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SOLAR RADIATION INFORMATION FOR ENERGY TECHNOLOGISTS

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RESUMEN

Se presentan algunas consideraciones acerca de la producción útil y adecuada de datos de radiación solar para los planificadores y diseñadores de los sistemas de energía solar. Se le dedica especial atención a las técnicas de estimación de la radiación solar incidente en superficies horizontales e inclinadas mediante métodos sencillos para ser utilizados particularmente en los países en vías de desarrollo. Los resultados que aquí se muestran se han obtenido principalmente a partir de mediciones efectuadas en nuestro Observatorio Central de Radiación Atmosférica en la Ciudad de México.

ABSTRACT

Some considerations of the adequate production of solar radiation information useful for solar energy planners and designers are shown here. Techniques for estimation of solar radiation on horizontal and inclined surfaces are discussed and methods of application for developing countries in particular, are illustrated. The results shown were obtained from measurements at the Central Observatory of Atmospheric Radiation in Mexico City.

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INTRODUCTION

The assessment of the solar radiation resource for solar energy applications is becoming more and more necessary. However, such an assessment involves solar irradiance and meteorological parameters whose time and spatial resolution are far beyond what the actual observing network operated by National Meteorological Services can provide. In most cases such networks primarily measure only global solar irradiance on a horizontal surface. In many cases the archived data sets from measuring networks contain gaps. Also, very common is the lack of regular pyrheliometer calibrations or pyranometer comparisons of the exposed radiation sensors. The situation is even more critical in developing countries.

In this paper I will present some simple methods for assessment of the solar radiation resource. These methods can be easily applied by National Meteorological Services of developing countries; the data used, mainly global solar radiation, sunshine and direct solar radiation. With the exception of direct solar radiation, most of the data already exist in meteorological services. The time scales are hourly integrals and daily totals whereas the spatial resolution is regional. The results of this report will be useful mainly for solar energy planners and designers.

QUALITY OF MEASUREMENTS AND DATA

Although the World Meteorological Organization (WMO) through its different Commissions (Commission for Instruments and Methods of Observation, Commission of Atmospheric Sciences) have produced recommendations for site selections, types of instruments for different measurements, calibration techniques and quality control of data, one frequently finds that enthusiastic planners made large investments in instrumentation to be installed at inadequate sites and that calibration is not considered. For engineers and planners it is absolutely essential to have reliable solar information. Here we confront two aspects: firstly, instrumental control including periodic calibration of sensors and secondly, quality of information used to produce preliminary estimates of incoming radiation. In the first case it is recommended by WMO to perform pyrheliometric calibrations or pyranometric comparisons with national or regional reference instruments at least every two years such that the instrumental error will not be larger than ± 5%. In the second case, a review of the literature shows that in using approximation techniques, solar radiation information will be characterized by a statistical bias which normally is not larger than 10%. Further information is found in the excellent monographs published by the International Energy Agency (1980) and the World Meteorological Organization (1981).

ESTIMATES OF SOLAR RADIATION

The estimation of incident solar radiation is an interesting mathematical problem, different approaches have been developed ranking from simplest linear statistical relations between incoming solar radiation and other meteorological elements (Ångström type relationships) to nonlinear relationships including the inversion technique and radiative transfer theory (Breslau and Dave, 1973).

In what follows, four different aspects of this problem are presented, referring in particular to techniques of easy access such that they can be directly applied:

Climatological charts of solar global radiation

The main objective is to produce sets of monthly average values of solar global radiation incident on a horizontal plane. The data used can be both from satellites or from ground based measurements. The use of satellite data implies the reasonable assumption that satellite brightness is strongly correlated with cloudiness which is known to be the main modulator of the radiation field; this method uses as a reference available surface global radiation, the best example of this is given in the Annex of the WMO Monograph (1981). The space scale used is world-wide. However new approaches correlating satellite data with ground measured meteorological data are also available (Dedieu *et al.*, 1983, IEA, 1980; Hisar and Sen, 1980; Tarpley, 1979; Vonder Haar and Ellis, 1978). Calculations using surface data assume linear relationships between incident global radiation and sunshine, and/or cloudiness. The first reference to this approach was produced by Ångström (1924). At present, several authors have published sets of climatological charts for their countries (Dogniaux, 1979). In our country, Almanza and López (1975) published first in Spanish (1975) and then in English (1978) a set of monthly and annual climatological charts of global radiation for Mexico from sunshine and meteorological data using Jeevaranda's empirical formula (1971). Later in other work Galindo and Chávez (1977) have determined the Ångström's regression coefficients *a* and *b* from daily measured data for different lengths of time (1957-1967) of global solar radiation and sunshine. The application of the coefficients was made using sunshine data from 136 stations following the Köppen climate classification and the type of vegetation according with Löf's criteria (Löf *et al.*, 1966), Figures 1 and 2 show this type of computation, the largest error detected is ± 10%. Let us briefly note some important features found in these charts; the irregular topography of Mexico, through local convective cloudiness, produces an uneven distribution of useful radiation at the

