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Analysis of solar radiation measurements at El-Kharga (25° N, 30°E), Egypt

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सार– ऐल –खारगा, 1984–1988 के दैनिक भूमंडलीय सौर विकिरण आंकड़ों को 4.19 एम जे एम $^{-2}$ दिन$^{-1}$ के अन्तराल की दूरी में आठ विकिरण स्तरों पर संसाधित, विश्लेषित और वर्गीकृत किया गया । माध्य वार्षिक, मासिक और दैनिक योग, दैनिक विचरण तथा भूमंडलीय सौर विकिरण के दैनिक योग के आवृत्ति वितरण का अभिकलन किया गया और उस पर विचार किया गया है । स्पष्टता के निरंतर मूल्यों और विसलित सूचकांक के बीच परस्पर संबंध का पता लगाया गया है । और संस्तुत सहसंबंध समीकरण भी दिये गए । विश्लेषण में प्रस्तुत परिणाम उत्साहजनक है क्योंकि इनसे यह पता चलता है कि 8.38 एम जे एम$^{-2}$ दिन$^{-1}$ के कई दिनों के निम्न विकिरण की अवधि विरल है । इसका अर्थ यह है कि सौर संसाधन अभिकल्प से संबद्ध भंडारण की समस्या को देखते हुए मौसम अनुक्रम विचरणों के बहुत अधिक महत्वपूर्ण होने की आशा नहीं है ।

ABSTRACT. Daily global solar radiation data of El-Kharga for five year (1984-88) have been processed, analysed and classified into eight radiation levels spaced at an interval of 4.19 MJ m^{-2} day^{-1}. Mean annual monthly and daily totals, the diurnal variation, and the frequency distribution of daily totals of global solar radiation are computed and discussed. A correlation between the hourly values of the clearness and diffuse indices were obtained and the recommended correlation equations were also given. The results presented in this analysis are encouraging, since they indicate that periods of several days of low radiation of less than 8.38 MJm^{-2} day^{-1} are rare. This in turn means that the weather sequence variations are not expected, to be of great importance when considering the storage problems involved in solar process design.

Key words — Global solar radiation, Clearness index, Diffuse index.

1. Introduction

Estimating the performance of a solar system, with or without storage systems, requires an accurate assessment of incident solar radiation. The choice of El-Kharga area (25°N, 30°E) was dictated by the fact that it is considered as one of the most important remote rural places in Egypt which is far from the *Nile*. The most important activity of the citizens at El-Kharga is *cultivation*. They depend on the underground water irrigation using diesel systems. The strategy is to find out the scope about the site potentiality of the plateau region of El-Kharga for photovoltaic applications specially in the field of water pumping.

In simulating solar systems on a digital computer, designers generally use one-hour time step, this being the minimum interval over which radiation and meteorological data are available. Pioneering work of Liu and Jordan (1960) related the hourly diffuse index (diffuse to global solar radiation, K_d) to the hourly clearness index (global to extra-terrestrial solar radiation, K_t) based on the daily values. Moreover, a recommended correlation equation was not given (Orgill and Hollands 1977). The paper presents a new seasonal recommended correlation equations for diffuse index, based on El-Kharga data, but based on the hourly measured values rather than a detailed study of the frequency distribution of daily totals of global solar radiation at specified values of radiation levels.

2. Monthly and annual totals of global solar radiation falling on a horizontal surface

The monthly and annual values of global radiation recorded at El-Kharga weather station, during the period from January 1984 to December 1988 at an elevation of 0.0778 km are listed in Table 1. It can be seen from Table 1 that in an average year the total global solar radiation received on a horizontal surface is about 8198 MJ m^{-2}. The annual global solar radiation, in the five-year period, has ranged between 8062 and 8294 MJ m^{-2}. In an average year, the winter season (November-February), (Bendt *et al.* 1981) contributes 24.2% to the annual total and the spring and fall seasons (March, April, September, October) contribute 34.3% while the summer four-month season (May-August) contributes 41.3% to the annual total. The highest month was July (876 MJ m^{-2}) and is responsible for 10.6% of the mean annual total. However, the absolute maximum and minimum monthly recorded totals occurred in July 1985 (911 MJ m^{-2}) and December 1988 (405 MJ m^{-2}) respectively. The variability from year to year for the annual totals is very low, the overall range (Max-Min) being only 2.8% of the mean value. The most variable month is December where the range is 12.5% of the monthly mean value and the steadiest month is May with a range of 1.8% of the monthly mean value.

