul was presented throughout year in a tabular form. It is seen that both long-term measured and the TRY data are very random throughout the year.

The daily global solar radiation for İstanbul was also expressed with a trigonometric equation, which is only function of day. The accuracy of the equation is very good especially on monthly bases. It is expected that this equation will be useful to the designers of solar energy systems as well as those who need to have fairly good estimates of daily solar radiation in İstanbul.

NOMENCLATURE

TRY	= test reference year
TMY	= typical meteorological year
WYEC	= weather year for energy calculations
FS	= Finkelstein–Schafer function
$S_n(X)$	= increasing step function
CDF	= cumulative distribution function
δ_i	= absolute difference between the long-term CDF and one year CDF
X_i	= an order sample value in a set of n observations in an increasing order
n	= number of daily readings
$\bar{X}$	= sample average
max	= maximum
min	= minimum
I	= daily global solar radiation on a horizontal surface (MJ/m^{2}day)
I_1, I_2	= coefficients (Equation (5))
d	= number of the day
MAE	= mean absolute error
MRE	= mean relative error

RMSE	= root-mean-square error
r	= correlation coefficient
S_t	= standard deviation
S_r	= deviation from calculated value
CV	= calculated value
MV	= measured value
m	= number of values
m_p	= number of the parameters
MMV	= average of measured values

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