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Full Length Research Paper

Generation of representative solar radiation data for Aegean Region of Turkey

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Typical solar radiation data is needed in calculation and assessment of many solar energy applications. In this study, typical solar radiation years for seven provinces located in Aegean Region of Turkey were generated from the daily global solar radiation data measured during at least for 15 years, using the Finkelstein-Schafer statistical method. The typical daily global solar radiation data for the locations considered were presented throughout a year in a tabular form. The data obtained were also analyzed. It is expected that the typical data presented for Aegean Region will be useful to the designers of solar energy systems.

Key words: Finkelstein-Schafer method, solar radiation, test reference year, Aegean region, Turkey.

INTRODUCTION

Solar radiation is the fuel of solar energy systems. Solar radiation data are the key parameter for building energy analysis and designing and performance evaluation of solar energy systems. So, it is crucial to know the solar radiation data for determining solar potential and technical and economic analysis of solar energy systems. Nowadays, it is known that there are energy simulation computer programs for evaluating the performance of solar energy systems and building energy systems and they require the relevant meteorological data series of the location as part of their input. The meteorological data series consist of solar radiation, temperature, relative humidity and wind speed. Long term averages of these weather data are not used, but preferably the repress-entative weather data sets of the site are generated to use for this purpose. Since weather conditions can vary significantly from year to year, there is a need to derive a customized weather data set that can well represent the long term averaged weather conditions over a year.

The need for such appropriate meteorological data led to the development of methodologies for generating the so- called typical meteorological years (TMYs), a term mainly used in the USA, or test reference years (TRYs) or Design reference years (DRYs), terms mainly used in Europe (Skeiker, 2004). TMY or TRY is a representative data that consists of the month selected from the individual years and concatenated to form a complete year. The intended use is for computer simulations of solar energy conversion systems and building systems. A TMY or TRY is not necessarily a good indicator of conditions over the next year or even the next five years. Rather, it represents conditions judged to be typical over a long period of time (Marion and Urban, 1995). Typical weather year data sets can be generated for several climatic variables or only for solar radiation (Shaltout and Tadros, 1994; Bulut, 2004; Bulut et al., 2009).

Many attempts have been made to generate such weather databases for different areas around the world using various methodologies. Pissimanis et al. (1988) generated a typical meteorological year for the city of Athens. Shaltout and Tadros (1994) created a typical solar radiation year for Egypt by using daily data of global solar radiation obtained from long-term measurements. Said and Kadry (1994) generated typical weather years for the cities of Dhahran, Riyadh, Jeddah, Khamis-Mushayt and Hail in Saudia Arabia. A test reference year for Ibadan, Nigeria was presented by Fagbenle (1995). Petrakis et al. (1998) produced a typical year for Nicosia, Cyprus. A total of 17 methodologies for generating test reference years (TRYs) reported in literature were applied to 20-year hourly measurements of weather data from Athens, Greece by Argiriou et al. (1999). They

Abbreviations: TRY, Test reference year; **TMY,** typical meteorological year.