TABLE 1

Monthly and annual totals of global solar radiation on a horizontal surface (MJ m^{-2})

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1984	514	574	710	797	855	843	858	843	714	605	517	449	8270
1985	471	564	660	782	843	871	911	857	731	652	499	438	8270
1986	495	536	688	755	858	846	861	806	680	602	475	460	8062
1987	500	542	701	804	854	862	885	825	729	634	511	450	8294
1988	467	554	719	765	837	843	863	796	707	636	502	405	8094
Mean	489	554	696	781	848	853	876	825	712	626	501	440	8198
Max	514	574	719	804	858	871	911	857	731	652	517	460	8294
Min	467	536	660	755	843	843	858	796	680	602	475	405	8062
Max — Min	47	38	59	49	15	28	53	61	51	50	42	55	232
(Max—Min/Mean) × 100	9.6	6.9	8.5	6.3	1.8	3.3	6.1	7.4	7.2	8.0	8.4	12.5	2.8

TABLE 2

Average daily totals of global solar radiation (G) on a horizontal surface (MJ m^{-2} day^{-1}) and the corresponding values of K_t and K_d

Year		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1984	G	16.6	19.8	22.8	26.6	27.6	28.1	27.7	27.2	23.8	19.8	17.3	14.5
	K_t	0.66	0.73	0.69	0.69	0.69	0.7	0.72	0.74	0.66	0.7	0.73	0.65
	K_d	0.2	0.17	0.17	0.15	0.15	0.15	0.16	0.15	0.17	0.18	0.18	0.21
1985	G	15.3	20.2	21.5	26.1	27.2	29.1	29.4	27.7	24.4	21.0	16.6	14.2
	K_t	0.65	0.67	0.67	0.69	0.69	0.73	0.74	0.72	0.72	0.72	0.65	0.63
	K_d	0.2	0.18	0.18	0.16	0.16	0.16	0.16	0.15	0.16	0.17	0.19	0.21
1986	G	16.1	19.1	22.0	25.2	27.7	28.3	27.8	26.0	22.6	19.5	15.8	15.0
	K_t	0.68	0.68	0.72	0.69	0.71	0.71	0.71	0.69	0.71	0.69	0.6	0.66
	K_d	0.19	0.18	0.17	0.16	0.15	0.16	0.15	0.16	0.18	0.18	0.21	0.2
1987	G	17.3	19.1	22.5	26.8	27.6	28.7	28.5	26.6	24.3	20.4	17.1	14.5
	K_t	0.7	0.71	0.66	0.74	0.69	0.72	0.72	0.73	0.69	0.66	0.7	0.65
	K_d	0.19	0.17	0.17	0.15	0.16	0.16	0.16	0.16	0.16	0.19	0.18	0.21
1988	G	15.2	19.2	22.8	25.5	27.0	28.1	27.9	25.7	23.9	20.5	16.8	13.1
	K_t	0.62	0.66	0.72	0.71	0.68	0.7	0.7	0.7	0.68	0.7	0.71	0.58
	K_d	0.21	0.19	0.17	0.16	0.16	0.16	0.16	0.16	0.17	0.18	0.19	0.23
Overall average	G	16.1	19.5	22.2	26.0	27.4	28.5	28.3	26.6	23.8	20.2	16.7	14.3
	K_t	0.66	0.69	0.69	0.7	0.69	0.71	0.72	0.72	0.69	0.69	0.63	0.63
	K_d	0.2	0.18	0.17	0.16	0.16	0.16	0.16	0.15	0.17	0.18	0.19	0.21

TABLE 3

Maximum recorded daily totals of global solar radiation (MJ m^{-2} day^{-1}) and the corresponding values of K_t and K_d

