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TECHNICAL NOTE

Solar radiation statistics for Iran

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1. INTRODUCTION

Knowledge of the incoming solar radiation is of fundamental importance for all the solar energy research and development programs which are presently being undertaken in various countries. This data may either be obtained by daily measurements of the direct, diffuse and total solar radiation over a number of years or may be predicted by using meteorological data such as number of hours of sunshine, relative humidity and maximum temperature during the day.

In general, the prediction methods for the mean monthly solar radiation parameters may be divided into three different groups. The first group of methods[1–3] suggests empirical relationships which use meteorological data, such as bright sunshine hours, the maximum air temperature and the relative humidity, in order to calculate the mean monthly total solar radiation. These methods are not capable of predicting the mean monthly values of the direct or the diffuse component of solar radiation. In the second group of methods[4, 5] the direct and diffuse components of solar radiation are first calculated at different times of the day. The values of the direct and diffuse solar radiation are then averaged over the length of the day in order to obtain the mean daily values for a representative day of each month. In a third group of methods[7] the attenuating properties of the atmosphere are presented in a form which permits the calculation of direct, diffuse and global spectral solar radiation at the ground level. The radiation parameters can then be integrated with respect to wavelength and over the length of the day in order to obtain the mean daily values.

The purpose of the work reported in this paper was to examine the various prediction methods for the mean monthly solar radiation parameters and propose a suitable method for predicting the mean monthly values of direct, diffuse and total solar radiation at different locations in Iran.

2. THEORETICAL CONSIDERATIONS

Two methods for predicting the mean monthly solar radiation parameters were examined. The first method was of the first type discussed in the introduction and the second method was of the second type.

Method 1

In this method the following empirical formula for predicting the mean daily value of the total solar radiation was used:

$$Q = 1.53K \exp L\left(D - R^{1/3}/100 - \frac{1}{t}\right)\ldots \tag{1}$$

where

- Q the mean daily total solar radiation in cal/cm^2 day
- L the location latitude in rad
- D the ratio of the bright sunshine hours relative to 12 hr
- R the relative humidity
- t the maximum air temperature in °C
- K $(\lambda N + w_{i,j} \cos L)10^2$
- N mean length of day during the month
- $w_{i,j}$ a seasonal factor (1)
- λ $0.2/(1 + 0.1\phi)$
- ϕ the location latitude in degrees.

Equation (1) may be used to calculate the mean daily value of the total solar radiation for a representative day of each month. This method is not capable of predicting the mean monthly values of direct or diffuse components of solar radiation, however.

Method 2

In this method the instantaneous values of direct and diffuse components of solar radiation were first calculated and then used in order to compute the mean monthly radiation parameters.

Direct beam fluxes

In clear skies both I and D are functions of atmospheric water vapor, regional albedo, atmospheric aerosols and the solar zenith angle. For the present predictions, however, it is assumed that the dependence of I and D on the atmospheric water vapor, regional albedo and atmospheric aerosols is small. Therefore, I and D are assumed primarily to be functions of the solar zenith angle. This assumption is supported by the work described in Refs. [4, 5].

A single empirical curve relating direct radiation to the solar zenith angle was therefore proposed:

$$I(\theta) = C\left\{1 - \exp\left|-0.075\left(\frac{\pi}{2} - \theta\right)\right|\right\} \tag{2}$$

where I and C are in cal/cm^2 hr and C is taken to be equal to 81.738 cal/cm^2 hr. This value is the same as that used for Australia[5].

The calculation of the direct beam energy over a day is simply a matter of calculating θ as a function of time, integrating $I(\theta)$ over a day, and reducing the integral value by the observed fractional cloud cover CF, since the presence of cloud in the solar beam normally reduces 1 to zero. Mathematically, the appropriate formula used in method 2 for the mean daily input of direct energy $\bar{I}_h$ on a horizontal plane is:

$$\bar{I}_h = (I - CF)\sum_{T_{SR}}^{T_{SS}} I(\theta)\cos\theta \tag{3}$$

where T_{SR} and T_{SS} are the times of sunrise and sunset and

$$\cos\theta = \sin S \sin\phi + \cos S \cos\phi \cos T_0 \tag{4}$$

where

- θ the location latitude
- S the solar declination for the time of the year
- T_0 the hour angle.