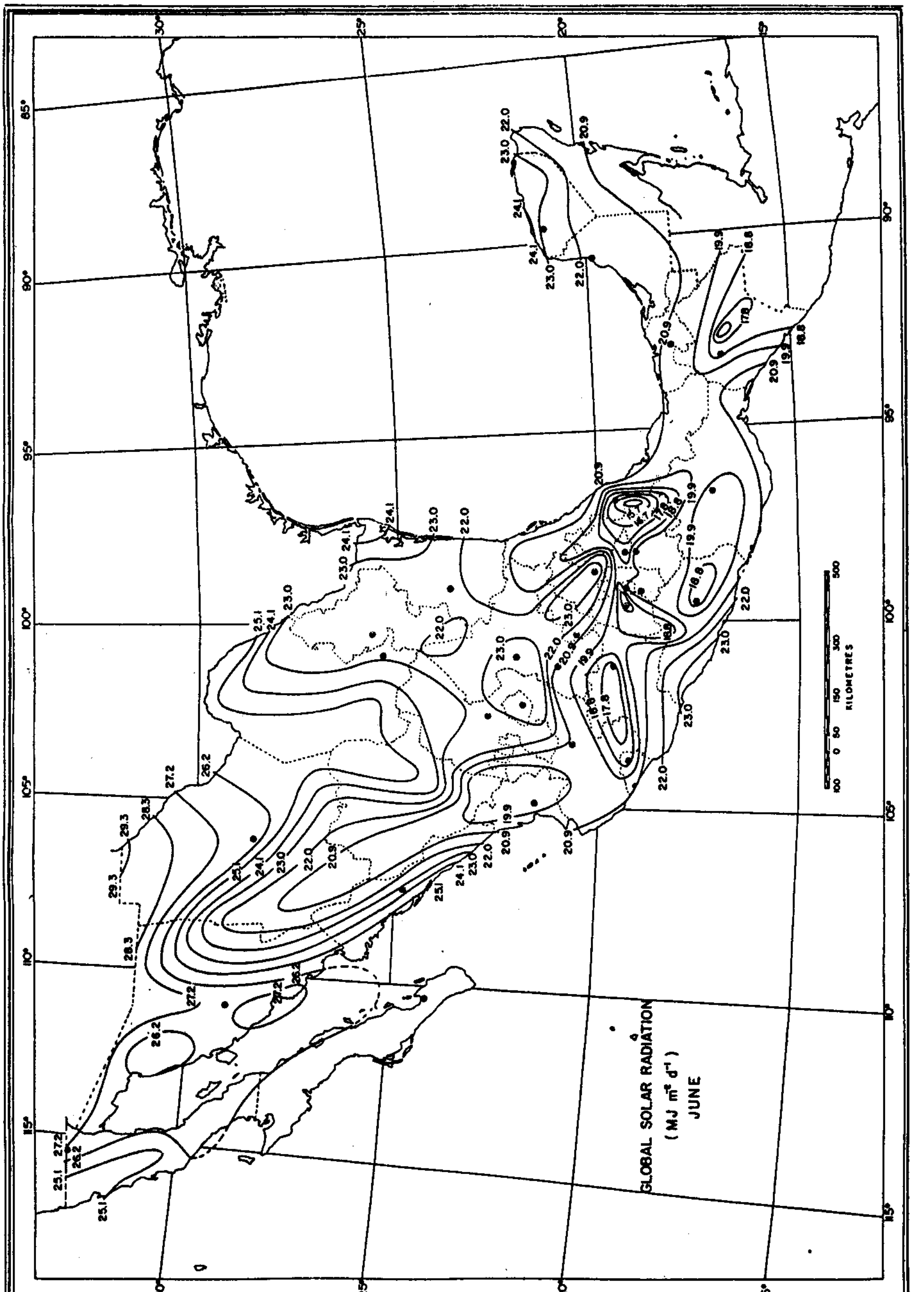

Fig. 2. Daily means of global solar radiation for June at Mexico ($MJm^{-2}d^{-1}$).

