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The Sun as Source of Radiation**

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Many research programs in the fields of photochemistry, photoelectricity, and photo-electrochemistry are aiming at processes for solar energy utilization. The sun as source of radiation, however, exhibits some characteristics which are very different from those of artificial light sources usually used in the laboratory. – The scope of this paper is to acquaint the researcher not already familiar with radiation meteorology, with some basic principles and facts. The most important properties of the sun as a source of radiation are surveyed and the different aspects of radiation and their relationships discussed. The intensity of radiation, an important property, is described with some statistical examples. After some remarks on radiation variability and transients, this account finally looks at the spectral distribution of radiation under different conditions.

1. Introduction

At present, the fields of photochemistry and photoelectricity are being investigated mainly for the purpose of producing energy carriers and raw materials with solar energy. Research takes mostly place in laboratories where artificial light is used. In this way, it is possible to vary the characteristics of the source of radiation within wide ranges. However, the results of these experiments are representative only for these conditions. Should the same photochemical process be taken outside, using the sun as radiation source, results will inevitably be different. It may therefore be useful – even for the laboratory researcher – to better understand the basic characteristics of the sun.

Bandwidths and ranges of some characteristic parameters of the sun as a source of radiation will be shown by means of examples. Researchers in photochemistry will then be able to compare these conditions with those required by the application being considered. Certainly, a meteorological data base (e. g. Ref.[5]) should be consulted for more detailed information and especially for model calculations.

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2. The Sun

Nuclear fusion has been taking place for the past $5 \cdot 10^9$ years in the sun, converting hydrogen into helium. The gain of energy from this reaction amounts to 640000 GJ per kilogram of hydrogen. By burning $2.16 \cdot 10^{15}$ kg of hydrogen per hour, the sun has a power of $3.85 \cdot 10^{20}$ MW. The fuel reserve in the sun will still last for another $5 \cdot 10^9$ years. The most important data concerning the sun is presented in Table 1.

The earth circles in an elliptical orbit around the sun. The average distance is 149.6 million kilometres. The distance between the sun and earth is longest in summer and shortest in winter, varying by 1.7% around the average.

The sun's energy output is mostly in the form of electromagnetic radiation which is evenly spread out into space. Given the average distance R_0 between earth and sun, the power of radiation reaching the earth outside the atmosphere amounts to:

$$4\pi R_0^2 \cdot I_0 = 4\pi \cdot (1.496 \cdot 10^{11})^2 \cdot I_0 = 3.85 \cdot 10^{26}\ \mathrm{W} \quad (1)$$

$I_0 = 1367\ \mathrm{W/m^2}$ (data of 1981)

Table 1. Data of the sun.

Solar Characteristics	Values
power of radiation	$3.85 \cdot 10^{26}$ W
diameter	$1.39 \cdot 10^9$ m
mass	$1.9891 \cdot 10^{30}$ kg
constant of gravity	273.4 m s^{-2}
age	$4.55 \cdot 10^9$ a
composition	75% hydrogen 23% helium 2% heavy elements

This average value is called «solar constant». Today it is being measured with satellites. Previous estimates were calculated from measurements taken with balloons. Therefore, values like 1322, 1353, or 1370 $\mathrm{W/m^2}$ are still in use. Because of the varying distance from sun to earth due to earth's elliptical orbit, the resulting radiation intensity outside earth's atmosphere changes by $(1 \pm 1.7\%)^2 = 1 \pm 3.3\%$.

At the surface of the earth, solar radiation intensity is reduced to approximately 1 $\mathrm{kW/m^2}$ with clear skies. Under special atmospheric conditions, higher values of 1.2 $\mathrm{kW/m^2}$ or more may appear for short periods of time. In the specifications for photovoltaic cells, 1 $\mathrm{kW/m^2}$ is usually taken as reference input value. Average intensity is significantly less, depending on the geographic situation and local climate.

As an example, average intensity amounts to only 120 $\mathrm{W/m^2}$ in the Swiss plateau with regard to a horizontal surface. In desert areas, values above 300 $\mathrm{W/m^2}$ can be observed.