In the present work the values of T_0 were calculated by using

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the following relationship

$$T_0 = \frac{360}{24}(12 - t) \tag{4a}$$

where t = the number of hours before and after solar noon.

Furthermore, eqns (4) and (4a) enable the sunrise and sunset hours to be calculated as θ is equal to $\pi/2$ at sunrise and sunset.

Diffuse solar fluxes

In clear skies D is assumed to be primarily a function of the solar zenith angle θ;

$$D(\theta) = A_1 + A_2\left(\frac{\pi}{2} - \theta\right). \tag{5}$$

In order to introduce the effect of clouds on the diffuse radiation a relationahip of the form

$$D(\theta, CF) = A_1 + A_2\left(\frac{\pi}{2} - \theta\right) + A_3 CF \tag{5a}$$

was used where CF equal to zero indicates a clear sky and CF equal to one indicates the sky is fully covered with clouds. A_1, A_2 and A_3 were taken to be equal to 0.218, 0.299 and 17.269 respectively. These values are the same as those proposed for the United States[8]. Subsequent comparison of the predictions of eqn (5a) with the experimental data of Tehran indicated however, that the constants A_1, A_2 and A_3 should be multiplied by the factor 0.604. The reduction of constants A_1, A_2 and A_3 for Tehran may be due to the high altitude of Tehran (1191 m). The high altitude reduces the air mass and hence the scattering of solar radiation is decreased. As, most of the other locations in Iran have altitudes and climatic conditions similar to Tehran. The following equation for the prediction of diffuse solar radiation was therefore proposed:

$$D(\theta, CF) = 0.123 + 0.181\left(\frac{\pi}{2} - \theta\right) + 10.43 CF \tag{5b}$$

where D is in cal/cm^2 hr.

In order to calculate the mean daily value of the diffuse solar radiation $\bar{D}$ the following relationship was used:

$$\bar{D} = \sum_{T_{SR}}^{T_{SS}} D(\theta, CF). \tag{6}$$

For computing the values of total solar radiation on a horizontal surface the instantaneous value of $Q_h(\theta)$ is first calculated:

$$Q_h(\theta) = (1 - CF)I(\theta)\cos\theta + D(\theta). \tag{7}$$

The mean monthly total solar radiation on a horizontal surface $\bar{Q}_h$ is obtained by a simple summation

$$\bar{Q}_h = \sum_{T_{SR}}^{T_{SS}} Q_h(\theta). \tag{8}$$

A computer program was developed in order to calculate the values of the mean monthly direct, diffuse and total solar radiation on horizontal, tilted and sun tracking surfaces. The time step for the summations in eqns (3), (6) and (8) was every 15 min. The solar zenith angle calculations and integrations of eqns (3), (6) and (8) were performed for the 15th of each month. The cloud factor CF was, however, a true monthly average obtained by using the meteorological data over the last 10 yr. Therefore, the values of direct, diffuse and total solar radiation on horizontal, sun tracking and tilted surfaces are those of monthly means.

3. COMPARISON WITH EXISTING EXPERIMENTAL DATA

Daily measurements of total and diffuse solar radiation in Tehran have been carried out by the Tehran Meteorological Weather Station over the last four years and for the comparisons presented in this section the mean monthly values of total and diffuse solar radiation obtained by averaging the experimental data over the four year period were used. Furthermore, measurements of total solar radiation in Karaj (40 km west of Tehran) were also available for 1976.