ground, this fact is denoted mainly around 20° of latitude where the Mexican Volcanic Axis is transversally located, south of this portion, the average estimate values are of the order of 16.75 to 21.14 $MJm^{-2}d^{-1}$ for January and June, respectively; but farther as 25° of latitude the presence of the desertic belt known as Tropic of Cancer leads in summer to a relative cloud-free atmosphere permitting a positive horizontal gradient polewards giving as absolute maximum values 27.22 $MJm^{-2}d^{-1}$ whereas, during January this portion of the territory is frequently invaded with cloudy and cold air masses coming from the north producing values less than 16.75$MJm^{-2}d^{-1}$. However, January shows its maximum values around the center of the country, namely 18.84 $MJm^{-2}d^{-1}$. These charts of climatological monthly values of solar irradiance will be better as the density of geographical coverage increases, in particular such charts are required for planning of different kinds of collectors (Hamilton and Thomas, 1976). On the other hand, solar global radiation is needed for most of the applications of solar energy systems. Berdhal *et al.* (1977) categorizes the applications in order of decreasing desirability as follows: heating and cooling, agricultural, solar electric, photovoltaic conversion and biomass conversion. As for user category, these authors (Berdhal *et al.*, 1977) find that global radiation is useful for at least nine different users, starting from agricultural engineers, architects. etc. . . . , up to planners. However, charts of solar radiation do not give the desired accuracy for some countries such as specified by the Federal Republic of Germany (± 2 - 5%) or Belgium (± 1 - 5%) according to IEA, 1976.

Radiation flux density

In the last years, the user community has been identified and their needs as solar radiation and meteorological data determined. Recently, the Atmospheric Environmental Service of Canada designed a survey to determine solar radiation data accuracy, time period, and length of record required (McKay, 1984). In this survey and in many others (Galindo and Castro, 1985), horizontal surface radiation data for mean hourly for a month, actual daily, mean daily for a week and mean daily for a month are *necessary* with a required accuracy within ± 5%. For an operating solar radiation network to attain a ± 5% for the above mentioned time periods is not an easy matter, it requires solar radiation specialists and good-dedicated technicians besides good instruments and data acquisition systems. There are several approaches to the use of solar radiation data. One is to use average solar energy available, for example is the use of past hourly or daily data for different locations to estimate what the performance of a process would have been under those past conditions, and on this basis project future performance (Duffie and Beckmann, 1976). Table 1 is shown as an example of hourly averaged global solar radiation data. These climatological records represent mean radiation flux values obtained from different sky conditions such as cloudless, cloudy, hazy, foggy, etc. Madison data are used here to show the latitudinal effect. One sees in Table 1 that solar global radiation attains its maximum about noon local time but, in the stations of Mexico City and Orizabita there is an asymmetry in the energy distribution, i.e., there is more irradiance in the afternoon as in the morning hours. This effect tends to disappear in Chihuahua and is not seen in Madison. Finally, Mexico City, in spite of its altitude receives less energy than Orizabita (rural area) and Chihuahua (farther North) since they do not have air pollution problems (Galindo, 1984).

Table† 1

Hourly averaged global solar radiation ($Wm^{-2}hr^{-1}$) for several places in the hour ending at:

Place	10	11	12	13	14	15	16
Mexico City* (19°20′N, 99°11′W, 2,268 m a.s.l.) 21 years	6373	8172	9280	9137	8315	6790	4991
Orizabita, Hgo.* (20°58′N, 99°12′W, 1,745 m a.s.l.) 8 years	6743	8589	9911	10292	9804	8577	6683
Chihuahua, Chih.* (28°32′N, 106°04′W, 1,430 m a.s.l.) 16 years	6187	7898	9137	9554	9137	8029	6373
Madison, Wisconsin** (43°04′N, 89°22′W, 270 m a.s.l.) 10 years	4954	5652	6257	6187	5652	4640	3349

* Measured data from Instituto de Geofísica, UNAM.
** Madison data are here used to show the latitudinal effect. Taken from Duffie and Beckmann (1976).
† Modified after Galindo, 1979.

