2. Solar Energy Reaching The Earth's Surface

2.1. The Solar Constant

The Sun is considered to produces a constant amount of energy. At the surface of the Sun the intensity of the solar radiation is about 6.33×10^7 W/m^2 (note that this is a power, in watts, per unit area in meters). As the Sun's rays spread out into space the radiation becomes less intense and by the time the rays reach the edge of the Earth's atmosphere they are considered to be parallel.

Figure 2.1: The Sun's rays incident on the Earth. I_0 = irradiance on a plane perpendicular to the Sun's rays

The *solar constant* (I_{SC}) is the average radiation intensity falling on an imaginary surface, perpendicular to the Sun's rays and at the edge of the Earth's atmosphere (figure 2.1). The word 'constant' is a little misleading since, because of the Earth's elliptical orbit the intensity of the solar radiation falling on the Earth changes by about 7% between January 1st, when the Earth is nearest the Sun, and July 3rd, when the Earth is furthest from the Sun (figure 1.2). A yearly average value is thus taken and the solar constant equals 1367 W/m^2. Even this value is inaccurate since the output of the sun changes by about ±0.25% due to Sun spot cycles.

The solar radiation intensity falling on a surface is called *irradiance* or *insolation* and is measured in W/m^2 or kW/m^2. The solar constant can be used to calculate the irradiance incident on a surface perpendicular to the Sun's rays outside and the Earth's atmosphere (figure 2.1) on any day of the year (i.e. as the distance between the Sun and Earth changes thought the year):

$$I_0 = I_{SC}\left[1 + 0.034\cos\left(2\pi\frac{n}{365.25}\right)\right] \tag{2.1}$$

Where:
I_0 = extraterrestrial (outside the atmosphere) irradiance on a plane perpendicular to the Sun's rays (W/m^2),
I_{SC} = the solar constant (1367 W/m^2),
n = the day of the year such that for January the 1st n = 1.

Figure 2.2 shows the variation in I_0 over the course of a year. Most solar power calculations use I_0 as a starting point because, for any given day of the year it is the maximum possible energy obtainable from the Sun at the edge of the Earth's atmosphere.

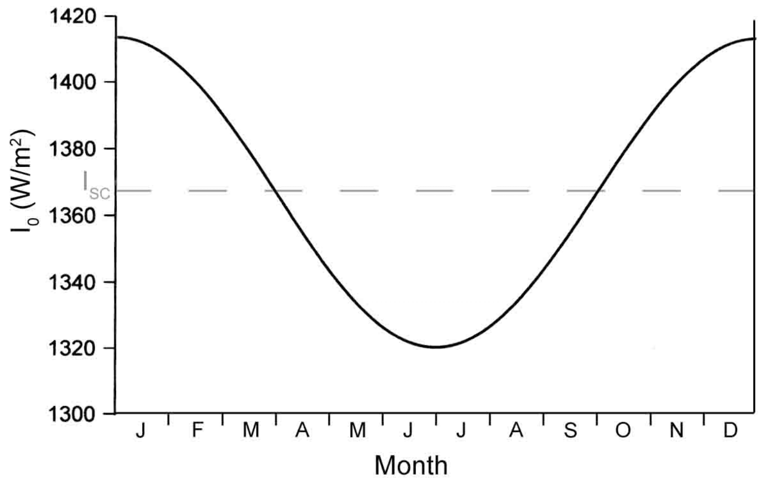


Figure 2.2: The variation in I_0 over the course of a year. The dashed line shows the value of the solar constant (I_{SC}).

2.2. The Cosine Effect

The value of I_0 is the same no matter where you are on the Earth's surface, however not all points on the Earth's surface are perpendicular to the Sun's rays. A useful quantity to calculate is the solar irradiance incident on an imaginary surface that is parallel to a horizontal plane on the Earth's surface (figure 2.2). The irradiance on such a surface is smaller than I_0 because of the *cosine effect* and is the maximum amount of solar energy that could be collected on a horizontal plane at the Earth’s surface if the atmosphere did not scatter and absorb any radiation..