Figure 1 shows a comparison between the values of the mean

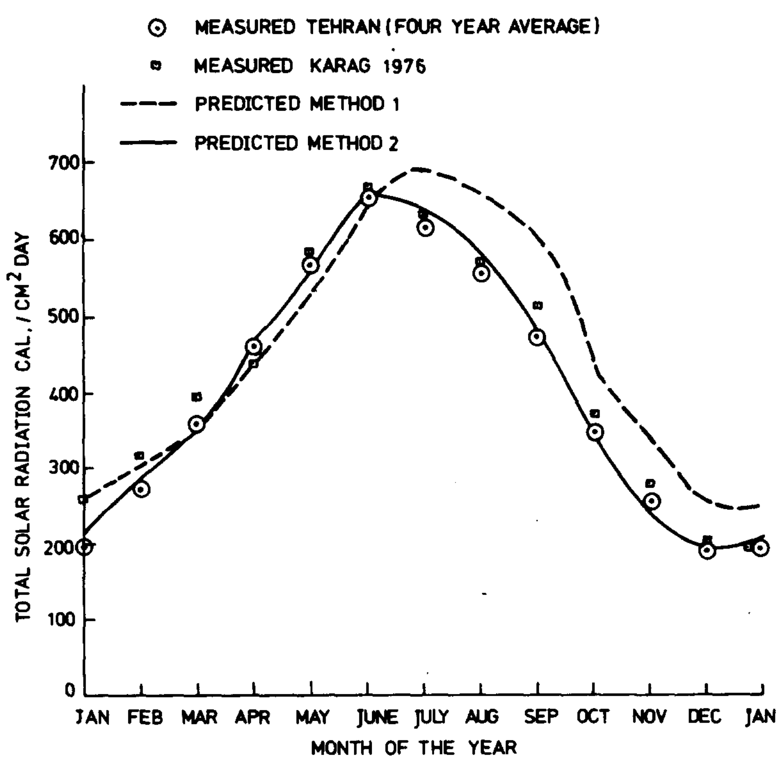

Fig. 1. Total solar radiation on a horizontal surface.

monthly total solar radiation as predicted by eqn (1) and the measured values. The comparison indicates that Method 1 is not suitable for the prediction of monthly values of the total solar radiation accurately. This method over-estimates the values of the mean montly total solar radiation by an average amount of 10 per cent. Furthermore, this method is not suitable for the prediction of the mean daily values of the direct or the diffuse solar radiation. The predictions of the mean monthly values of total solar radiation on a horizontal surface using Method 2 are also presented on Fig. 1. It is seen that this method predicts the values of total solar radiation to a very high degree of accuracy. The average prediction error over the year is 2.0 per cent.

Figure 2 shows a comparison between the predicted values of the mean monthly direct solar radiation on a horizontal surface using eqn (3) and the experimental data. The values of CF used in eqn (3) were calculated by using the monthly recorded number of sunshine hours for Tehran in the last 10 yr (1966–76). Figure 2 indicates that Method 2 is suitable for the prediction of the mean monthly values of the direct solar radiation to a very high degree of accuracy. The average error in the prediction was 2.0 per cent.

Figure 3 shows a comparison between the predicted values of diffuse solar radiation using eqn (5b) and the experimental data. Here again it is clear that eqn (5b) is suitable for the prediction of the diffuse radiation to a very high degree of accuracy. The average error in the predictions was 2.5 per cent. If, however, the constants in eqn (5b) were replaced by those used in the United States then the diffuse solar radiation was over-estimated.

In summary, it appeared that Method 2 was suitable for the prediction of the mean monthly values of direct, diffuse and total solar radiation to a degree of accuracy similar to that of the experimental data. Therefore, Method 2 was used in order to compute tables of monthly mean solar radiation parameters at various locations in Iran. These tables are presented and discussed in the next section.