Regional cloudiness

Since clouds and atmospheric turbidity are the main modulators of solar radiation received at the ground, one useful parameter to analyse is sunshine, this is due to the fact that the burning of the strip chart depends upon the presence or absence of clouds. We have developed a method (Galindo *et al.*, 1972 - 73) that represents the mean value of sunshine for a given hour j during the month m. Where $j(1 \leqslant j \leqslant 13)$ is the number of sunshine hours in a day and obviously $1 \leqslant m \leqslant 12$. Therefore, one has the matrix d_{jm}. The distribution of sunshine for a given year is represented in the coordinate system (j, m). The isolines of sunshine will have the form $f(j, m) = C$. Where constant C has the following values C = 1.0, 0.8, 0.6, 0.4, 0.2, then one draws these isolines having four main areas; namely, sunshine between 100 and 80%, 80 to 60%, 60 to 40%, and finally 40 to 20%. Figures 3 and 4 show this representation for Mexico City during the years 1960 and 1970. An analysis of Figures 3 and 4 shows that in the case of Mexico City, two well-defined areas of sunshine are

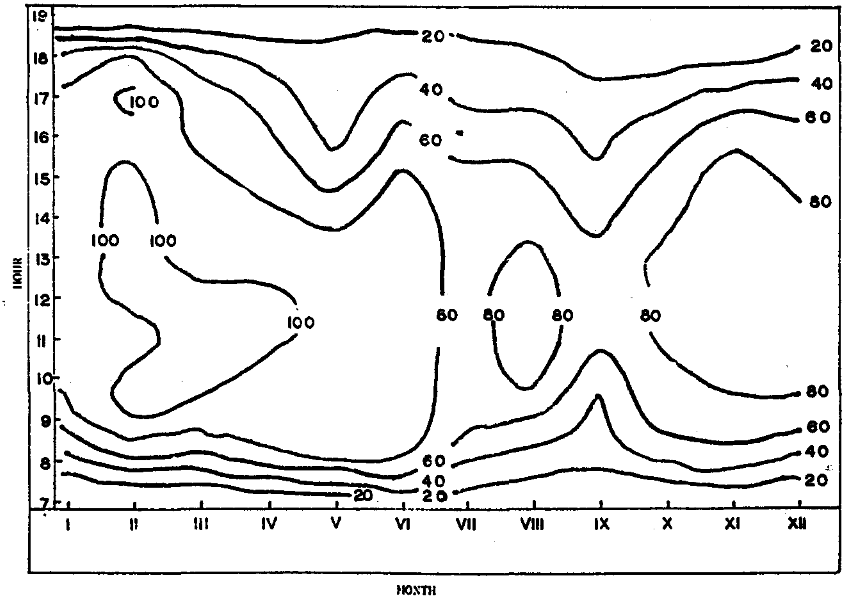

Fig. 3. Daily variation of duration of sunshine at Mexico City, 1960.

depicted, one of high sunshine ($S_S > 80\%$ from 9 to 16 - 17 hours) starting during October and lasting until April-May; a second are of variable sunshine ($S_S < 80\%$, with predominance of the 60% contour level between 10 to 16 hours) which stays between May and lasts until September. These findings coincide with the dry season (October-April) and the wet season from May to September (Galindo *et al.*, 1972 - 73). Other result seen in Figures 3 and 4 refers to the diurnal variation. During the dry season sunshine varies from 10 to 16 hours to 80% during October to December but from January to April this station receives the higest insolation from 9 to 18 hours. Obviously there are yearly fluctuations. Since these contour levels are repre-

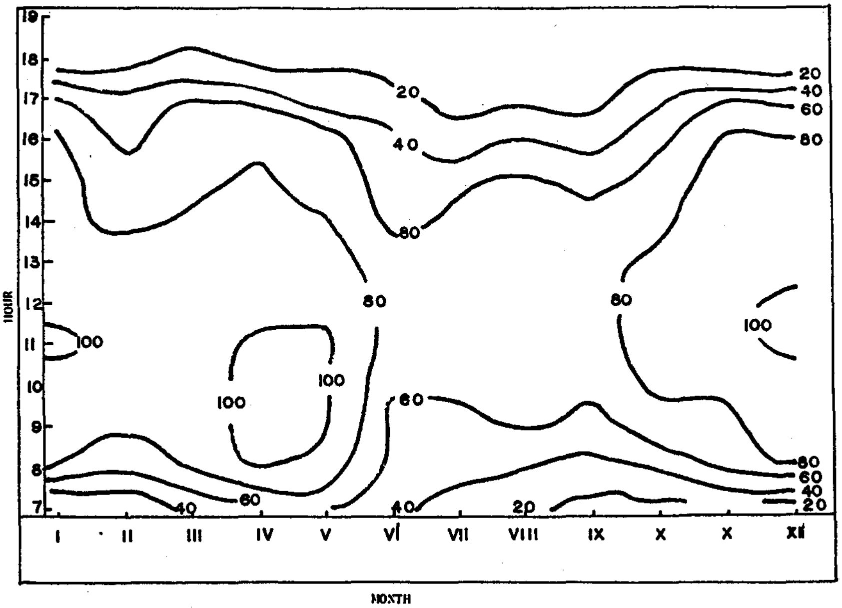

Fig. 4. Daily variation of duration of sunshine at Mexico City, 1970.

sentative of the solar climate for a given place one can use them in the election of probable sites for installation of solar power systems, also one can study hourly efficiencies of a given solar energy design as a function of time distribution of irradiance in a given place. The method can also be used to represent irradiance values.