showed that the TRY giving the closest performance of the systems as predicted using long-term data, is the modified Festa-Ratto method. Kalogirou (2003) presented a new type typical meteorological year for Nicosia, Cyprus. The presented typical meteorological year was generated from a simple typical meteorological year created from available hourly meteorological data recorded during the period 1986 – 1992 using the Filkenstein–Schafer statistical method. Bilbao et al. (2004) generated test reference years for two cities, Madrid and Valladolid (Spain) using three different methodologies. Skeiker (2004) generated a typical meteorological year for Damascus zone using the Filkenstein–Schafer statistical method. Sawaqed et al. (2005) reported on the development of typical meteorological years (TMYs) for seven different locations in Oman based on measured meteorological data Rahman and Dewsbury (2007) discussed the methods of selecting typical weather data and described the selection of test reference years (TRYs) for Subang, Malaysia. Typical meteorological years (TMYs) for 60 cities in the five major climatic zones (severe cold, cold, hot summer and cold winter, hot summer and warm winter, mild) in China were investigated and presented by Yang et al. (2007). Janjai and Deeyai (2009) compared the performance of three TMY generation methods: the Sandia, the Danish and the Festa–Ratto methods and they used these methods to generate TMYs at four meteorological stations in Thailand. The generation of typical meteorological year (TMY) for eight typical cities representing the major climate zones of China was conducted by Jiang (2010). A set of ISO test reference year (TRY) data have been developed for 7 Korea locations by Lee et al. (2010). David et al. (2010) introduced a new weather data generation tool, Runeole, which is capable of generating a set of typical meteorological year (TMY) data directly from inconsistent hourly databases. The tool developed was used to create a large set of typical meteorological years for Reunion Island by David et al. (2010). There are some useful studies present TMYs or TRYs for different locations of Turkey. Üner and İleri (2000) generated typical hourly weather data for the selected 23 provinces that represent demographic and climatic conditions of Turkey. Ecevit et al. (2002) used daily sunshine duration instead of daily global solar radiation to generate a TMY for Ankara. Bulut (2003) generated a test reference year for daily global solar radiation on a horizontal surface for Istanbul, Turkey using 19 years measured data. Bulut (2004) also presented typical solar radiation years for South-Eastern Anatolia, Turkey. Bulut et al. (2009) generated typical solar radiation years for six provinces located in the Aegean Region of Turkey from the daily global solar radiation data. When examining the literature, one of the most common methodologies for generating a TMY or TRY is the one proposed by Hall et al. (1978) using the Filkenstein– Schafer (FS) statistical method (Filkenstein and Schafer, 1971). So, the main aim of this study is to generate representative solar radiation data for seven provinces located in the Aegean region of Turkey using the Filkenstein–Schafer statistical method.

MATERIALS AND METHODS

Description of the study area and data sets

In Turkey, meteorological measurements are taken and the related records are kept by the Turkish State Meteorological Service (Turkish initials "DMİ"). Meteorological stations are located in city centers and there is generally only one station in each city. In this study, the global solar radiation data were taken from the Turkish State Meteorological Service in computer diskettes for each province. The daily global solar radiations recorded during the period 1981 - 2001 are used for generation of the typical solar radiation data. There were missing and invalid measurements in the data and they were marked and coded as 99999 in the files. So, the data were checked for wrong entries and missing data. The missing and invalid measurements, accounting for approximately 0.25% of the whole database, were replaced with the values of preceding or subsequent days by interpolation. In the calculations, the year was excluded from the database if more than 15 days measurements were not available in a month. Table 1 provides the geographical characteristics of provinces such as latitude, longitude and altitude above sea level and the periods of the data considered. The location of Aegean region with its provinces is shown on Turkey's map in Figure 1. Provinces in the region are Afyon, Aydin, Denizli, İzmir, Kütahya, Manisa, Muğla, Uşak. Manisa is excluded in this study because of lack of solar radiation data. The Aegean region is situated in the western part of Turkey which took the name of the Aegean Sea that extends from the Mediterranean Northward between Greece and Turkey. The region occupies 11% of the total area of Turkey with its 79.000 square kilometers of land. Most of the population and cities are concentrated on the coast line because of its convenience for sea transportation and tourism. The Aegean region is also both industrialized and agriculturalized. The Aegean coastal plain enjoys an exceptionally mild climate, with soft, verdant springs, hot summers, sunny autumns and warm winters marked by occasional showers. Aegean region has perpendicular mountains to its shores and many valleys between them, thus permitting the sea climate reach inner parts of the region, although some of the provinces inland show also characteristics of continental climate.

Method

Finkelstein-Schafer (FS) statistics (Filkenstein and Schafer, 1971) are the most common methodology for generating typical weather data. This method is an empirical methodology for selecting individual months from different years over the available period. According to FS statistics (Filkenstein and 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,…,X_n, the cumulative frequency distribution Function (CDF) of this variable is given by a function $S_n(X)$ which is defined as follows:

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

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:

Table 1. Geographical and solar radiation database information for the provinces located in Mediterranean Aegean of Turkey.