4. APPLICATION OF THE PREDICTION METHOD

In Table 1 the latitude angle and the monthly averaged values of the cloud factor, calculated by using the measured monthly hours of sunshine over the last ten years in the 34 locations, are

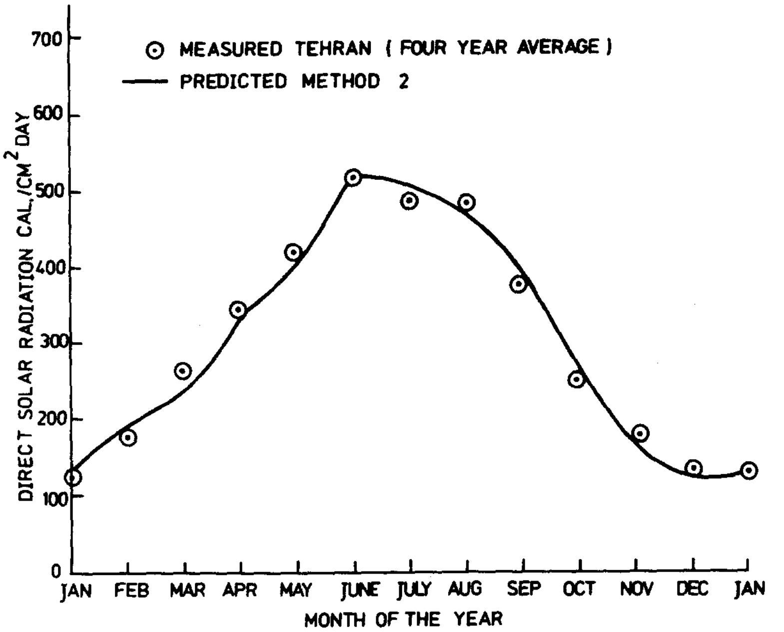

Fig. 2. Direct solar radiation on a horizontal surface.

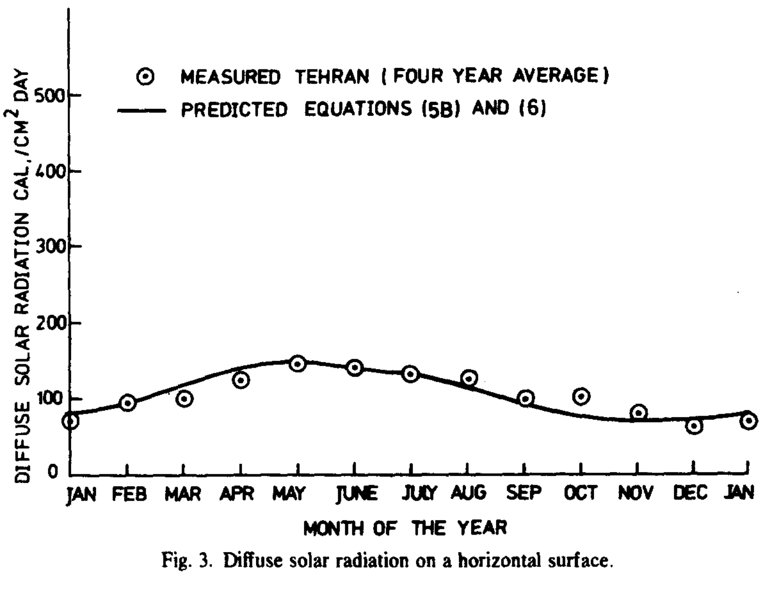

Fig. 3. Diffuse solar radiation on a horizontal surface.