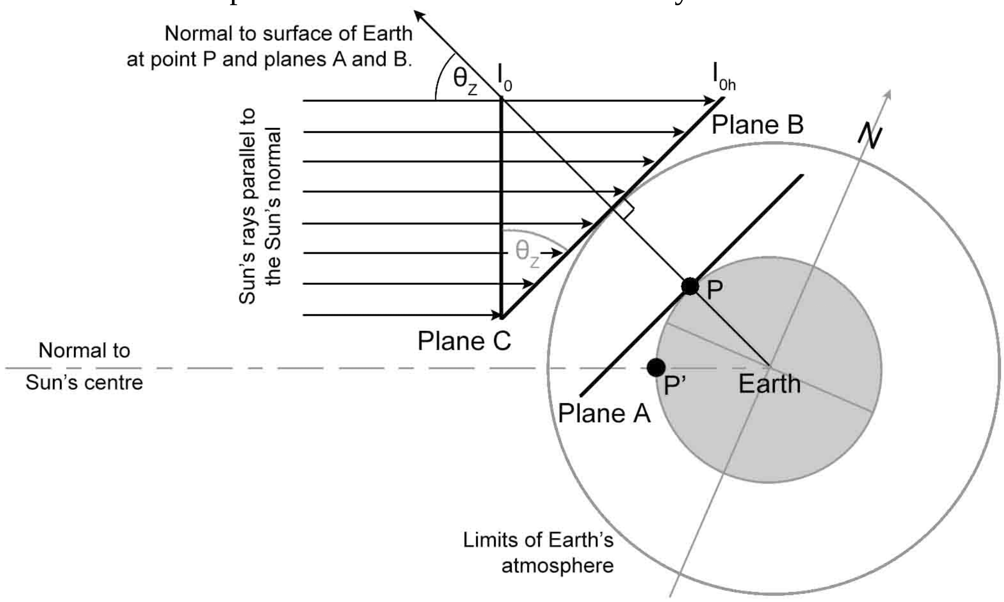


Figure 2.2: The cosine effect.

Figure 2.2 shows three plane surfaces:

- *plane A*, a horizontal plane at the point P on the Earth's surface;
- *plane B*, a surface parallel to plane A but on the edge of the Earth's atmosphere, often referred to as the horizontal plane;
- *plane C*, a surface perpendicular to the Sun's rays, often referred to as *the normal plane*.

I_0 is the irradiance intensity on the normal plane and the irradiance intensity on the horizontal plane can be calculated from:

$$I_{0h} = \cos\theta_Z \quad (2.2)$$

Where θ_Z is the solar zenith angle described in section 1.2 and I_{0h} is the extraterrestrial irradiance intensity on a horizontal plane. It can be seen from figure 2.2 that θ_Z is also the angle of incidence of the Sun's rays on a horizontal plane. Note that since cosine values fall between 1 and –1, I_{0h} will never be greater than I_0, and $I_{0h} = I_0$ at point P' where $\cos\theta_Z = 1$ ($\theta_Z = 0°$).

2.3. Irradiation

Just to be confusing the intensity of solar radiation is called *irradiance* and is measures in the units of power per unit area (W/m^2 or kW/m^2) however, the total amount of solar radiation energy is called *irradiation* and is measures in the units of energy per unit area (J/m^2). Irradiation is given the symbol H, so that:

- H_0 is the total daily amount of extraterrestrial radiation on a plane perpendicular to the Sun's rays;
- H_{0h} is the total daily amount of extraterrestrial radiation on a plane horizontal to the Earth's surface.

Note that these planes are considered to rotate with the Earth so that H_0 and H_{0h} are daily values, and the planes are shaded at night.

Figures 2.3 and 2.4 shows how the values of H_0 and H_{0h} varies throughout the year in the northern hemisphere. Note that for any given day the value of H_0 changes from latitude to latitude despite the value of I_0 being constant for all latitudes. This occurs because the length of the days changes and the effects is most obvious inside the Arctic circle where much of the year is either 24 hours of darkness or 24hours of daylight.