Other use of the above methods is in the field of satellite cloud determination, if one considers that sunshine and clouds are mutually exclusive events: the field of view of the sunshine recorder is given by the glass sphere, whose projection covers the largest part of the horizon and since the only event that may obstruct the burning of the strip chart is the presence of clouds in the instrument field of view, one can represent the event sunshine S_S as the probability $P(S_S)$ that clouds are not present therefore, clouds become a conditional probability P(N) that the sun rays will not burn the strip chart, i.e.

$$P(S_S|N) = 1 - P(N)$$

In the presence of clouds, $P(S_S) \to 0$ and consequently $P(N) \to 1$.

Contour lines depicted in figures 3 and 4 may be regarded as probabilities of sunshine for a given place. Conversely, one can have also

$$P(N/S_S) = 1 - P(S_S)$$

In the absence of clouds, $P(N) \rightarrow 0$ and consequently $P(S_S) \rightarrow 1$. In this case the contour lines represent the inverse probability of having clouds. Actually we are extending this approach to determine clouds in a bidimensional grid (latitude-longitude) for the Mexican territory (Galindo and Castro, 1985).

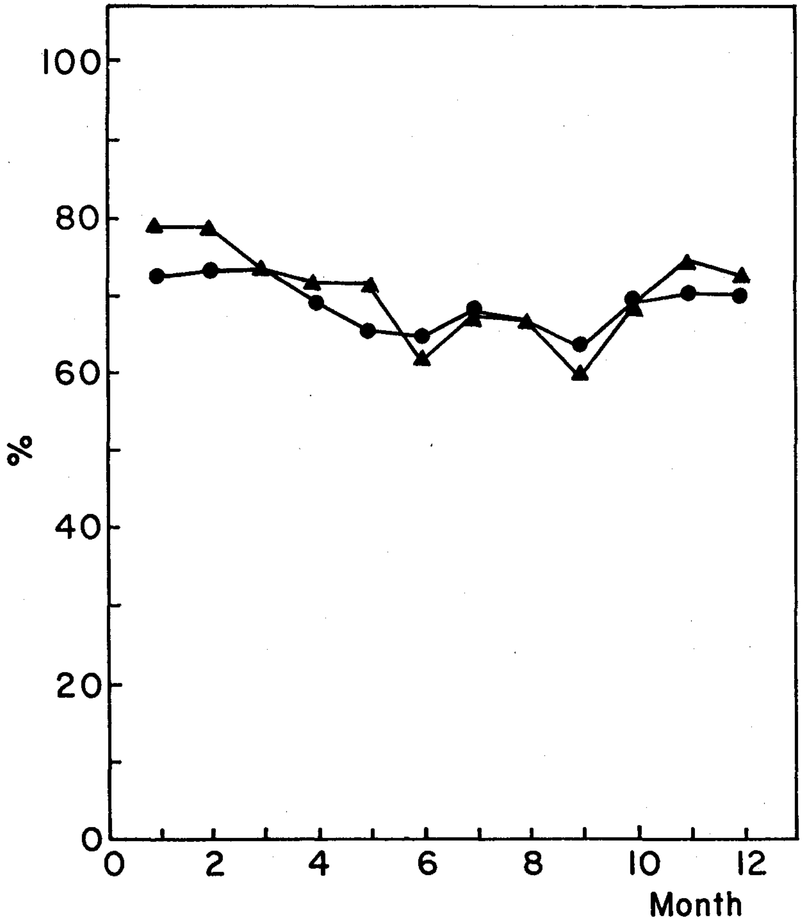

Fig. 5. Solar radiation at Orizabita (1968-1980) ● in % of extraterrestrial flux and duration of sunshine ▲ in % of astronomical possibility.