3. The Components of Solar Radiation

For the purpose of exploiting solar energy, three components of radiation are usually defined:

(a) *direct radiation*, $\dot{B}$ [$\mathrm{W/m^2}$], is the radiation which comes directly from the sun, without being reflected or absorbed;

(b) *diffuse radiation*, $\dot{D}$ [$\mathrm{W/m^2}$], is the radiation component coming in at all angles, spread by clouds, dust particles, or the atmosphere itself;

(c) *reflected radiation* contains diffuse radiation and that portion of direct radiation which is reflected from the surroundings onto the surface being considered.

All three components add up to the *global radiation*, $\dot{G}$ [$\mathrm{W/m^2}$]. The global radiation outside the atmosphere is known as $\dot{G}_0$ [$\mathrm{W/m^2}$]. Fig. 1 illustrates the three components mentioned above.

Besides these values and their integrals (sums over hours, days, and years), the sunshine duration (i. e. the cumulative pe-

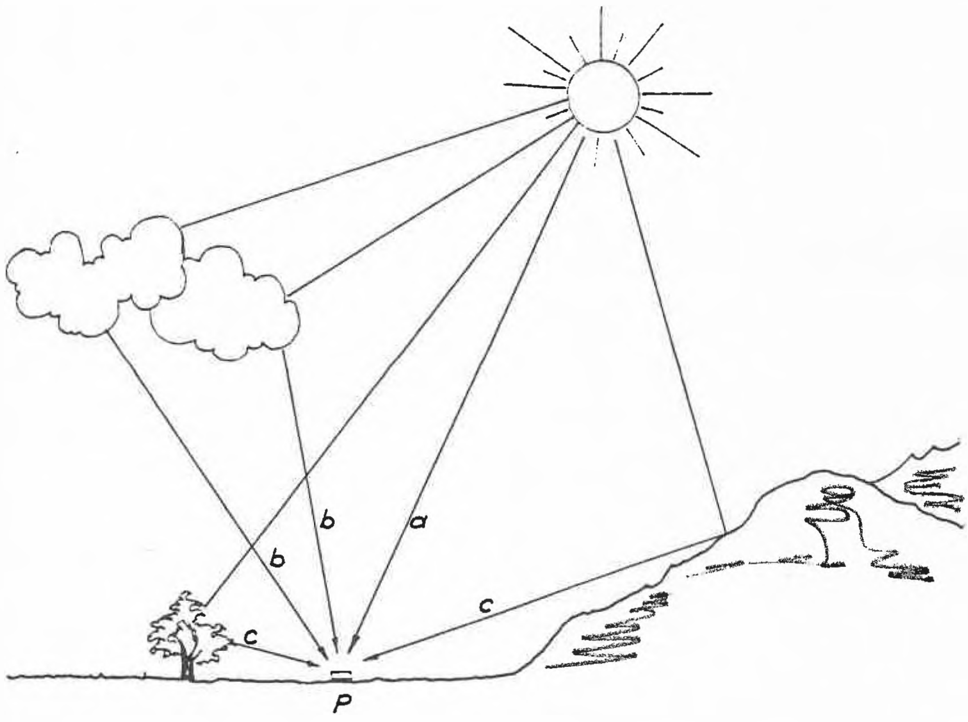

Fig. 1. The components of solar radiation (a: direct radiation, b: diffuse radiation, c: reflected radiation).

riods when the sun is visible) is often used. A difference is made between the absolute sunshine duration, S [h], the maximum possible sunshine duration, S_g [h], and the relative sunshine duration, $S_r = S/S_g$.

S stands for the hours during which we observe the sun in reality, depending on the presence of clouds and shades. S_g can be measured if the sky is absolutely clear, its value however is usually calculated.

