The Intensity of Solar Radiation

Solar Radiation outside the Atmosphere

The spectrum of the radiation emitted by the sun is close to that of a black body at a temperature of 5,900 K. About 8% of the energy is in the ultra-violet region, 44% is in the visible region, and 48% is in the infra-red region.

The *solar constant* I_o is the beam solar radiation outside the Earth's atmosphere when the sun is at its mean distance from the Earth. Its value is

$$I_o = 1.37 \pm 0.02 \text{ kW/m}^2.$$

Variations in the distance of the sun from the Earth due to the ellipticity of the Earth's orbit cause the actual intensity of solar radiation outside the atmosphere to depart from I_o by a few percent. Allowance for these variations can be made by means of the factor

$$F = 1 - 0.0335 \sin 360(n_d - 94)/365,$$

where n_d is the day of the year (on 1 January $n_d = 1$; on 31 December $n_d = 365$); the argument of the sine function is in degrees. All the values of solar radiation intensity given below, which are for the sun at its mean distance from the Earth, must be multiplied by F to obtain the actual values on day n_d. When the Earth is nearest the sun in January the solar radiation in clear weather is 3% greater than the average; when the Earth is farthest from the sun in July the solar radiation is 3% less than the average.

Effects of the Atmosphere and the Earth

The processes affecting the intensity of solar radiation that are important in solar energy work are scattering, absorption, and reflection. Reflection occurs in the atmosphere and on the Earth's surface.

The **scattering** of solar radiation is mainly by molecules of air and water vapor, by water droplets, and by dust particles. This process returns about 6% of the incident radiation to space, and about 20% of the incident radiation reaches the Earth's surface as diffuse solar radiation.

Air molecules scatter sunlight with an intensity proportional to λ^{-4}, where λ is the wavelength of the radiation. This is called Rayleigh scattering; it is important for particles with radius less than $\lambda/10$. This wavelength effect can be seen in the blue color of the clear sky and the red color of the setting sun. The sky appears blue because the shorter wavelength blue light is scattered more strongly than the longer wavelength red light. The setting sun appears red because much of the blue light has been scattered out of the direct beam. Scattering from large particles with radius greater than 25λ is independent of the wavelength. As a result, sunlight scattered from the water droplets in mist and cloud, and from the dust particles in haze, is white.

The **absorption** of solar radiation is mainly by molecules of ozone and water vapor (Fig. 1). Absorption by ozone takes place in the upper atmosphere at heights above 40 km. It occurs mainly in the ultra-violet region of the spectrum, where it is so intense that very little solar radiation of wavelength less than 0.3 μm reaches the Earth's surface. About 3% of the solar radiation is absorbed in this way.

At low levels in the atmosphere about 14% of the solar radiation is absorbed by water vapor, mainly in the near infra-red region of the spectrum. Clouds absorb very little solar radiation, which explains why they do not evaporate in sunlight. The effect of clouds on solar radiation is mainly scattering and reflection.

There is a small amount of absorption of solar radiation by oxygen. The absorption of solar radiation by carbon dioxide is also slight, although the absorption and emission of long-wave atmospheric radiation by carbon dioxide is important in the greenhouse effect.

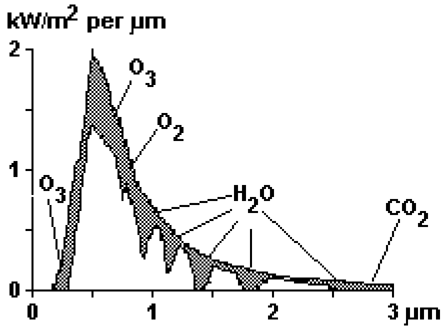

Fig. 1. The solar spectrum. The upper graph is for radiation outside the atmosphere; the lower graph is for radiation received at the earth's surface under a clear sky. Absorption bands by gases in the atmosphere are indicated by chemical formulas.