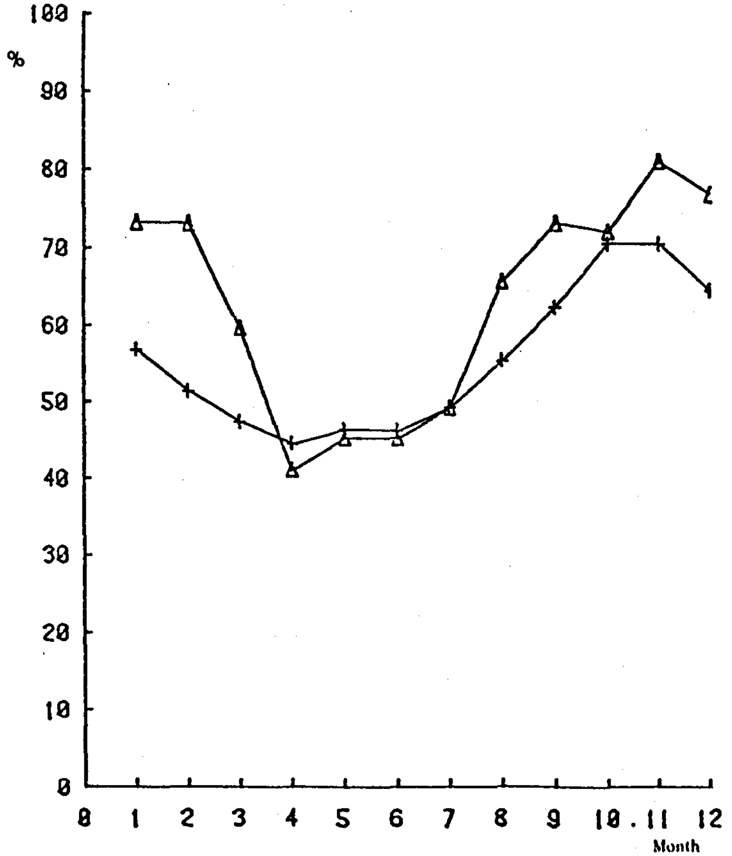

Fig. 6. Solar radiation at Mexico City (1970-1979) + in % of extraterrestrial flux and duration of sunshine △ in % of astronomical possibility.

Another way to study solar irradiance is simply to ignore the radiative transfer in the atmosphere and take the ratio between measured values of solar radiation and the corresponding extraterrestrial radiation for a given place and time. The reference value for this ratio may be the calculated irradiance without atmosphere or with a Rayleigh-atmosphere (WMO, 1981). In the absence of radiation data one can use sunshine data instead. The temporal distribution of both parameters strongly depends on local conditions. In what follows, we have taken as reference calculated irradiance values without atmosphere. Figure 5 corresponds to a solar radiation station located in a semi-desertic area without pollution sources; here the relative values for both global radiation and sunshine run very closely indicating that clouds produce two minima, normally in June and September, whereas during the rest of the year the ratios are near those theoretically expected for a clear atmosphere when only Rayleigh scattering attenuates the incoming radiation. The situation looks quite different for Mexico City (Fig. 6) where during April to July (wet season), cloudiness together with air pollution reduces the relative values down to 45%. During the dry season one finds an interesting result, namely, sunshine ratios tend to be those of a clear atmosphere but radiation values go down to values between 60 - 70%, the only possible interpretation is the reduction of the direct beam due to prevalent air pollution; this effect is more pronounced mainly during January, February and March where, because of wintertime, the frequency of temperature inversions is increased during the day after nocturnal radiational cooling. These results characterize quite well the annual and semiannual oscillation of solar climate for a given place. This information might be useful for site selection of solar power energy systems.

Direct solar radiation

The most simple and straightforward application of radiometric data is the calculation, with a pocket computer, of the irradiance of direct solar radiation on differently oriented inclined surfaces: this is due to the fact that the flux of solar radiation on an inclined surface depends on the angle of inclination and orientation of the surface (Kondratyev, 1965). Therefore, having continuous pyrheliometric measurements one can easily convert direct beam measurements to an inclined surface. This is not the case for global or diffuse solar radiation because the anisotropy of the radiation field (Kondratyev, 1965). The influence of the tilt angle of the plane and the angle at which the direct radiation falls on the plane, on the diffuse sky radiation reaching the plane is extremely complicated and is very dependent on the cloudiness, the atmospheric turbidity and the albedo of the ground, an excelent analysis of this problem due to the anisotropy in the sky is given by Kondratyev (1965) and Schüepp (1966).

In what follows, we show a simplified method (Coffari, 1977) for conversion of hourly pyrheliometric data received on a horizontal surface to radiation on inclined surfaces of any orientation:

The irradiance flux density (Wm^{-2}) of direct solar radiation is calculated, for variously oriented surfaces, by the formula

$$B'(\gamma, \alpha) = 1'_m \cos\theta_i \quad (1)$$

where I'_m is the irradiance of direct solar radiation at the Earth's surface on a surface perpendicular to the ray with an optical air mass m, and θ_i is the angle at which the Sun's rays fall on the given surface.