S (and therefore also S_r) is not very exactly defined, as it depends on the inferior limit of radiation intensity still leading to registration in a measuring instrument. This lower limit in turn depends on the type of measuring instrument used. Despite this ambiguity, there is a simple, useful relationship between $\dot{G}$, $\dot{D}$, and S_r known as the Angstrom equation[1]:

$$G/G_0 = (a + b \cdot S_r) \qquad (2)$$

with $G = \int \dot{G} \cdot dt$
$G_0 = \int \dot{G}_0 \cdot dt$
a, b are constants that depend on the local climate;
G, G_0, and S_r are monthly averages of daily values.

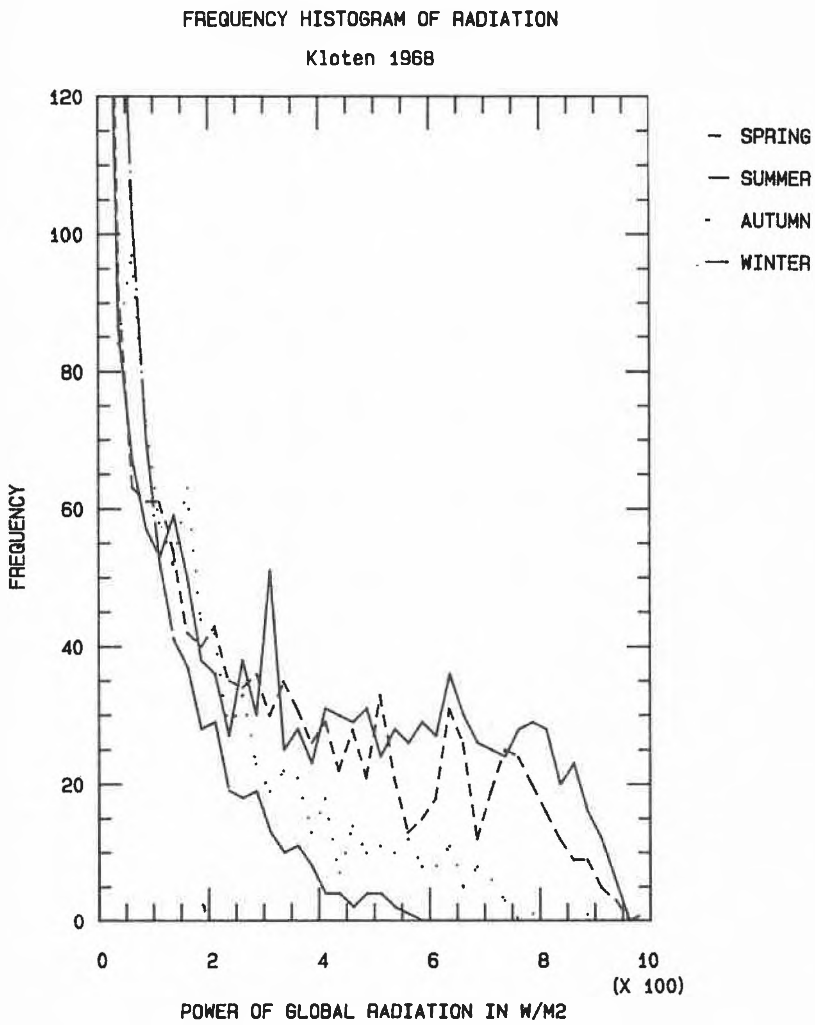

Fig. 2. Frequency diagram (number of hours) of global radiation on a horizontal surface for the four seasons (Kloten 1968).