				Daily global solar radiation data	
Province	**Latitude (N)**	**Longitude (E)**	**Altitude (m)**	**Period**	**Total years**
Afyon	38° 44'	30° 34'	1034	1984 - 1998	15
Aydın	37° 50'	27° 50'	56	1983 - 1998	16
Denizli	37° 45'	29° 5'	425	1984 - 1998	15
İzmir	38° 23'	27° 4'	29	1983 - 2001	19
Kütahya	39° 25'	29° 59'	969	1985 - 1998	14
Muğla	37° 17'	28° 22'	646	1983 - 1998	15
Uşak	38° 40'	29° 24'	919	1981 - 1995	13

Figure 1. Location of Aegean region and its provinces in Turkey.

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

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,…,n), n being the number of daily readings of the month.

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

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

$$F(X_i) = 1 - \exp(-X_i / \overline{X}) \quad (4)$$

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

Finally, the representative year for each month of the data set was determined on the basis that the representative year is that of the smallest value of FS, that is,

$$TRY = \min(FS) \equiv \min(\delta_i) \quad (5)$$

RESULTS AND DISCUSSION

By applying Finkelstein-Schafer (FS) statistics which the methodology given above for all the months in the database, the test reference year for daily global solar radiation data was formed for seven provinces of Aegean region of Turkey. Due to lack of wet-bulb temperature, relative humidity and wind speed data, the study could not be extended to include these parameters. However, detailed weather data such as new outdoor design conditions, heating and cooling degree-days and bin values for the Aegean region were presented by Bulut et al. (2001), Büyükalaca et al. (2001), Bulut et al. (2002) and Bulut et al. (2003) in previous studies. Table 2 gives the test reference years with minimum FS for monthly mean global solar radiation for all locations considered in this

Table 2. Test Refence Years with minimum Finkelstein-Schafer (min FS) and monthly mean of daily global solar radiation (I_{TRY}) for Aegean region of Turkey.

Province	Month	Year	Min(FS)	I_{TRY} (MJ/m^{2}day)	Province	Month	Year	Min(FS)	I_{TRY} (MJ/m^{2}day)
Afyon	Jan.	1986	0.045	7.17	Kütahya	Jan.	1991	0.07	6.4
	Feb.	1992	0.055	11.14		Feb.	1986	0.066	9.51
	Mar.	1985	0.054	15.8		Mar.	1986	0.064	14.14
	Apr.	1998	0.035	18.45		Apr.	1995	0.063	17.62
	May	1984	0.04	21.53		May	1986	0.068	21.01
	June	1989	0.04	24.55		June	1988	0.067	23.58
	July	1993	0.043	24.88		July	1986	0.068	24.33
	Aug.	1989	0.038	22.56		Aug.	1986	0.07	22.15
	Sep.	1984	0.04	18.86		Sep.	1990	0.068	17.88
	Oct.	1986	0.04	12.67		Oct.	1991	0.064	10.78
	Nov.	1998	0.037	8.17		Nov.	1988	0.059	7.35
	Dec.	1990	0.051	6.46		Dec.	1986	0.058	5.3
Aydın	Jan.	1998	0.035	8.66	Muğla	Jan.	1993	0.062	7.87
	Feb.	1990	0.037	11.34		Feb.	1995	0.038	9.6
	Mar.	1986	0.033	16.04		Mar.	1986	0.043	13.12
	Apr.	1998	0.042	20.07		Apr.	1986	0.042	16.7
	May	1989	0.041	23.64		May	1998	0.043	19.38
	June	1993	0.043	26.25		June	1993	0.043	21.92
	July	1988	0.046	26.1		July	1984	0.033	21.28
	Aug.	1988	0.048	23.69		Aug.	1993	0.035	19.4
	Sep.	1992	0.04	20.28		Sep.	1994	0.034	16.51
	Oct.	1993	0.045	14.15		Oct.	1984	0.047	12.35
	Nov.	1985	0.049	9.09		Nov.	1997	0.043	8
	Dec.	1995	0.051	7.1		Dec.	1989	0.041	5.86
Denizli	Jan.	1995	0.044	6.1	Uşak	Jan.	1993	0.051	8.27
	Feb.	1984	0.063	9.04		Feb.	1983	0.043	10.67
	Mar.	1995	0.035	11.56		Mar.	1983	0.045	15.18
	Apr.	1998	0.045	15.49		Apr.	1994	0.04	18.09
	May	1989	0.042	18.16		May	1992	0.039	21.13
	June	1998	0.038	20.9		June	1985	0.042	24.25
	July	1988	0.039	20.66		July	1988	0.041	23.62
	Aug.	1995	0.034	17.97		Aug.	1989	0.048	21.86
	Sep.	1985	0.045	15.24		Sep.	1985	0.045	18.49
	Oct.	1996	0.046	10.53		Oct.	1987	0.047	12.97
	Nov.	1990	0.035	6.58		Nov.	1995	0.039	8.38
	Dec.	1993	0.034	5.01		Dec.	1993	0.043	6.67
İzmir	Jan.	2000	0.035	8.32					
	Feb.	1983	0.034	10.73					
	Mar.	1983	0.03	15.28					
	Apr.	1987	0.031	19.27					
	May	1988	0.043	22.25					
	June	1997	0.044	25.11					
	July	1986	0.031	25.59					
	Aug.	1986	0.028	23.22					
	Sep.	1986	0.038	19.27					
	Oct.	1985	0.033	13.77					
	Nov.	1996	0.04	8.76					
	Dec.	1987	0.043	6.49					