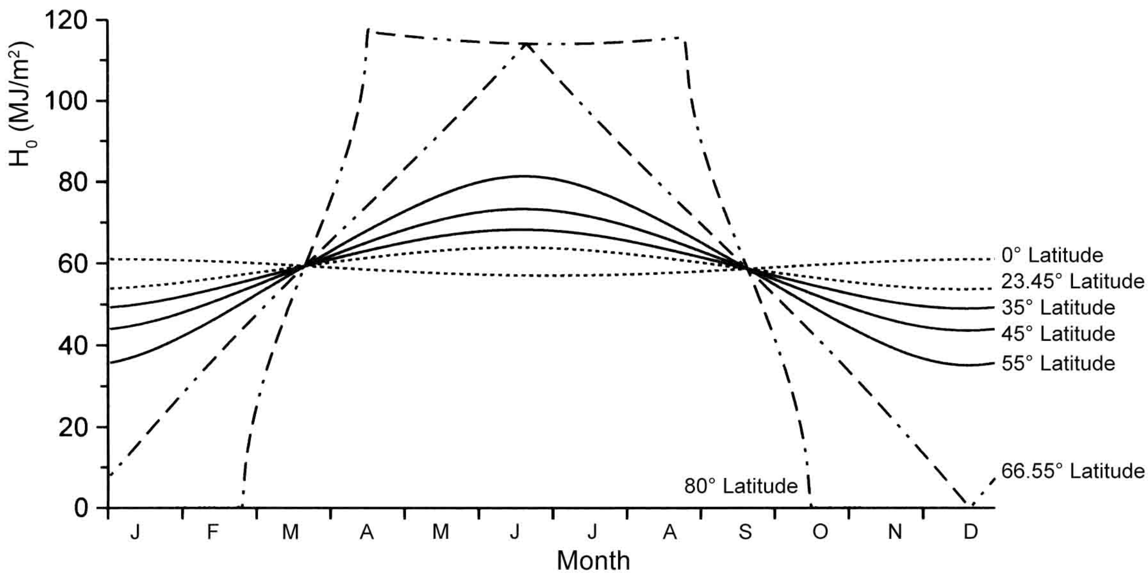


Figure 2.3: The total daily amount of extraterrestrial irradiation on a plane perpendicular to the Sun's rays (H_0) for different latitudes.

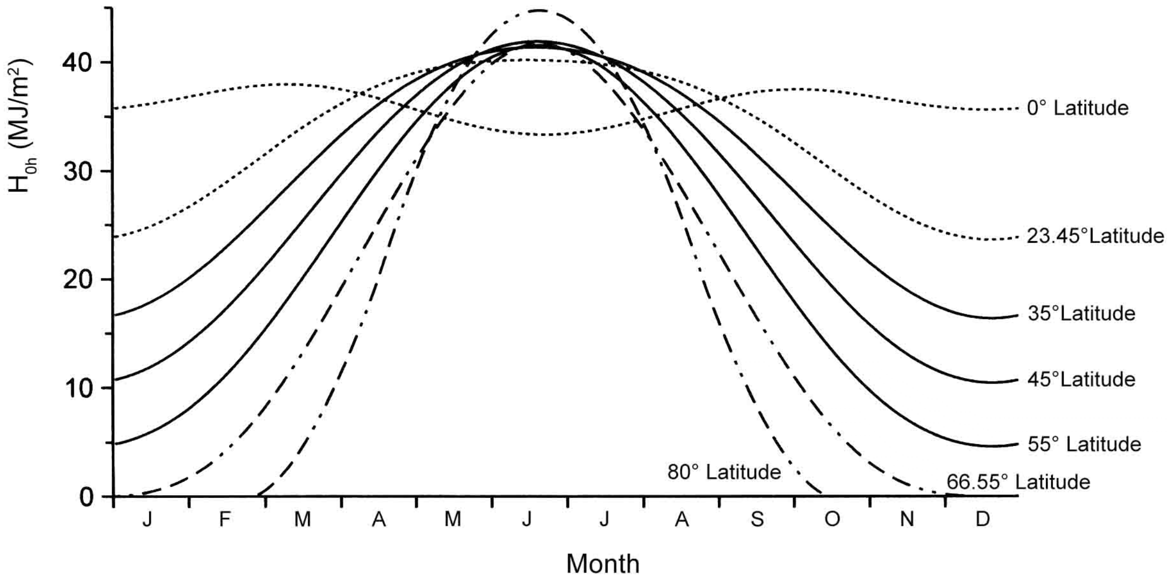


Figure 2.4: The total daily amount of extraterrestrial irradiation on a plane horizontal to the Earth's surface(H_{0h}) for different latitudes.