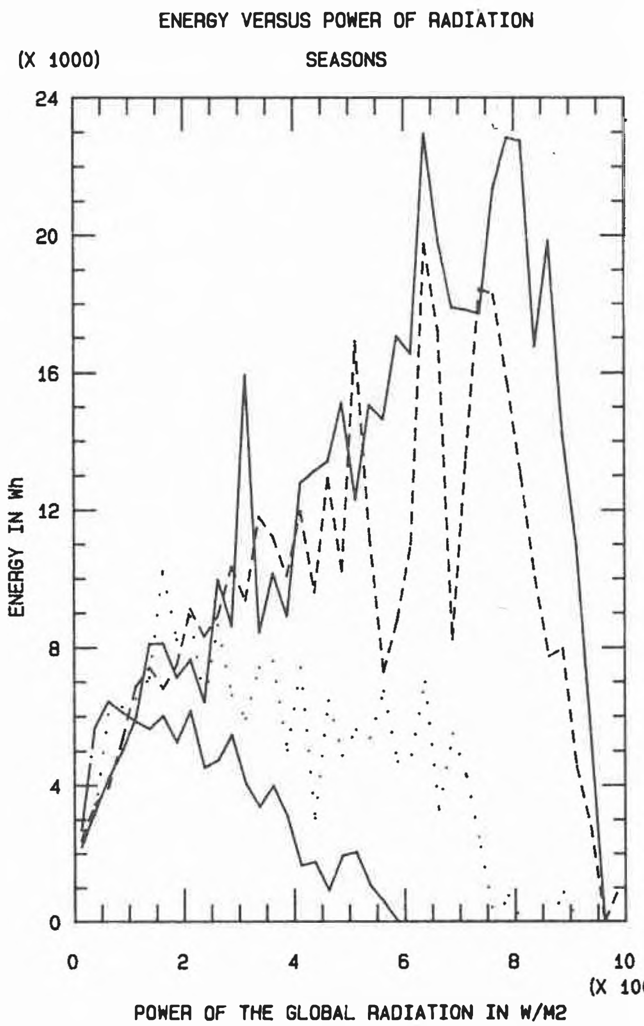

Fig. 3. Distribution of energy vs. intensity (hourly averages; Kloten 1968, global radiation on a horizontal surface for the four seasons).

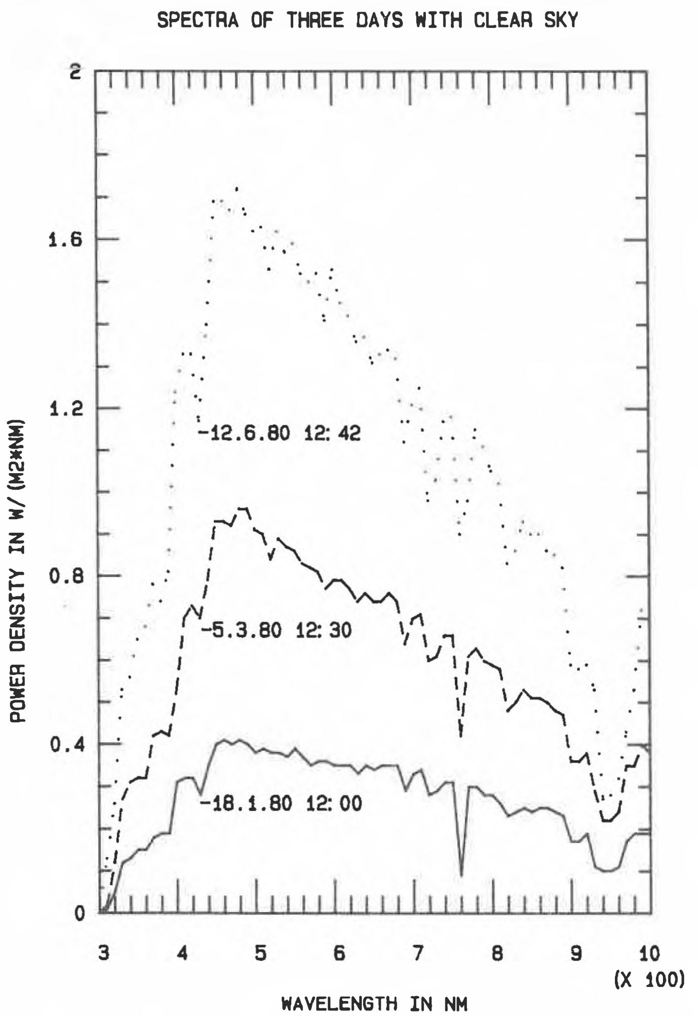

Fig. 4. Spectra of three days with clear sky.