Year		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1984	G_{Max}	18.6	23.0	27.0	29.1	30.1	30.2	28.9	28.7	25.9	22.2	18.8	16.6
	K_t	0.72	0.73	0.74	0.76	0.77	0.76	0.75	0.74	0.72	0.66	0.73	0.72
	K_d	0.18	0.17	0.16	0.14	0.14	0.14	0.15	0.15	0.16	0.19	0.17	0.19
1985	G_{Max}	18.8	22.9	25.0	28.6	30.2	30.0	31.2	29.0	26.2	23.0	18.8	15.8
	K_t	0.74	0.76	0.73	0.78	0.76	0.75	0.79	0.76	0.74	0.73	0.71	0.69
	K_d	0.17	0.16	0.16	0.15	0.15	0.16	0.15	0.15	0.15	0.17	0.17	0.19
1986	G_{Max}	18.1	21.8	25.4	28.7	29.2	29.4	29.2	27.5	24.5	21.8	18.2	27.1
	K_t	0.71	0.73	0.72	0.75	0.74	0.74	0.73	0.71	0.68	0.69	0.69	0.76
	K_d	0.18	0.17	0.16	0.15	0.155	0.16	0.15	0.15	0.16	0.18	0.18	0.18
1987	G_{Max}	18.0	22.7	26.1	29.4	29.6	30.7	29.5	28.8	25.5	22.5	18.6	15.7
	K_t	0.71	0.83	0.75	0.78	0.75	0.77	0.74	0.74	0.71	0.73	0.71	0.68
	K_d	0.18	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.16	0.17	0.17	0.2
1988	G_{Max}	18.0	21.5	26.2	27.7	30.0	30.0	29.3	27.3	25.6	22.5	18.8	15.6
	K_t	0.71	0.73	0.75	0.73	0.75	0.75	0.73	0.71	0.71	0.71	0.7	0.69
	K_d	0.18	0.17	0.15	0.15	0.15	0.15	0.16	0.15	0.16	0.18	0.17	0.19
Absolute max.	G_{Max}	18.8	23.0	27.0	29.4	30.2	30.7	31.2	29.0	26.2	23.0	18.8	17.1
	K_t	0.74	0.83	0.75	0.78	0.77	0.77	0.79	0.76	0.74	0.73	0.73	0.76
	K_d	0.18	0.17	0.16	0.15	0.15	0.16	0.16	0.15	0.16	0.19	0.18	0.2

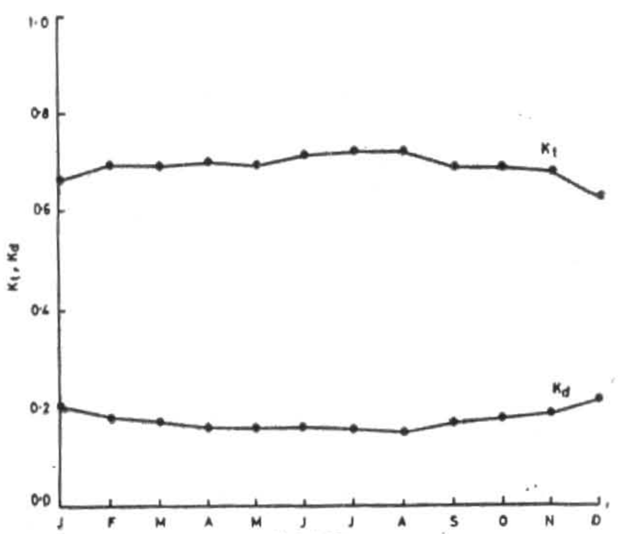

Fig. 1. Monthly variation of the average daily values of both clearness and diffuse indices

3. Average daily totals of global solar radiation

Table 2 shows the average daily totals of G and the corresponding values of the clearness index, K_t, and the diffuse index, K_d, which are computed for all days for each month during the five-year period.

In an average year, the annual average of daily total of G is about 22.5 MJ m^{-2} and the corresponding values of K_t and K_d are 0.69 and 0.17 respectively. Inside the winter season, February is the most active month while December is the worst (*see* Table 3). In spring and fall seasons, April is the highest and March is the lowest. The identification of the worst month is of great importance since it represents the design month when considering the design study for photovoltaic with and without storage systems (Salem *et al.* 1989).

The monthly variation of the average daily of the clearness index, K_t, and the diffuse index K_d, are shown in Fig. 1. It is clear from the figure that the average daily clearness index, K_t, has the range $0.60 < K_t < 0.75$. This range shows that the weather in the plateau region tends to be clear to moderate sky conditions.