The **reflection** of solar radiation depends on the nature of the reflecting surface. The fraction of the solar irradiation that is reflected from the surface of the Earth is called the **albedo** of the surface. The total albedo, which includes all wavelengths, is closely related to the visible albedo, which includes only light in the visible region of the spectrum. Table 1 shows some typical albedo values for the sun overhead. When the sun is low in the sky (with a large zenith angle ζ) the albedo of a water surface is much greater than the value tabulated. The albedo of clouds depends on how thick they are.

Table 1. Surface Albedos

Surface	Albedo
Vegetation	0.2
Pale soil	0.3
Dark soil	0.1
Water	0.1
Clouds	0.5-0.9

Solar Radiation under Clear Skies

A simplified presentation of the solar radiation at the earth's surface applicable in tropical Asia is given in this section.

The main parameters affecting the intensity of solar radiation are the zenith angle ζ of the sun, the water vapor content w of the atmosphere, and Schuepp's turbidity coefficient B.

The water vapor content w is given in centimeters of precipitable water. Exact determinations of w require the use of upper air data. If upper air data are not available, approximate estimates can be made with the help of the formula

$$w = 0.18\, e,$$

where e is the vapor pressure in the atmosphere at the Earth's surface in millibars. In a tropical wet and dry climate w typically varies from 2 cm in the dry season to 5 cm or more in the wet season.

The turbidity coefficient B is zero in a dust-free atmosphere, and increases in value as the air becomes more turbid. Direct determinations of B require measurements of beam solar irradiance in different ranges of the spectrum using colored filters. In a tropical wet and dry climate B typically varies from near zero in the wet season to about 0.2 during the dry season. If there is smoke in the air B can be greater. Inland in Thailand the equation

$$B = 0.25 - 0.017\, V,$$

where V is the mean visibility in kilometers, gives estimates of the mean values of B with an accuracy ±0.02.

The values of beam solar irradiance I_b at sea level are given in Table 2 for several values of the water content w of the atmosphere, the zenith angle ζ of the sun, and the turbidity coefficient B. Small corrections for variations in the ozone content of the atmosphere, and for variations in the surface air pressure, are ignored. Since the tabulated values are for application at sea level, they underestimate the beam solar irradiance at elevated mountain sites. The correction factor F for variations in the Earth-sun distance mentioned earlier should be applied.

Table 2. Beam Solar Irradiance at Sea Level

		$I_b(kW/m^2)$		
w(cm)	**ζ(degrees)**	**B = 0**	**B = 0.1**	**B = 0.2**
2	0	1.047	0.879	0.768
2	60	0.879	0.684	0.524
2	70	0.810	0.530	0.384
2	80	0.628	0.314	0.181
5	0	0.977	0.838	0.698
5	60	0.838	0.628	0.475
5	70	0.740	0.489	0.349
5	80	0.572	0.286	0.161

Diffuse solar irradiance is determined mainly by the solar zenith angle ζ, the turbidity B, and the albedo of the ground around the site. Table 3 gives values of the diffuse solar irradiance I_d for several values of ζ and B when the albedo of the ground is 0.25. For albedos 0.1, 0.2, and 0.3 multiply the tabulated values of I_d by the correction factors 0.90, 0.96, and 1.04 respectively.

Table 3. Diffuse Solar Irradiance

	$I_d(kW/m^2)$		
ζ(degrees)	**B = 0**	**B = 0.1**	**B = 0.2**
0	0.063	0.133	0.202
60	0.045	0.087	0.119
70	0.034	0.063	0.084

80	0.018	0.034	0.039

Table 4 gives the daily total global solar irradiation under clear skies in tropical latitudes on the 15th day of the critical months March, June, September, and December. The tabulated values are for water vapor content w = 2 cm and turbidity B = 0. For water vapor content w = 5 cm multiply the tabulated values by the correction factor 0.93; for turbidity B = 0.1 and 0.2 multiply the tabulated values by 0.90 and 0.84 respectively.