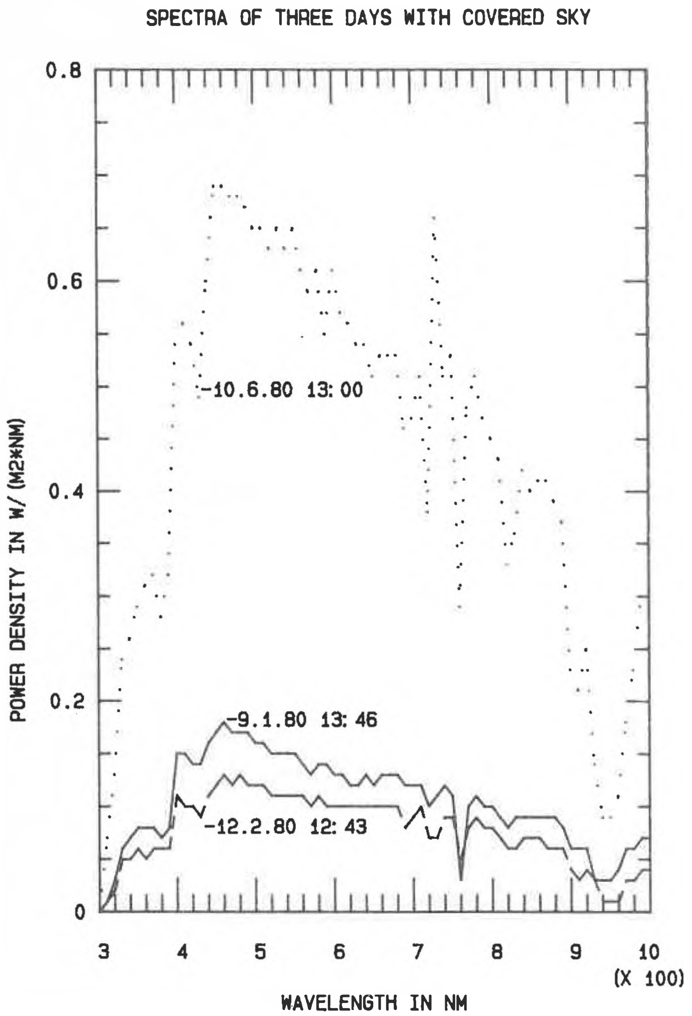

Fig. 5. Spectra of three days with covered sky.

The constants a and b can be determined by linear regression from a set of measurements of G and S_r. With defined values of a and b, G can be determined for regions with similar climatic conditions when values of S_r are known, and vice versa.

There are also a number of widely used similar empiric relations regarding the diffuse component of radiation, e.g. the equation of *Liu* and *Jordan* [2], but we will not discuss them within the frame of this paper.

4. Examples of Statistical Descriptions

In order to evaluate the performance of processes, it is often useful to reduce data of meteorological networks by statistical methods to a quantity which can easily be handled. Two examples will be discussed:

- Most of the processes which use the sun as source of energy are non-linear. Averages are therefore of limited use. To be able to compute with a reasonable level of precision, additional statistical data is required, such as a frequency diagram of radiation intensity (see Fig. 2). From this frequency diagram, a cumulative frequency diagram can be drawn. Should a process require a certain threshold intensity, the cumulative frequency diagram will show how often this process will work.
- Besides the frequency diagram of intensity, it is also important to know how much energy is received at each intensity. This is illustrated in Fig. 3 for all four seasons. For instance, should a process require a threshold intensity of 200 W/m^2, half of the energy in winter is not usable, whereas only about 10% of the energy available in summer is not usable.

These two examples show how the source of radiation influences the process. Using the sun as source of energy is quite different from the classic procedure where first the process is defined and then the source of energy is adapted to the process' needs.

Besides frequency distributions, dynamic aspects are also of interest. When a process is sensitive to transients, this factor cannot be overlooked. In principle, it is possible to use Fourier analysis of time series of radiation measurements. Climatological stations, however, usually supply data with a maximum resolution of 10 minutes whereas radiation intensity may change significantly within 0.1 seconds (10 Hz).