Table 3. Typical daily global solar radiation values obtained from test reference Year data for Aydın.

Day	Global solar radiation on a horizontal surface (MJ/m^{2}day)											
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
1	9.88	11.82	17.48	17.53	20.57	26.92	27.02	22.25	20.94	16.25	12.81	9.34
2	8.66	11.54	5.37	18.67	17.77	27.44	24.08	24.78	22.09	15.85	11.96	7.79
3	5.88	12.28	15.02	22.29	13.24	16.62	26.87	24.5	20.2	14.99	7.46	8.39
4	9.39	12.66	5.17	22.97	27.02	24.51	27.42	24.64	21.06	12.79	8.39	5.11
5	9.43	11.85	12.03	23.31	21.51	25.64	25.89	24.97	21.69	16.22	6.57	5.5
6	7.01	9.07	17.38	24.29	27.36	22.78	27.36	24.16	21.97	17.33	10.38	6.71
7	7.48	11.05	16.45	20.49	23.21	28.03	24.39	22.26	22.22	16.94	7.4	5.18
8	10.45	13.14	15.54	21.72	7.82	28.68	26.47	22.13	22.76	16.73	11.92	9.78
9	9.94	12.96	16.43	21.86	21.07	24.28	25.14	25.06	21.68	16.9	12.08	10.21
10	9.46	11.64	16.5	19.06	27.96	23.66	25.74	24.56	21.98	16.9	13.06	7.66
11	10.22	5.34	16.73	21.04	28.12	27.78	27.01	24.76	21.19	14.35	12.7	9.58
12	11.05	14.17	18.85	23.8	26.74	26.82	27.96	25.29	21.12	15.87	12.16	9.83
13	9.62	3.79	15.52	24.12	27.44	27.98	27.28	24.21	20.88	15.61	12.04	8.07
14	9.68	7.87	18.98	5.11	25.84	27.95	26.84	24.41	20.92	16.21	11.94	9.12
15	9.06	4.47	19.98	24.1	20.64	27.75	26.36	24.34	20.38	14.34	11.32	8.54
16	7.11	1.61	18.84	23.82	26.72	21.05	27.45	23.8	20.03	14.8	10.93	9.28
17	8.17	14.27	17.33	22.76	22.78	25.27	27.49	22.85	19.78	14.49	10.71	9.49
18	9.37	16.2	18.98	24.81	24.16	22.1	27.81	24.25	20.8	14.47	6.54	8.21
19	7.86	15.95	20.97	12.52	27.6	28.21	25.27	23.41	19.58	13.97	3.16	1.34
20	4.23	15.42	20.12	26.86	14.89	29.59	26.17	23.37	19.26	13.09	4.95	3.16
21	4.27	15.52	11.19	23.04	11.93	28.32	25.12	23.11	19.72	13.19	10.26	8.38
22	2.63	15.6	11.12	20.59	26.95	27.69	25.29	21.55	19.72	13.12	9.95	8.07
23	10.64	13.17	16.44	26.84	21.55	27.08	25.19	22.76	19.31	12.44	9.67	9.02
24	12.29	16.44	19.46	22.28	25.06	27.28	26.59	23.33	19.09	11.63	7.33	2.17
25	12.29	16.4	19.15	2.12	25.78	27.06	25.8	23.53	18.89	11.79	5.25	4.91
26	10.51	15.85	7.68	11.7	28.86	26.01	25.64	22.62	18.94	10.94	7.92	1.75
27	2.91	6.22	19.21	22.88	27.7	27.85	25.34	22.79	17.86	11.79	3.78	9.39
28	4.63	1.26	17.45	13.17	27.35	28.18	24.16	24.24	18.89	11.83	7.45	6.63
29	10.5	-	12.79	11.68	28.66	28.57	25.84	24.85	18.46	10.23	1.68	6.19
30	10.63	-	18.24	26.81	28.41	26.37	24.78	23.42	17.06	11.28	10.81	2.06
31	13.07	-	20.79	-	28.09	-	25.18	22.23	-	12.18	0	9.32