4. Maximum and minimum values of daily totals of global solar radiation

The maximum daily totals, the absolute and the average of the maximum daily totals of G besides the corresponding values of K_t and K_d, as obtained by the method given by Klein (1977), are listed in Table 3. It is clear that the absolute maximum of daily total of G was in July 1985 (31.2 MJ m^{-2}) with K_t and K_d values of 0.79 and 0.16 respectively. In general, days with global solar radiation within the range $15.8 < G$ 31.2 MJm^{-2} day^{-1} were characterized by average daily clearness index, K_t, between 0.73 and 0.83 in a month. On the other hand, the absolute minimum of daily total of G recorded during the five-year period was in December 1984 (5.1 MJ m^{-2}) [*see* Table 4]. Days with global solar radiation within the range $5.1 < G < 26.5$ MJ m^{-2} correspond to K_t values between 0.23 and 0.69. The correlation among the maximum,

TABLE 4

Minimum recorded daily totals of global solar radiation (MJ m^{-2} day^{-1}) and the corresponding values of K_t and K_d

Year		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1984	G_{Min}	13.8	12.7	17.2	21.4	24.3	25.3	24.1	25.0	21.5	16.9	15.1	5.1
	K_t	0.45	0.47	0.48	0.57	0.63	0.63	0.69	0.66	0.65	0.65	0.58	0.23
	K_d	0.3	0.26	0.25	0.19	0.17	0.17	0.16	0.15	0.19	0.19	0.21	0.56
1985	G_{Min}	9.9	17.3	13.5	7.0	17.0	27.4	28.0	25.6	22.0	18.7	13.2	7.0
	K_t	0.41	0.62	0.4	0.21	0.44	0.69	0.71	0.71	0.69	0.69	0.56	0.31
	K_d	0.31	0.2	0.29	0.5	0.24	0.16	0.16	0.16	0.18	0.18	0.23	0.42
1986	G_{Min}	13.1	14.1	14.6	16.8	20.6	26.4	26.4	22.8	19.7	16.5	7.8	12.3
	K_t	0.58	0.54	0.47	0.44	0.53	0.66	0.68	0.6	0.6	0.61	0.34	0.54
	K_d	0.23	0.23	0.26	0.24	0.2	0.16	0.16	0.18	0.2	0.2	0.38	0.25
1987	G_{Min}	11.2	15.9	16.7	17.1	22.8	22.0	27.9	24.7	22.8	18.1	14.5	11.4
	K_t	0.47	0.57	0.49	0.48	0.58	0.55	0.7	0.64	0.69	0.68	0.63	0.5
	K_d	0.28	0.21	0.23	0.23	0.18	0.19	0.16	0.17	0.18	0.18	0.21	0.26
1988	G_{Min}	8.1	15.1	16.7	21.7	12.4	25.8	26.0	17.8	20.9	18.1	12.7	5.2
	K_t	0.35	0.55	0.54	0.59	0.32	0.64	0.67	0.47	0.6	0.64	0.53	0.23
	K_d	0.37	0.22	0.22	0.19	0.34	0.17	0.16	0.23	0.19	0.19	0.24	0.55
Absolute min	G_{Min}	8.1	12.7	13.5	7.5	17.0	22.0	24.1	22.8	19.7	16.5	7.8	5.1
	K_t	0.35	0.47	0.4	0.21	0.32	0.55	0.67	0.47	0.6	0.61	0.34	0.23
	K_d	0.23	0.2	0.22	0.19	0.17	0.16	0.16	0.15	0.18	0.18	0.21	0.25