Table 1. Cloud factor and latitude

CODE	CITY	J	F	M	A	M	J	J	A	S	O	N	D	LATITUDE
1.1	BANDAR PAHLAVI	.678	.706	.724	.625	.484	.442	.402	.469	.523	.664	.655	.673	37.46
1.2	RASHT	.707	.770	.790	.672	.514	.540	.500	.573	.605	.625	.649	.691	37.31
1.3	RAMSAR	.607	.651	.753	.667	.579	.545	.526	.614	.656	.678	.597	.641	36.90
1.4	BABOLSAR	.532	.587	.649	.591	.484	.436	.434	.483	.531	.542	.520	.562	36.71
2.1	KHOY	.633	.612	.548	.521	.494	.402	.333	.245	.303	.366	.519	.595	38.13
2.2	TABRIZ	.586	.530	.528	.500	.379	.198	.192	.178	.183	.304	.392	.541	38.13
2.3	REZAEYEH	.645	.550	.563	.510	.389	.205	.176	.152	.201	.337	.431	.560	37.53
2.4	SAGHEZ	.638	.563	.560	.532	.380	.261	.227	.201	.194	.221	.418	.605	36.25
2.5	TEHRAN	.429	.391	.456	.400	.352	.209	.216	.186	.180	.242	.316	.423	35.68
2.6	HAMEDAN	.575	.536	.501	.502	.387	.194	.214	.201	.226	.297	.419	.525	35.20
2.7	KERMANSHAH	.574	.543	.486	.477	.359	.157	.168	.166	.181	.291	.412	.520	34.31
2.8	KASHAN	.559	.453	.497	.482	.431	.430	.380	.292	.268	.370	.441	.465	33.98
2.9	KHORRAMABAD	.468	.431	.465	.478	.350	.184	.187	.193	.194	.212	.383	.488	33.48
2.10	SHAHREKORD	.464	.393	.392	.441	.282	.208	.243	.191	.151	.173	.319	.356	32.31
3.1	SHAHROUD	.407	.400	.422	.412	.353	.250	.233	.174	.189	.235	.284	.397	36.41
3.2	MASHHAD	.447	.502	.591	.499	.343	.188	.174	.142	.171	.265	.317	.441	36.26
3.3	SABZEBAR	.458	.410	.490	.433	.326	.252	.209	.170	.180	.221	.304	.428	36.21
3.4	SEMNAN	.386	.395	.453	.430	.358	.246	.226	.184	.186	.229	.277	.348	35.55
3.5	TORBATHEIDARIEH	.461	.489	.523	.397	.327	.203	.175	.132	.168	.222	.278	.474	35.26
4.1	TABAS	.350	.361	.373	.386	.297	.225	.204	.186	.147	.141	.276	.377	33.60
4.2	BIRJAND	.372	.387	.398	.384	.294	.207	.180	.158	.127	.145	.276	.319	32.86
4.3	ISFAHAN	.304	.324	.299	.349	.320	.162	.206	.168	.149	.159	.277	.330	32.61
4.4	YAZD	.419	.348	.379	.423	.338	.274	.241	.164	.141	.148	.272	.358	31.90
4.5	AHWAZ	.458	.438	.465	.457	.379	.267	.266	.217	.177	.258	.357	.346	31.33
4.6	ZABOL	.397	.377	.395	.345	.273	.205	.219	.206	.178	.164	.244	.360	31.03
4.7	ABADAN	.418	.377	.360	.398	.347	.258	.262	.232	.185	.228	.386	.415	30.36
4.8	KERMAN	.391	.367	.359	.435	.297	.244	.235	.207	.192	.219	.226	.320	30.25
4.9	SHIRAZ	.342	.307	.347	.381	.223	.147	.195	.184	.131	.130	.239	.306	29.53
4.10	ZAHEDAN	.422	.366	.403	.409	.317	.264	.257	.201	.171	.203	.227	.313	29.46
4.11	BAM	.292	.326	.340	.354	.248	.211	.222	.183	.172	.127	.163	.200	29.10
4.12	BOSHEHR	.295	.382	.337	.366	.260	.182	.216	.200	.168	.168	.253	.339	28.98
4.13	BANDARABBAS	.325	.304	.353	.354	.212	.254	.357	.299	.251	.176	.195	.246	27.21
4.14	IRANSHAHR	.263	.298	.315	.319	.231	.312	.364	.266	.190	.122	.117	.183	27.20
4.15	CHAHBAHAR	.261	.254	.262	.249	.215	.314	.373	.382	.291	.165	.160	.217	25.28

presented. The latitude angle and the mean monthly values of cloud factor were used in Method 2, described in Section 2, and the values of the mean monthly direct, diffuse and total solar radiation for the 34 chosen locations were computed.

The computed data reported consists of tables of total solar radiation on a horizontal surface (Table 2) and direct solar radiation on a horizontal surface (Table 3). In addition, tables of direct and total solar radiation on a sun tracking surface and on a south facing surface inclined at latitude angle were also calculated but these tables are not reported in the present publication.