study. As can be seen from the Table, the minimum and maximum values of monthly mean of daily global solar radiation on a horizontal surface (I_{TRY}) in the Aegean Region are, respectively, 5.01 MJ/m^2 in December in Denizli, and 26.25 MJ/m^2 in June in Aydın, with an annual average value of 15.42 MJ/m^2.

Although typical solar radiation years were formed for each province considered, it is not practical to present all of them in this paper due to space limitations. Table 3 and 4 show typical solar radiation year for Aydın and Muğla, respectively. Discontinuities between the adjacent months are evident, because the adjacent months are generally selected from different years. Variation of daily global solar radiation on a horizontal surface generated from test reference year and the all available long-term measured data for Aydın and Muğla are shown in Figure 2 and 3, respectively. It can be seen from the Figures that both data fluctuate significantly and are very random throughout the year.

In Figure 4, the generated typical solar radiation (I_{TRY}) data is compared with long-term measured data set to see differences between I_{TRY} data and the measured data for all the locations considered in this study. Comparisons were made on a monthly basis for daily global solar radiation. As shown from Figure 4, there is a reasonably good agreement on a monthly basis. It is seen that the I_{TRY} data is quite favorable on monthly basis and always bigger than the long-term measured data.

Conclusion

Typical solar radiation data is very important for calculations concerning many solar applications and building energy analysis. In this study, representative years for daily global solar radiation for seven provinces located in

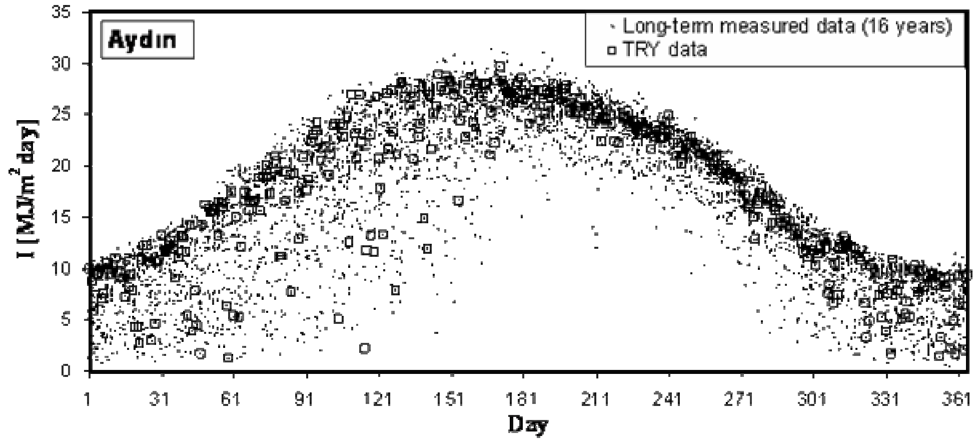

Figure 2. Annual variation of long-term measured daily global solar radiation for Aydın and comparison with the generated typical solar radiation (I_{TRY}) data.

