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Calculation of solar radiation data on horizontal and tilted surfaces for Trabzon, Turkey

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Abstract
An analysis of measured solar radiation data in Trabzon (lat. 41o10'N, long. 40o20'E, placed on the Black Sea side) is presented in the form of hourly-average, monthly-average daily and percentage frequency distribution. The calculated data corresponds to period from January 2000 to December 2000. Applying measured data, correlation models for calculating the hourly and monthly diffuse radiations derived.

Keywords: solar radiation, global solar radiation, correlation models.

1. Introduction

Recently, interest increasingly focused on the use of solar energy following the energy crisis in the 1970s and due to an increase in conventional energy prices and environmental effects, such as air pollution, depletion of the ozone layer, greenhouse effects. Solar energy is one option for reducing greenhouse gas emissions in thermal electricity generation by photovoltaics. On the other hand, solar energy seriously considered for satisfying part of the energy demand in the Turkey as in the world. In this respect, the importance of climato-logical and solar radiation data for the design and efficient operation of solar energy sytems and associated energy storage system has been recognized [1-19].

The long-term performance analysis and the design of solar energy systems require long-term average values of solar radiation. The measurement of solar radiation on the horizontal surface has started in Turkey, in 11997 by State Meteorological Works (DMI), at 65 locations, using Rebitzsch type bimetallic pyranographs.

However, these pyranograps have not been calibrated due time. Effort has been devoted to correct the data of these instruments, and it is concluded that neither the corrected nor the uncorrected data of Robitzsch type bimetallic pyranographs should be used in solar energy analysis. An attempt to establish a network of calibrated pyranometers at six locations also failed [6]. Figure 1 and 2 shows global horizontal radiation (irradiation) and direct normal radiation maps, respectively for Turkey [1-9].

This paper presents the results of measured and calculated solar radiation data and relevant parameters for between January 2000 and December 2000 [7].

2. Measured data

The obtained data is global and diffuse radiations on a horizontal surface measured using the Kipp-Zonen pyranometer during the heating season in Trabzon. The hours of bright sunshine also measured by the Regional Meteorological Station in Trabzon used. Obtained radiation data from the Meteorological Station used to calculate solar radiation on horizontal and tilted surface solar data.

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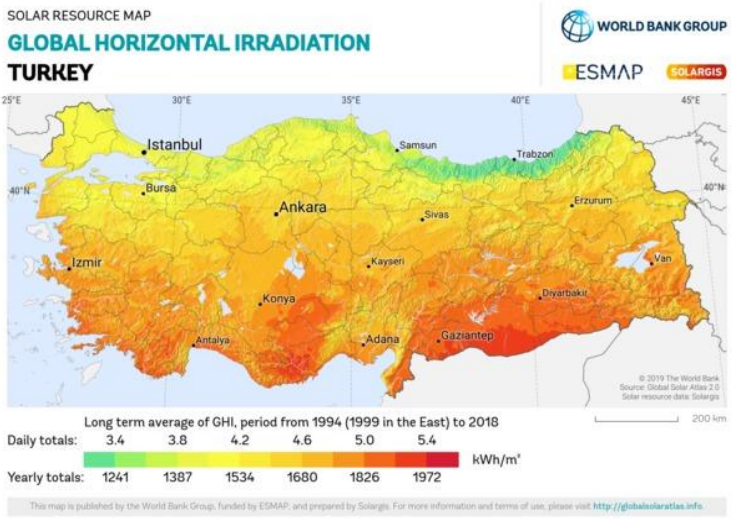

Figure 1. Global horizontal radiation map for Turkey.

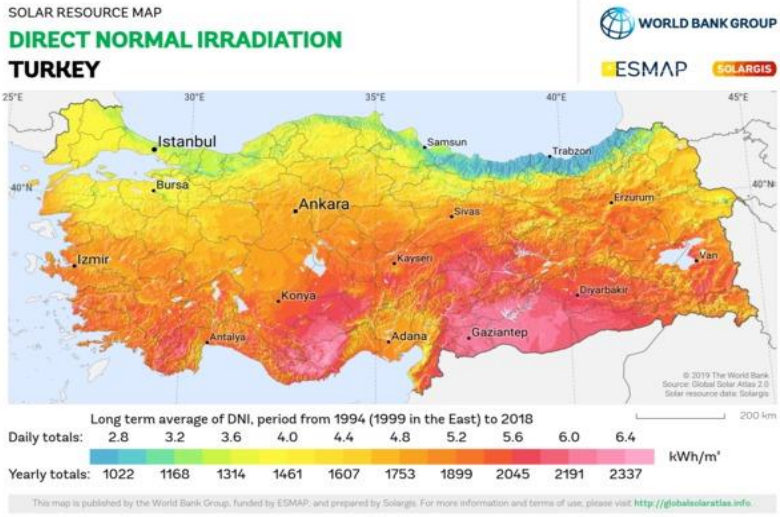

Figure 2. Direct normal irradiation map for Turkey.