5. Radiation Spectrum

The last characteristic of solar radiation which will be looked at is the spectral distribution. The spectrum shows the distribution of photons as a function of photon energy (wavelength). Thus it is an important factor for all processes with non-thermal absorption of photons. Just as radiation intensity, the spectrum varies geographically and in time.

Outside the atmosphere, the sun is fairly similar to a black body with a temperature of 5500 K. At this temperature, maximum radiation intensity is to be found at $\lambda = 560$ nm, corresponding to the color green. Most of the radiative power lies within the visible part of the spectrum. In other words, the human eye is sensitive to the most important part of the solar spectrum. Under clear skies, the solar spectrum on earth is still quite well approximated by black body radiation.

Spectral changes (i.e. distribution changes at different wavelengths) are observed (i) at different times of the day, due to the varying airmass crossed by solar rays and (ii) with varying weather conditions. To our knowledge, there are no systematic measurements of the solar spectrum for Switzerland. The following examples are therefore based on data from the Royal Institute of Belgium [3,4].

Spectral data from three days with clear skies and three days with covered skies were chosen in order to show spectral changes in the course of the year. Fig. 4 and Fig. 5 show that, although the spectral envelopes practically do not change under different sky conditions, some absorption lines and absorption windows are significantly different.

Radiation distributions in the wavelength range between 300 and 1000 nm, and above 1000 nm are shown in Table 2. The fraction of the latter varies from 7 to 23%. It tends to be less when the sky is covered but a simple correlation with radiation intensity cannot be seen.

Looking at spectral distribution changes during a day with clear sky, one recognizes small relative movements. The fraction of radiation at short wavelengths is smaller in the morning and in the evening, the fraction at long wavelengths larger than in the middle of the day. Fig. 6 illustrates this.

Table 2. Radiation values [W/m^2] at bandwidth between 300 and 1000 nm, remaining radiations at superior wavelengths, in absolute and relative terms.

Date	Weather	Global Radiation ($\dot{G}$)	Radiation 300–1000 nm	Radiation > 1000 nm	idem, as a % of $\dot{G}$
18.01.80	clear	245	188	57	23
05.03.80	clear	536	415	121	23
13.06.80	clear	875	743	132	15
09.01.80	covered	88	73	15	17
12.02.80	covered	58	54	4	7
10.06.80	covered	375	308	67	18

Besides instantaneous spectra, sums over longer periods are also of interest. Fig. 7 illustrates an example of sums of radiation energy for three different months.

Concluding, one must recognize that very limited statistically relevant data exists on spectral distributions. As a complement to research and development in the areas of photochemistry and photovoltaics, additional systematic investigations on this subject would be highly desirable.

6. Conclusions

The advantage that the sun is a free source of energy must be paid by a number of disadvantages, particularly in the temperate climatic zones. Radiation density is small and radiation intensity as well as spectrum are subject to strong periodic and stochastic changes. These properties set a big challenge to the flexibility of processes which would use the sun as source of energy.

Scientists working in basic research, e.g. in photochemistry, should be aware of how their processes fit with solar characteristics. It is certainly even more important for the engineer, who puts such processes