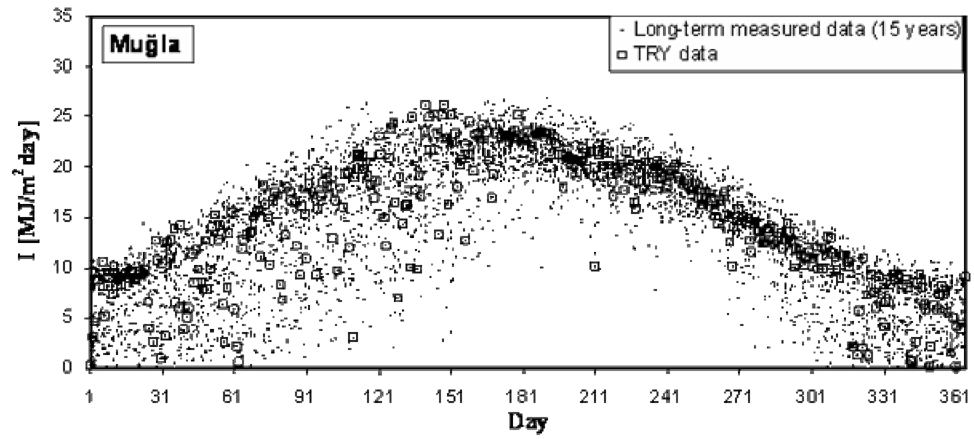

Figure 3. Annual variation of long-term measured daily global solar radiation for Muğla and comparison with the generated typical solar radiation (I_{TRY}) data.

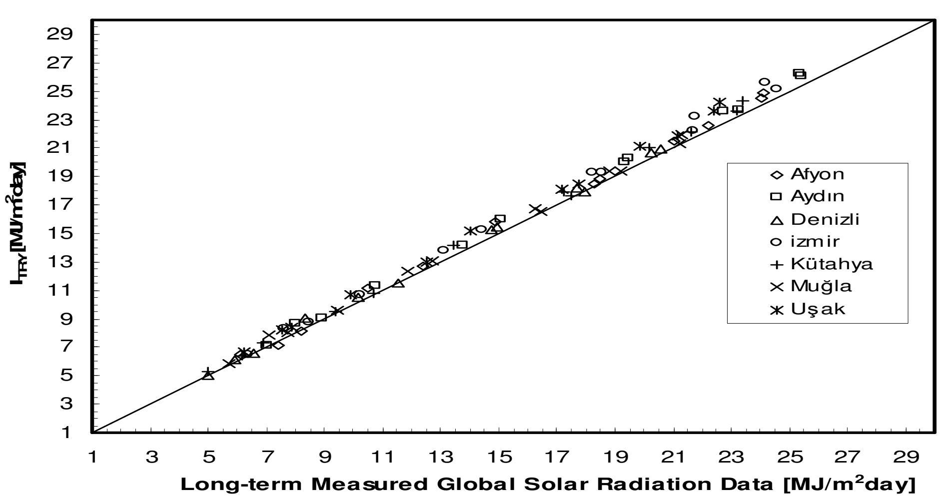

Figure 4. Comparison of monthly averages of long-term measured global solar radiation data with TRY data for provinces of Aegean Region.

Table 4. Typical daily global solar radiation values obtained from test reference year data for Muğla.