The values of the mean monthly total solar radiation on a horizontal surface are given in Table 2. This table indicates that region 1 receives the minimum monthly and annual total solar radiation. This to be expected as region 1 is the Caspian Sea region and the values of *CF* for this region are higher compared with the other three regions.

The values of the mean monthly direct solar radiation on a horizontal surface are presented in Table 3. The table indicates that region 1 receives the minimum direct solar radiation and region 4 receives the maximum direct solar radiation. The amount of direct solar radiation received in region 1 per annum is approximately half the amount received in region 4. This is to be expected as both the *CF* values and the latitude angles are larger for region 1 when compared with those of region 4.

CONCLUSIONS

The work presented in this report has shown that the computation methods, which are based on the assumption that the direct and diffuse solar radiation are primarily functions of solar zenith angle and cloud cover, enable computations of the mean monthly values of direct, diffuse and total solar radiation to be performed with a high degree of accuracy.

Table 2. Total solar radiation on a horizontal plate in cal/cm^2 day

CODE	CITY	J	F	M	A	M	J	J	A	S	O	N	D	ANNUAL
1.1	BANDAR PAHLAVI	171	214	265	371	486	539	549	462	366	250	190	160	335
1.2	RASHT	169	203	247	353	479	489	500	423	338	260	191	159	318
1.3	RAMSAR	182	228	259	355	447	486	486	405	322	250	201	167	316
1.4	BABOLSAR	189	241	290	387	492	547	531	463	366	283	213	173	348
2.1	KHOY	171	228	317	406	482	562	585	559	438	315	206	162	369
2.2	TABRIZ	176	243	323	414	536	664	655	588	479	329	223	167	400
2.3	REZAEYEH	174	243	311	418	531	658	661	600	476	327	219	170	399
2.4	SAGHEZ	180	249	318	411	541	635	632	589	485	365	232	172	401
2.5	TEHRAN	210	288	352	467	554	659	645	597	494	365	252	195	423
2.6	HAMEDAN	195	257	340	425	536	664	645	590	480	355	241	188	410
2.7	KERMANSHAH	202	261	350	437	548	679	664	606	500	364	245	195	421
2.8	KASHAN	206	283	348	436	513	549	558	550	471	339	243	201	391
2.9	KHORRAMABAD	219	291	360	438	560	672	652	594	500	384	257	202	427
2.10	SHAHREKORD	229	309	390	456	590	655	631	606	522	405	279	230	442
3.1	SHAHROUD	206	280	358	460	554	641	629	602	487	360	250	191	418
3.2	MASHHAD	202	261	309	425	559	672	657	616	493	354	246	188	415
3.3	SABZEBAR	201	280	339	451	567	639	640	603	491	366	249	189	418
3.4	SEMNAN	216	288	353	454	550	639	640	597	492	369	259	204	422
3.5	TORBATHEIDARIEH	209	266	333	468	565	660	664	621	500	374	262	193	426
4.1	TABAS	234	306	389	476	586	652	644	597	516	402	274	215	441
4.2	BIRJAND	238	306	385	478	585	658	664	610	528	407	281	229	447
4.3	ISFAHAN	251	323	418	493	573	680	650	605	521	406	283	230	453
4.4	YAZD	240	323	396	464	563	620	630	618	527	415	291	233	443
4.5	AHWAZ	238	306	371	450	542	621	616	593	517	389	281	241	430
4.6	ZABOL	251	323	396	498	592	651	637	598	517	418	306	237	452
4.7	ABADAN	253	328	411	477	555	631	614	587	518	406	278	235	441
4.8	KERMAN	254	332	412	469	579	638	627	598	516	409	311	250	450
4.9	SHIRAZ	269	346	420	493	623	683	655	608	542	441	316	260	471
4.10	ZAHEDAN	256	332	401	481	577	624	623	601	527	420	319	259	452
4.11	BAM	282	345	425	506	610	649	639	609	539	446	336	282	472
4.12	BOSHEHR	283	331	426	501	604	663	642	601	540	435	318	260	467
4.13	BANDARABBAS	295	366	430	508	622	628	565	554	515	447	349	289	464
4.14	IRANSHAHR	307	368	443	524	613	599	561	569	539	464	367	300	471
4.15	CHAHBAHAR	321	397	473	557	626	588	558	523	505	466	370	315	475