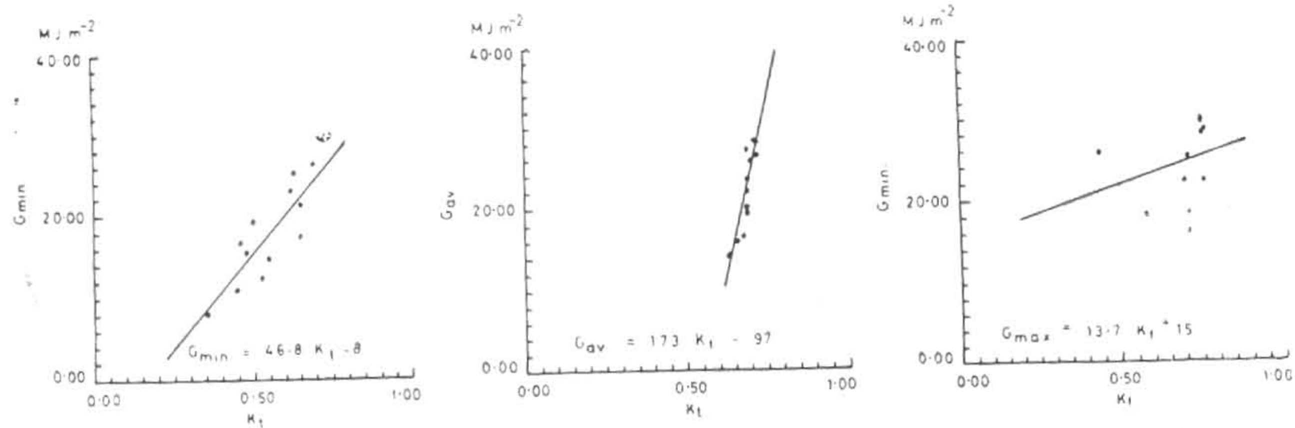

Fig. 2. Correlation among the average daily clearness index with daily minimum average, and maximum global solar radiation (MJ m^{-2})

the average, and the minimum daily totals of G with the clearness index, K_t are shown in Fig. 2.

In all ranges of K_t and K_d, the average contribution of the diffuse solar radiation did not exceed 25% of the recorded daily total of the global solar radiation falling on a horizontal surface at El-Kharga.

5. K_t to K_d correlation

The clearness index, K_t, the ratio of the global (beam *plus* diffuse) radiation on a horizontal surface (E) to the extra-terrestrial radiation on a horizontal surface (E_0), was correlated with the diffuse index, K_d, the ratio of the diffuse (E_d) to global solar radiation on a horizontal surface. The hourly correlation between K_t (E/E_0) and K_d (E_d/E) was investigated for the three seasons, winter, spring and fall, and summer for the design month, the worst solar radiation month, of each season. The design month for the winter was December and for spring and fall was October while August was the design month for the summer season. The hourly values of the extra-terrestrial solar radiation, E_0 and the diffuse solar radiation, E_d, were calculated by the method given by Duffie and Beckman (1980) for each day from the design month. The hourly values of the global solar radiation, E, was obtained from the values measured by the Egyptian Meteorological Authority. From

TABLE 5

Hourly variation of global solar radiation falling on a horizontal surface (kJm^{-2})

Month	Time													
	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15	15-16	16-17	17-18	18-19
Jan	0	0	34.2	115.6	182.5	235.8	263.9	263.9	253.8	253.8	115.6	46.1	0	0
Feb	0	0	48.6	144.0	219.2	278.6	311.4	311.4	278.6	219.2	144.4	65.5	0	0
Mar	0	10.8	65.5	170.6	247.7	293.1	341.3	341.3	303.2	247.7	170.6	89.3	15.5	0
Apr	0	29.5	122.0	208.0	288.7	351.0	385.2	385.2	351.0	288.7	208.1	122.0	42.5	0
May	0	44.3	142.9	226.4	303.8	363.6	396.0	396.0	363.6	303.8	226.4	142.9	64.1	0
Jun	12.6	54.7	158.0	240.8	316.8	375.1	406.4	406.4	375.1	316.8	240.8	158.0	79.2	12.6
Jul	14.8	55.8	158.4	239.8	314.6	371.9	403.2	403.2	371.9	314.6	239.8	158.4	80.6	14.8
Aug	4.0	46.4	142.2	221.8	295.2	351.7	382.3	382.3	351.7	295.2	221.8	142.2	67.0	4.0
Sep	0	31.0	115.9	192.6	263.9	319.3	349.6	349.6	319.3	263.9	192.6	115.9	44.6	0
Oct	0	14.4	63.0	157.3	225.0	277.6	306.4	306.4	277.6	225.0	157.3	86.0	20.5	0
Nov	0	0	43.6	124.6	187.6	236.9	265.0	265.0	236.9	187.6	124.6	59.0	0	0
Dec	0	0	31.3	103.0	162.0	208.4	234.0	234.0	208.4	162.0	103.0	42.1	0	0

TABLE 6

Percentage frequency distribution of daily totals of global solar radiation

Month	Radiation levels (MJ m^{-2} day^{-1})							
	0–4.19	4.19–8.38	8.38–12.57	12.57–16.76	16.76–20.95	20.95–25.14	25.14–29.33	29.33–33.52
Jan	0.0	0.65	6.45	62.58	29.68	0.0	0.65	0.0
Feb	0.0	0.0	0.0	8.57	71.4	21.4	0	0.0
Mar	0.0	0.0	0.0	4.52	19.36	16.29	14.84	0.0
Apr	0.0	0.67	0.0	0.0	2.00	19.3	78.00	0.67
May	0.0	0.0	0.65	0.0	2.58	5.21	33.87	7.10
Jun	0.0	0.0	0.0	0.0	0.0	2.00	75.3	22.7
Jul	0.0	0.0	0.0	0.0	0.0	0.65	87.10	12.26
Aug	0.0	0.0	0.0	0.0	1.29	7.10	91.61	0.0
Sep	0.0	0.0	0.0	0.0	3.33	85.30	12.00	0.0
Oct	0.0	0.0	0.0	0.65	65.20	34.10	0.0	0.0
Nov	0.0	0.67	0.0	47.3	52.00	0.0	0.0	0.0
Dec	0.0	3.23	6.45	89.68	0.65	0.0	0.0	0.0