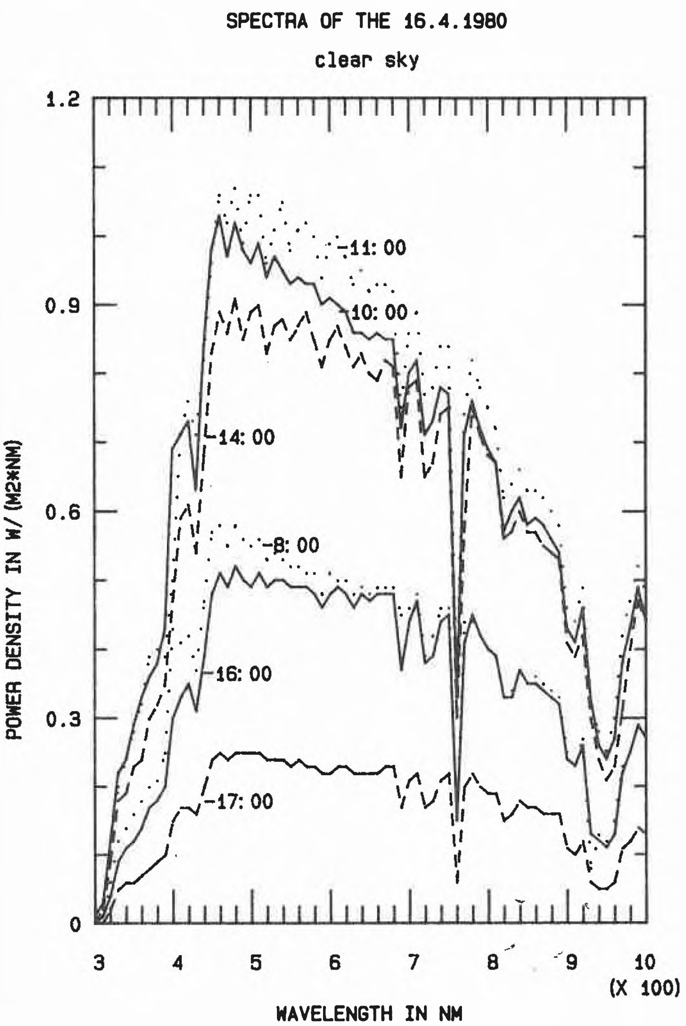

Fig. 6. Spectrum of one day at different times of the day.

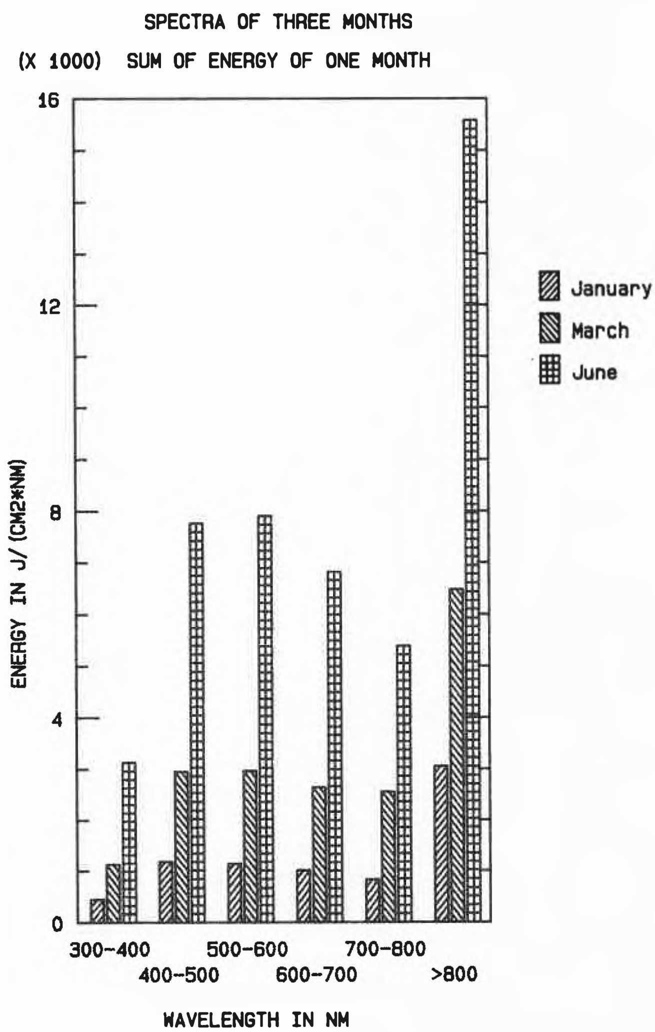

Fig. 7. Spectral distribution of radiation energy for three different months.

CHIMIA 42 (1988) Nr. 4 (April)

into practice. Only the knowledge of solar characteristics will make it possible to plan and construct sensible and efficient systems.

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