3. Analysis of the data and the correlations

The calculations are given below are based on generally accepted equations [8-19]. The monthly average clearness index K_T is:

$$K_T = H/H_o \quad (1)$$

where H_o is the monthly average daily extraterrestrial radiation and can be calculated as:

$$H_o = [(24*G_{sc})/\pi][1+0.033 \cos(360n/365)][(\cos\Phi \cos\delta \sin\omega_s + [(\pi\omega_s/180)\sin\Phi \sin\delta] \quad (2)$$

where G_{SC} is the solar constant (1367 W/m^2), n is the day of the for each month in Table 4, ϕ is the latitude of the location and the declination δ is calculated using

$$\delta = 23.45 \sin[360(284+n/365)] \quad (3)$$

and ω_s can be found from the following equation

$$\cos\omega_s = -\tan\Phi \tan\delta \quad (4)$$

The hourly clearness index k_T can also be defined as:

$$k_T = (I/I_o) \quad (5)$$

I_o is calculated by the following equation

$$I_o = [(12*3600)/\pi]*I_{SC}*[1+0.033 \cos(360 n/365)]*\{\cos\Phi \cos\delta(\sin\omega_2 - \sin\omega_1) + [(\omega_2 - \omega_1)/180]\sin\Phi \sin\delta\} \quad (6)$$

The value of N can be calculated from the following

equation:

$$N = (2/15)\cos^{-1}(\tan\Phi \tan\delta) \quad (7)$$

Applying statistical methods to the measured values, the following equations have been derived;

$I_D/I = 0.670 \quad k_T \leq 0.267$

and

$I_D/I = 0.785 - 0.803\ k_T$

$0.267 < k_T < 0.620$

$(r^2 = 0.928)$ (8)

$H_D/H = 0.789 - 0.869\ K_T$

$0.252 < K_T < 0.610$

$(r^2 = 0.978)$ (9)

Table 1. Hourly averaged global solar radiation on a horizontal surface (W/m^2)

Hour	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
4-5	0.0	0.0	0.0	0.0	63	81	75	82	0.0	0.0	0.0	0.0
5-6	0.0	0.0	0.0	133	210	253	217	193	140	31	0.0	0.0
6-7	0.0	66	87	321	381	477	392	335	314	167	70	0.0
7-8	94	244	230	474	545	644	588	481	453	300	216	77
8-9	223	419	475	565	678	777	692	617	586	454	342	216
9-10	384	523	656	663	768	860	779	691	670	544	426	356
10-11	433	615	733	740	817	902	827	726	698	593	475	391
11-12	419	631	742	747	827	916	837	719	684	572	461	405
12-13	356	614	719	733	795	853	805	677	642	523	398	349
13-14	230	530	607	621	719	777	728	610	537	412	279	244
14-15	98	370	447	530	614	637	624	481	384	244	140	147
15-16	0.0	174	166	370	433	519	443	368	209	77	27	49
16-17	0.0	0.0	73	174	258	344	267	187	56	0.0	0.0	0.0
17-18	0.0	0.0	0.0	27	70	120	77	68	0.0	0.0	0.0	0.0
Total	2242	4187	4936	6097	7178	8160	7351	6235	5372	3907	2836	2236

Table 2. Hourly averaged diffuse solar radiation on a horizontal surface (W/m^2)

Hour	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
4-5	0.0	0.0	0.0	0.0	31	40	35	36	0.0	0.0	0.0	0.0
5-6	0.0	0.0	0.0	62	103	122	101	85	60	32	0.0	0.0
6-7	0.0	30	38	148	187	229	184	147	135	75	32	0.0
7-8	38	113	99	218	267	308	278	212	195	135	97	30
8-9	90	193	204	260	332	374	325	272	253	204	154	84
9-10	154	241	282	305	376	413	366	304	288	245	192	139
10-11	174	283	315	341	400	433	389	320	300	267	214	153
11-12	168	290	321	344	404	439	394	316	294	258	208	158
12-13	143	282	309	337	390	410	378	298	276	235	179	136
13-14	92	244	261	286	352	372	342	268	231	186	126	95
14-15	39	170	192	244	300	304	293	211	165	110	63	57
15-16	0.0	80	110	170	212	249	208	162	90	36	22	19
16-17	0.0	0.0	32	80	127	165	126	82	24	0.0	0.0	0.0
17-18	0.0	0.0	0.0	13	34	58	36	30	0.0	0.0	0.0	0.0
Total	898	1926	2165	2808	3515	3916	3455	2743	2311	1783	1277	870

Table 3. The monthly-average-daily hours of bright sunshine for Trabzon

Month	Duration of bright sunshine (hour.min)
Jan.	2.48
Feb.	2.42
March	4.30
April	4.31
May	4.36
June	7.35
July	4.30
Aug.	5.45
Sept.	4.60
Oct.	3.60
Nov.	3.65
Dec.	2.40

4. Results and discussion

The hourly-average global and diffuse solar radiation data are given in Tables 1-6. The monthly average daily global, extraterrestrial, diffuse and beam radiations are also presented in these tables. The averaged hours of bright sunshine are also given in Table 3. The long-term average of the k_T and K_T values are given in Tables 5 and 6. The values of N also given in Table 6.