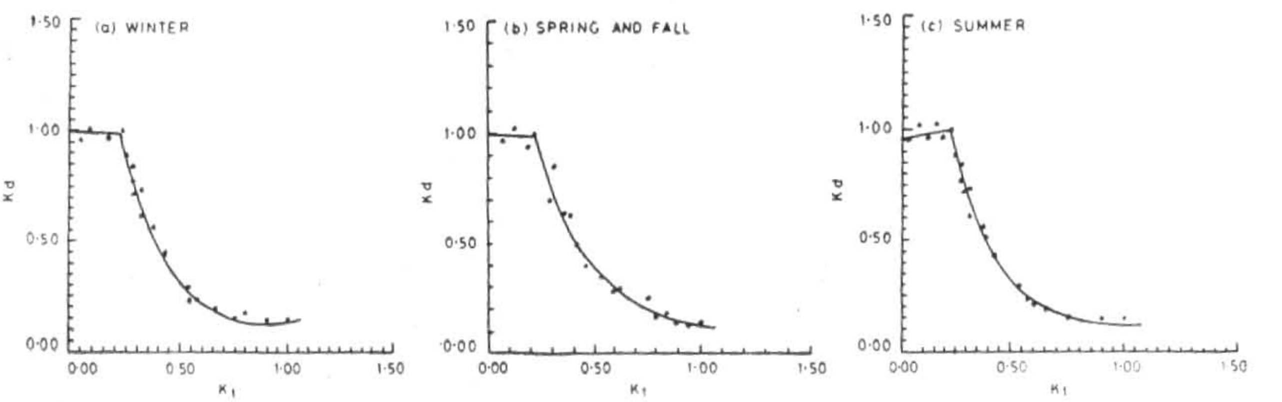

Fig. 3. Correlation between hourly values of clearness and diffuse indices

this understanding K_t was correlated with K_d and the recommended equations are as follows :

(a) For winter season [Fig. 3(a)]

$$K_d = -0.17 K_t + 1 \quad \text{for } K_t \leqslant 0.23 \tag{1}$$

$$K_d = 2.03 - 5.95 K_t + 5.97 K_t^2 - 1.62 K_t^3 - 0.28 K_t^4 \quad \text{for } K_t \geqslant 0.23$$

(b) For spring and fall seasons [Fig. 3 (b)]

$$K_d = -0.206 K_t + 1 \quad \text{for } K_t \leqslant 0.22 \tag{2}$$

$$K_d = 1.94 + 22.09 K_t - 63.08 K_t^2 + 70.24 K_t^3 - 27.22 K_t^4 \quad \text{for } K_t \geqslant 0.22$$

(c) For summer season [Fig. 3(c)]

$$K_d = 0.123 K_t + 0.975 \quad \text{for } K_t \leqslant 0.20 \tag{3}$$

$$K_d = 1.79 - 4.44 K_t + 3.06 K_t^2 + 0.53 K_t^3 - 0.85 K_t^4 \quad \text{for } K_t \geqslant 0.20$$