The cosine of the angle of incidence of the Sun's rays is calculated from the formula

$$\cos\theta_i = \sin\beta \cos\gamma - \sin\gamma \cos\beta \cos(A - \alpha) \quad (2)$$

where β is the solar elevation, γ is the angle of inclination of the surface in relation to the horizontal plane. A and α are the Sun's azimuth and that of the inclined plane. The orientation angle α is defined as the angular distance from the true North to the projection of the perpendicular to the inclined plane onto the horizontal plane, i.e., positive to the West and negative to the East.

The inclination γ of the surface with respect to the horizontal plane is taken positive facing South and negative facing North.

Obviously for a horizontal surface $\gamma = 0$ and for vertical surface $\gamma = 90^o$ (North).

Since $\beta = \beta(\phi, \delta, \omega)$, i.e., ϕ latitude, δ solar declination and ω hourly angle, then expression (2) can be evaluated for any surface $S(\gamma, \alpha)$.

In what follows we shall present some results for Mexico City from pyrheliometric measurements performed on an heliostatic mounting with an Eppley normal incidence pyrheliometer during March 1980 - March 1981, data acquisition was continually recorded with paper tape. The instrument had been calibrated and the total error of instrumental coupling and the computation is estimated as not being larger than 8%.

To illustrate the results we have chosen a clear day (19 October, 1980) where total sunshine was 10.3 hrs. Figure 7 depicts the direct beam flux received on the sensor together with hourly sunshine values. One sees that although no clouds were present, the direct beam shows considerable fluctuations, the most pronounced is precisely given at the Sun's culmination. This fact is due to the invasion of the smog plume. Coming back to energy matters one deduces that air pollution may affect solar energy systems considerably. In particular, for that day at 11:00 hrs. there is an absolute reduction of 32% (246 Wm^{-2}) with respect to the recorded maximum value (760 Wm^{-2}).

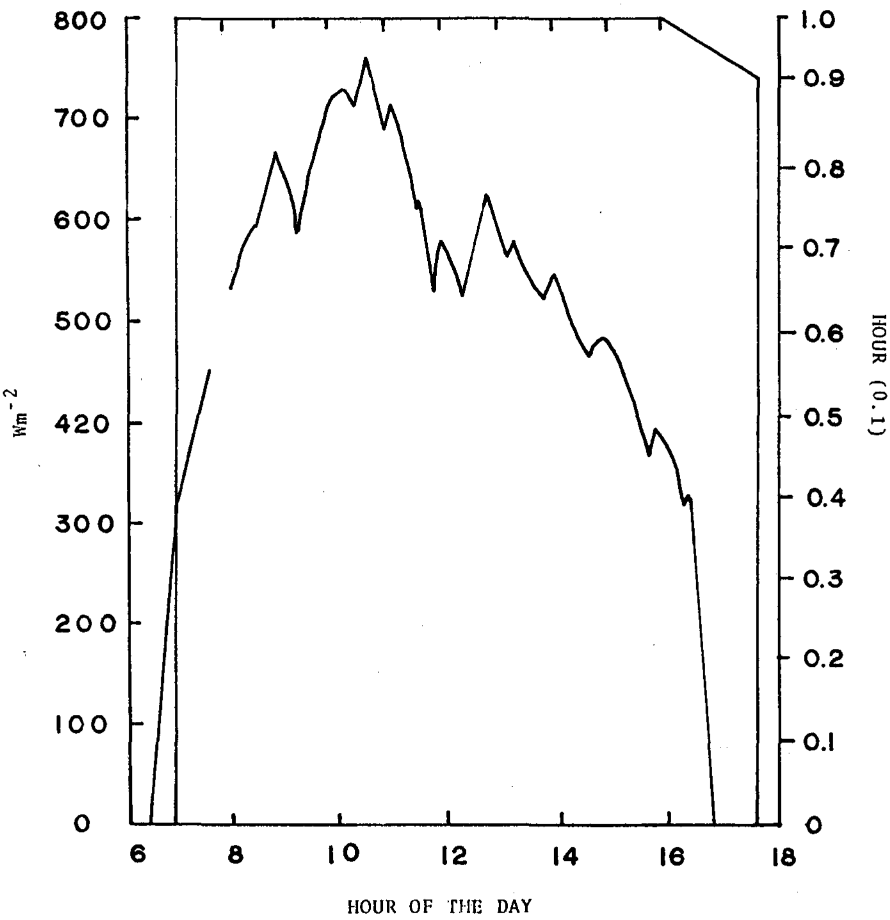

Fig. 7. Direct solar radiation in Wm^{-2} and duration of sunshine in tenths of an hour the 19th October, 1980 at Mexico City.