	Global solar radiation on a horizontal surface (MJ/m^{2}day)											
Day	**Jan.**	**Feb.**	**Mar.**	**Apr.**	**May**	**June**	**July**	**Aug.**	**Sep.**	**Oct.**	**Nov.**	**Dec.**
1	0.33	3.27	15.57	10.91	23.03	22.34	22.51	21.42	19.77	14.41	11.96	9.38
2	3.05	12.36	5.81	18.21	21.15	23.33	23.44	20.18	20.19	12.65	9.8	8.8
3	4.67	10.87	2.22	17.53	14.95	18.03	21.96	20.13	18.81	11.5	11.87	9.23
4	8.82	12.76	0.59	17.18	12.19	20.04	21.9	21.41	18.54	14.21	13	8.87
5	9.29	13.84	11.85	9.18	20.85	20.68	23.01	20.16	18.34	14.51	12.9	8.24
6	10.57	6.44	12.79	15.85	23.75	12.66	23.22	18.46	18.34	13.45	11.32	8.73
7	5.21	5.93	13.2	17.09	24.29	21.26	23.45	17.03	17.89	12.85	11.09	7.96
8	8.21	14.12	13.36	18.36	16.36	24.41	23.4	19.7	17.62	12.22	9.78	0.75
9	9.45	3.79	13.46	19.31	6.84	19.48	23.17	19.39	17.62	12.47	8.94	0.68
10	7.42	5.04	15.06	17.95	18.89	23.2	23.18	20.29	18.34	13.57	11.23	2.68
11	10.13	6.02	15.58	18.17	14.33	23.4	23.39	17.63	16.81	13.79	11.28	8.51
12	8.92	11.34	15.7	12.82	16.18	22.68	22.54	21.5	16.32	12.76	10.59	9.14
13	8.78	8.47	11.02	16.58	16.31	24.06	22.86	20.58	16.2	12.25	10.06	8
14	8.24	11.65	18.1	9.67	10	22.76	22.25	19.65	17.55	12.99	2.22	6.36
15	9.24	9.9	16.29	17.86	24.85	23.51	21.22	16.48	16.88	13.4	1.96	5.8
16	9.43	8.45	14.95	16.04	17.63	20.51	21.17	15.76	17.34	11.86	1.21	0.19
17	8.97	7.79	10.25	19.23	9.9	16.93	17.91	18.54	16.59	12.68	5.68	2.12
18	9.61	12.61	16.6	19.39	19.04	19.23	20.98	20.09	15.07	14.23	1.94	6.18
19	8.79	7.84	17.47	12.02	17.09	23.32	21.68	17.86	14.31	13.52	10.91	5.85
20	8.97	9.87	17.15	3.09	23.52	24.14	20.56	20.47	16.53	12.56	7.2	7.3
21	9.74	13.98	8.36	18.91	26.06	22.82	20.73	19.72	17	9.99	1.23	8.09
22	9.21	15.26	6.83	20.97	24.94	23.22	19.39	20.46	17.56	11.88	9.19	7.26
23	9.29	12.79	13.14	21.14	21.67	23.02	20.6	19.41	15.27	11.68	7.56	7.71
24	9.82	14.05	18.01	19.64	25.19	22.43	20.35	20.03	12.39	11.24	6.02	5.58
25	6.56	6.27	17.46	20.99	23.36	22.89	21.81	20.19	10.09	10.23	9.08	1.52
26	4.06	2.57	16.58	20.4	13.17	22.77	21.27	19.92	13.96	10.9	6.43	5.1
27	2.66	8.05	16.43	19.01	24.95	23.56	19.68	19.36	14.61	11.58	4.19	0.23
28	12.52	13.42	12.13	18.15	26.15	24.99	21.45	19.11	15.79	10.88	6.53	4.09
29	10.67	-	9.2	16.81	22.87	23.21	19.09	17.76	14.55	10.88	6.4	3.86
30	0.93	-	16.16	18.54	16.34	22.84	10.15	19.2	15.09	12	8.3	4.51
31	10.37	-	15.32	-	25.03	-	21.45	19.46	-	9.77	-	9.07

Aegean region of Turkey were produced using the data measured at least for 15 years. The daily global solar radiation data on a horizontal surface for the region was presented throughout year in a tabular form. It was seen that both long-term measured and the typical data are very random throughout the year. It was found that there is a good agreement between long-term data and typical data on monthly basis. It was also seen from the data that the region has a high solar energy potential. It is expected that the presented typical solar radiation data for Aegean Region will be useful to the designers of solar energy systems and energy experts.

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