Table 4. Daily Global Solar Radiation Under Clear Skies

	Daily Global Solar Irradiation (MJ/m^2)		
Latitude φ:	**0°**	**10°**	**20°**
March	28.8	28.1	26.3
June	25.4	28.2	30.2
September	28.3	28.2	27.3
December	26.9	23.3	18.9

The Effects of Cloud

The effects of cloud on the solar radiation received at the Earth's surface are complex. If there is cloud between the sun and the point of observation, then the beam solar irradiation is weakened or eliminated. Diffuse solar radiation, on the other hand, may be greater or less in the presence of cloud than under a clear sky, depending on the type and amount of the cloud. Thin layers of cloud, and scattered clouds reflecting sunlight, increase the diffuse solar irradiation; thick layers of cloud reduce diffuse solar irradiation.

Global solar irradiation is usually reduced by cloud, but if the sun is shining in a clear part of the sky and there are brightly illuminated clouds nearby, then global solar irradiance may be greater than it would be under a completely clear sky.

Geographical, seasonal, and diurnal variations of solar radiation at the Earth's surface are controlled as much by the incidence of cloud as they are by the movement of the sun. Consequently, the study of these variations is closely linked to the study of climate, and many observations are required to build up an adequate description of them.

In Thailand the highest mean values of daily global solar irradiation are about 20 MJ/m^2 per day, and are widespread in April and May. The lowest values of daily global solar irradiation are below 15 MJ/m^2 per day in restricted locations with heavy rainfall in August and September. Diffuse solar irradiation averages 8.4 MJ/m^2 per day.

The **statistical frequency distribution** of daily totals of global solar irradiation has a peak near 20 MJ/m^2 per day at Bangkok during the dry season. This distribution is skewed towards low values, which has the important result that about 60% of days have global solar irradiation greater than the mean value. During the wet season the distribution is more dispersed and symmetrical.

A study of the diurnal variation of global solar irradiance in Thailand shows that the mean midday global solar irradiance ranges from 0.81 kW/m^2 in April and May to 0.58 kW/m^2 in August and September. On the average the irradiance is slightly more in the morning than in the afternoon, but the difference between the morning and afternoon values is not significant for most applications of solar energy.

We may define a **sky clearness factor** to be the actual solar irradiation divided by the solar irradiation from a completely clear sky. Studies then show that the clearest months over Thailand are December and January, except in the southern part of the country. During these months the mean clearness is between 70% and 80% (except in the south). The lowest values of clearness occur in July, August, and September, with values between 50% and 60% over the whole country.

The Measurement of Solar Irradiance

An instrument for measuring irradiance is called a **radiometer**. It is usually desirable for radiometers to respond equally to equal amounts of energy at all wavelengths over the wavelength range of the radiation to be measured. Most radiometers therefore work by using a thermopile to measure the temperature rise of a sensitive element whose receiving surface is painted dull black. Instruments for measuring solar irradiance using a photovoltaic cell as the sensitive element have a non-uniform spectral response.

A **pyrheliometer** is an instrument for measuring beam solar irradiance at normal incidence. It is so designed that it measures only the radiation from the sun's disk (which has an apparent diameter of ½°) and from a narrow annulus of sky of diameter 5° around the sun's disk.

A **pyranometer** is an instrument for measuring solar irradiance from the solid angle 2π onto a plane surface. When mounted horizontally facing upwards it measures global solar irradiance. If it is provided with a shade that prevents beam solar radiation from reaching the receiver, it measures diffuse solar irradiance.

These radiometers must be calibrated periodically against a standard. An accuracy of about 3% is then obtainable in good instruments.

Great care is needed when choosing a site for these radiometers, especially when the measurements are required for climatological studies in conjunction with measurements by other instruments over a large area. It is surprisingly difficult to find sites that have an uninterrupted view of the sky from the zenith to the horizon in all directions. Objects that stand above the horizontal plane of the instrument obscure part of the sky and influence the diffuse solar irradiance measured. Such objects may even obscure the beam solar irradiance for part of the day at some time in the year. It should also be remembered that a good site chosen at one time may become unsatisfactory later because nearby trees have grown taller, or because new buildings have been constructed.

By R. H. B. Exell, 2000. King Mongkut's University of Technology Thonburi.