The program runs for any orientation and inclination of a surface but, for sake of brevity we shall show the results only for the following configurations:

B′(90°, 0):	vertical, facing South,
B′(90°, – 90°):	vertical, facing East,
B′(90°, 90°):	vertical, facing West.

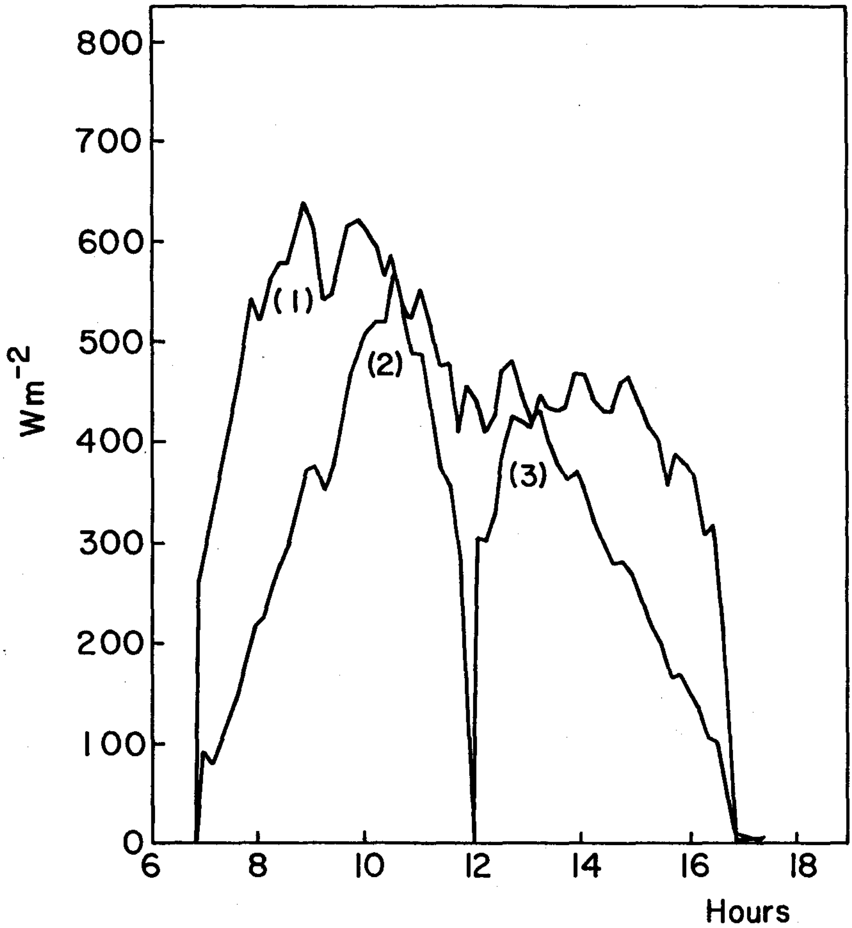

Fig. 8. Direct solar radiation and vertical planes in Wm^{-2} facing 1) B′ (90°, 0) South, 2) B′ (90°, −90°) East, and B′ (90°, 90°) West the 19th October, 1980 at Mexico City.

Figure 8 shows the results, from which some interesting conclusions can be derived. The symmetry on planes East and South is distortioned due to time of the year, air pollution and topography. At that time of year the direct beam falling on the North vertical plane is null.

This calculation can be processed for any time of the year under different sky conditions.

CONCLUSIONS

The methods presented here, although of easy access, are designed only to give a preliminary answer to the increasing demand of reliable meteorological and solar irradiance information by planners and engineers in developing countries.

If developing countries want to improve their application technology of solar energy, they need to utilize specialist resources on solar radiation studies. These specialists can modernize and expand existing solar radiation networks including measurements of other components of the radiation field. Good measurements of solar radiation need improved instruments. It is also urgent to consider regular pyrheliometric calibrations at national and regional radiation centers. Such calibration programmes have to be conducted uniformly if it is desired to have more accurate measurements. On the other hand, the evaluation of solar energy resources using meteorological satellites opens the possibility of assessing solar energy resources over larger areas. Of course, ground networks of solar radiation observations continue to be needed not only to offer a reference for satellite calibration but also for solar climate characterization. There is also a need for special measurements, such as spectral bands, irradiance on inclined surfaces, angular distribution of sky radiation, etc.

Last but not least, it is necessary to develop methods for statistical validation of past records of solar radiation measurements which not only contain gaps but more importantly, were obtained from non-calibrated instruments.

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