The solar radiation data have been analysed, and monthly-average-hourly and daily values have been reported for the global and diffuse radiations on a horizontal surface. The monthly-average-hourly and daily clearness index values are also have been calculated and analysed.

Table 4. The monthly-average day numbers and declinations

Month	Date	Day of the year (n)	Declination (δ)
January	17	17	-20.90
February	16	47	-13.30
March	16	75	-2.41
April	15	105	9.41
May	15	135	18.80
June	11	162	23.10
July	17	198	21.18
August	16	228	13.45
September	15	258	2.21
October	15	288	-9.60
November	14	318	-18.91
December	10	344	-23.03

Table 5. The monthly-average-hourly clearness index (k_T) for Trabzon

Hour	Jan.	Feb.	Mar.	Apr.	May	Jun	July	Aug.	Sept.	Oct.	Nov.	Dec.
5-6				0.456	0.312	0.348	0.280	0.245				
6-7			0.164	0.278	0.356	0.436	0.356	0.345	0.381			
7-8	0.152	0.161	0.230	0.326	0.424	0.482	0.465	0.442	0.412	0.397	0.391	0.323
8-9	0.198	0.210	0.248	0.378	0.467	0.510	0.486	0.487	0.424	0.401	0.345	0.325
9-10	0.271	0.285	0.306	0.412	0.478	0.521	0.495	0.521	0.465	0.442	0.382	0.290
10-11	0.298	0.315	0.342	0.432	0.495	0.543	0.532	0.535	0.488	0.465	0.406	0.305
11-12	0.325	0.336	0.396	0.458	0.513	0.551	0.546	0.543	0.512	0.471	0.402	0.301
12-13	0.336	0.356	0.386	0.442	0.500	0.546	0.524	0.513	0.502	0.458	0.391	0.318
13-14	0.343	0.372	0.380	0.414	0.495	0.544	0.520	0.518	0.486	0.453	0.368	0.290
14-15	0.317	0.354	0.365	0.400	0.479	0.532	0.509	0.498	0.469	0.425	0.324	0.265
15-16	0.310	0.334	0.348	0.398	0.463	0.512	0.496	0.470	0.445	0.390	0.346	0.271

16-17	0.330	0.324	0.338	0.364	0.444	0.487	0.472	0.463	0.412	0.360	0.276	0.283
17-18			0.396	0.321	0.410	0.467	0.432	0.435	0.386			
18-19				0.343	0.387	0.348	0.387	0.447				

Table 6. The monthly-average-daily clearness index (K_T) and the monthly-average of the maximum possible daily hours of bright sunshine for Trabzon

Month	**K_T**	**N**
Jan.	0.35	9.30
Feb.	0.40	10.10
March	0.29	11.54
April	0.33	13.12
May	0.39	14.24
Jun	0.47	15.10
July	0.43	14.48
Aug.	0.39	13.45
Sept.	0.40	12.30
Oct.	0.44	11.10
Nov.	0.43	9.50
Dec.	0.34	9.12

As a result of the one year measurement results, the following results are obtained:

(i) the maximum value of the monthly-average daily global radiation is 21.6 MJ/m^2 recorded in June, while that of the diffuse radiation is 10.0 MJ/m^2 recorded the same month, (ii) the maximum value of the monthly-average-daily global radiation is 4.6 MJ/m^2 recorded during December, while that of the diffuse radiation is 1.8 MJ/m^2 recorded the same month, (iii) the monthly-average-daily clearness index varies between 0.290 in March and 0.470 in June, (iv) the highest values of hourly radiation are recorded between hours 11-12 during the day and (v) applying statistical methods to the measured values two equations (8) and (9) have been derived.

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Nomenclature

H = Monthly-average daily global radiation (W/m^2)
H_D = Monthly-average daily diffuse radiation (W/m^2)
H_o = Monthly-average daily extraterrestrial radiation (W/m^2)
I = Monthly-average hourly global radiation (W/m^2)
I_D = Monthly-average hourly diffuse radiation (W/m^2)
I_o = Monthly-average hourly extraterrestrial radiation (W/m^2)
I_{sc} = Solar constant (1367 W/m^2)
K_T = Monthly-average-daily clearness index
k_T = Monthly-average-hourly clearness index
N = Monthly-average-daily maximum possible sunshine hours
n = Monthly-average-daily measured sunshine hours
Φ = Latitude
δ = Solar declination
ω_s = Sunset hour angle

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