Table 3. Direct solar radiation on a horizontal plate in cal/cm^2 day

CODE	CITY	J	F	M	A	M	J	J	A	S	O	N	D	ANNUAL
1.1	BANDAR PAHLAVI	67	88	113	202	316	365	384	305	225	118	82	61	194
1.2	RASHT	62	69	86	177	304	301	321	250	187	132	84	59	169
1.3	RAMSAR	85	107	102	180	262	297	304	226	163	115	98	70	167
1.4	BABOLSAR	100	127	145	221	322	374	362	302	223	164	118	84	212
2.1	KHOY	74	113	186	252	311	393	430	434	326	218	113	73	244
2.2	TABRIZ	83	137	194	263	381	527	521	472	382	240	143	83	286
2.3	REZAEYEH	74	134	178	264	375	520	530	487	376	232	135	82	282
2.4	SAGHEZ	79	137	184	254	386	488	494	468	386	283	147	78	282
2.5	TEHRAN	128	194	230	327	403	520	508	477	395	279	177	118	313
2.6	HAMEDAN	98	147	213	271	380	528	508	468	375	262	153	100	292
2.7	KERMANSHAH	103	149	223	286	396	549	535	489	400	270	158	106	305
2.8	KASHAN	108	180	219	284	351	376	398	415	359	237	152	117	266
2.9	KHORRAMABAD	130	190	235	287	408	537	520	473	398	300	171	115	314
2.10	SHAHREKORD	139	210	272	309	448	517	489	483	424	323	198	154	330
3.1	SHAHROUD	128	186	241	318	403	495	491	484	388	276	179	118	310
3.2	MASHHAD	121	156	171	272	409	536	528	503	397	266	172	110	303
3.3	SABZEBAR	118	185	213	307	419	493	505	486	393	283	176	113	308
3.4	SEMNAN	139	193	231	310	398	495	501	478	393	285	188	134	312
3.5	TORBATHEIDARIEH	124	162	203	329	418	523	533	508	403	289	190	110	316
4.1	TABAS	158	213	275	337	441	511	510	477	420	326	200	139	334
4.2	BIRJAND	158	209	267	340	442	519	532	494	433	330	206	158	341
4.3	ISFAHAN	177	232	312	359	425	548	514	488	424	327	208	158	348
4.4	YAZD	153	228	280	319	413	473	489	499	430	336	215	157	333
4.5	AHWAZ	146	200	243	301	386	475	472	467	415	296	194	164	313
4.6	ZABOL	165	224	276	363	452	514	500	474	415	336	231	159	342
4.7	ABADAN	164	228	295	335	404	485	470	458	414	315	188	150	325
4.8	KERMAN	168	232	296	321	435	494	488	473	411	319	238	175	337
4.9	SHIRAZ	187	254	304	352	488	554	520	486	445	361	240	185	365
4.10	ZAHEDAN	165	233	279	336	429	478	479	477	425	332	244	183	338
4.11	BAM	205	250	310	367	472	511	501	487	434	366	267	217	366
4.12	BOSHEHR	205	230	311	361	464	529	505	477	436	349	240	180	357
4.13	BANDARABBAS	210	271	311	369	490	484	408	417	398	359	274	216	351
4.14	IRANSHAHR	230	273	329	390	478	446	404	436	431	382	301	235	361
4.15	CHAHBAHAR	241	304	363	431	492	437	400	373	382	376	297	243	362

The computation method has been used in order to calculate the mean monthly values of direct, diffuse and total solar radiation at 34 locations in Iran and tables of the computed parameters are presented.

The accuracy of the theoretical predictions indicates that for time scales of a month or more, large scale radiation monitoring stations are not necessary and theoretical models similar to that proposed in the present paper may be used in order to compute the radiation parameters.

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