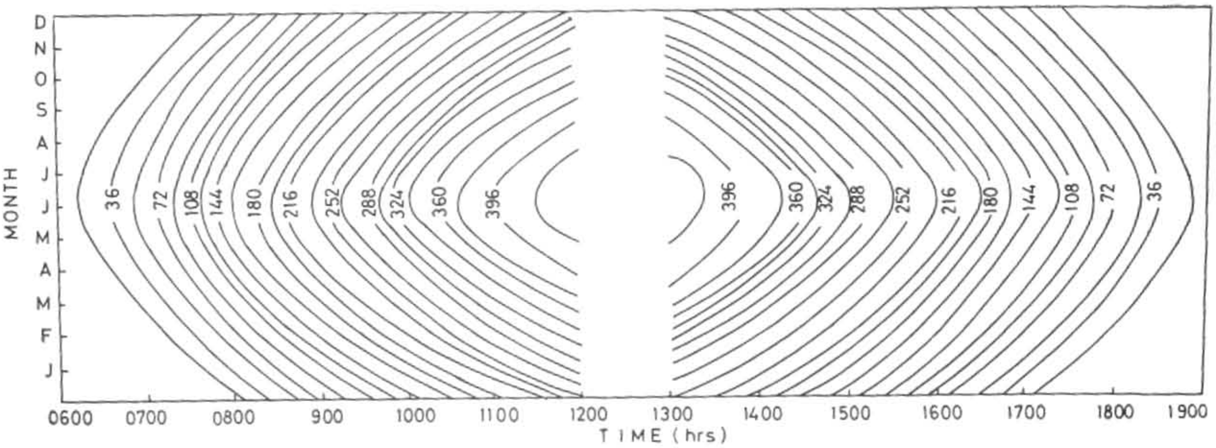

Fig. 4. Isopleths of global solar radiation (kJm^{-2}) at El-Kharga

6. Diurnal variation of the hourly global solar radiation

Table 5 summarizes the mean hourly values of the global solar radiation for all days of the considered five-year period. A feature of the diurnal variation of the global radiation is the fact that in almost all months the highest values are recorded in the interval between 1100 hr & 1400 hr. During an one-year period, the mean hourly values of the global radiation are generally higher in the forenoon period than those in the afternoon period. This behaviour can be explained by the fact that for the same solar altitude, the forenoon values of the direct solar radiation are a bit higher than the corresponding afternoon values. In general, the highest mean hourly values of the global solar radiation are recorded in the hours around midday (1000 hr-1300 hr), averaging about 254 kJm^{-2} in the winter period about 330 kJm^{-2} in the spring and fall seasons and about 383 kJm^{-2} during the summer season. For practical purposes, the data of Table 5 can be presented in the form of isopleths (Fig. 4). Radiation levels below 360 kJm^{-2} are expected between 600 hr & 1000 hr and 1400 hr & 1900 hr for any day of the year.

7. Frequency distribution of daily totals of global radiation

Among the common statistical characteristics, computed from solar radiation data for the purpose of solar system design is the frequency distribution of daily total of global solar radiation (Goh 1979). For this purpose, days are classified into eight radiation levels spaced at an interval of 4.19 MJ m^{-2} day^{-1}. In this way, the percentage frequency distribution of daily totals of global solar radiation, *i.e.*, the annual number of days as percentage of all days in the studied period, for each month was established and presented in Table 6. The choice of the space interval between the radiation levels (4.19 MJ m^{-2} day^{-1}) was to facilitate comparative studies with similar tables published for other geographical regions (Goh 1979).

On the seasonal basis, it turns out that during the winter period, 3% of all days receive less than 8.38 MJ m^{-2} day^{-1}, 20% exceed 16.76 MJ m^{-2} day^{-1}, and only 5% above 20.95 MJ m^{-2} day^{-1}. In the spring and fall periods, 70% of all days get between 12.57 and 20.95 MJ m^{-2} day^{-1} and only 8% exceed 25.14 MJ m^{-2} day^{-1}, while in the summer season, 84% of all days get between 20.95 and 29.33 MJ m^{-2} day^{-1} and only 9% receive less than 20.95 MJ m^{-2} day^{-1}. The percentage frequency distribution of radiation income had a high concentration in the mid-radiation level ranges. Only 8.5% of all days were below the 29.33 MJ m^{-2} day^{-1} while none of the days receive less than 4.19 MJ m^{-2} day^{-1} or exceed the 33.52 MJ m^{-2} day^{-1} level for the year as a whole.

8. Conclusions

The intension of the present analysis is to help designers and users in evaluating the site potential of El-Kharga region for solar energy applications. An integral view of the paper shows that there is an evident variation in the solar radiation activity among the seasons, winter, spring and fall, and summer. Due to this fact, designers are advised to track their systems in a seasonal tracking basis. This will reduce the high cost of instantaneous tracking specially in the developing countries. Also by using the isopleths (Fig. 4) designers can determine the critical level at which practical applications are expected.

It may also be concluded that the chances of having a period of low radiation long enough to be of concern in the use of solar energy systems for practical applications are probably small. This conclusion is of value when considering the economic and storage problems involved in solar process design.

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