2.4. The Solar Spectrum

The Sun's radiation is a good approximation of *black body radiation* (a continuous distribution of wavelengths with no wavelengths missing) with wavelengths in the range of about 0.2 µm to 2.6 µm (figure 2.5). The solar spectrum consists of ultra violate rays in the range of 200 to 400 nm, visible light in the range 390 nm (violet) to 740 nm (red) and the infra red in the range 700 nm to 1mm. Table 2.1 shows the subdivisions of the ultra violate range and table 2.2 shows the distribution of extraterrestrial solar radiation.

UV-A	320-400 nm	Not harmful in normal doses, vitamin D production.
UV-B	290-320 nm	Tanning, can burn.
UV-C	230-290 nm	Causes skin cancer.

Table 2.1: Ultra violate radiation.

Ultra Violet	200-400 nm	8.7%
Visible	400-700 nm	38.3%
Near Infra Red	700-3500nm	51.7%

Table 2.2: The distribution of extraterrestrial solar radiation.

As the Sun's rays pass through the atmosphere certain wavelengths are absorbed and a proportion of the total energy is scattered. Thus the solar spectrum at the Earth's surface has some wavelengths missing (shown blacked out in figure 2.5) and the overall intensity is reduced.

2.5. The Atmosphere And Air Mass

The atmosphere scatters and absorbs some of the Sun's energy that is incident on the Earth's surface. Scattering of radiation by gaseous molecules (e.g. O_2, O_3, H_2O and CO_2), that are a lot smaller than the wavelengths of the radiation, is called *Rayleigh scattering*. Roughly half of the radiation that is scattered is lost to outer space, the remaining half is directed towards the Earth's surface from all directions as *diffuse radiation*. Because of absorption by oxygen and ozone molecules the shortest wavelength that reaches the Earth's surface is approximately 0.29 µm. Other gas molecules absorbed difference wavelengths as indicated in figure 2.5.

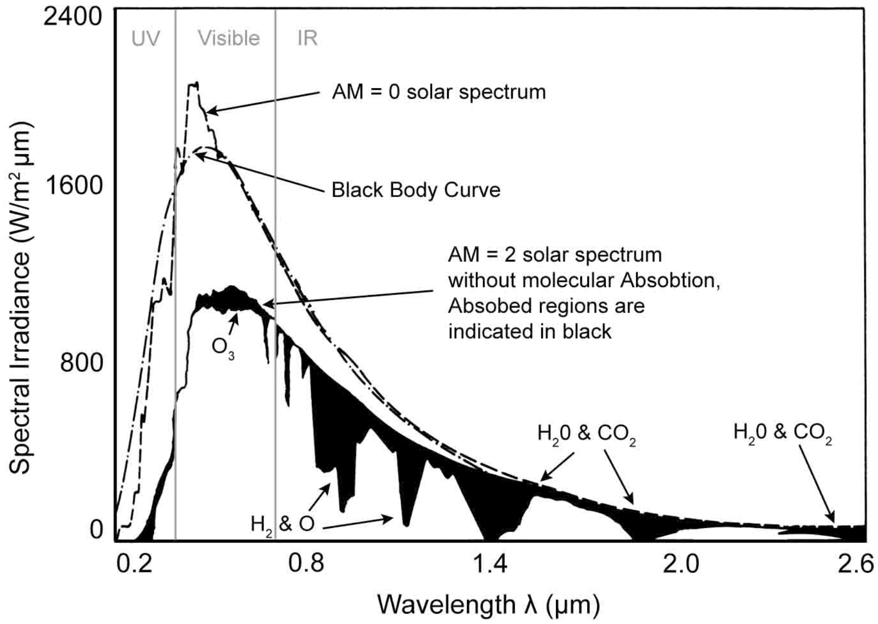


Figure 2.5: The extraterrestrial solar spectrum (AM = 0), the theoretical black body curve and the solar spectrum at the Earth's surface for AM = 2 and the absorbed regions shown in black.

Scattering by dust particles larger than wavelengths of light is called *Mie scattering*. This process includes both true scattering (where the radiation bounces of the particle) and absorption followed by emission, which heats the particles. The amount of radiation scattered by this process will vary a lot depending on location and the weather blowing particles about. A form of Mie scattering called the *Tyndall effect*, that preferentially scatters shorter wavelengths is responsible for the sky being blue.

Clouds reflect a lot of radiation and also absorbed a little, the rest is transmitted through. Globally, clouds reflect a lot of radiation and help regulate the surface temperature.

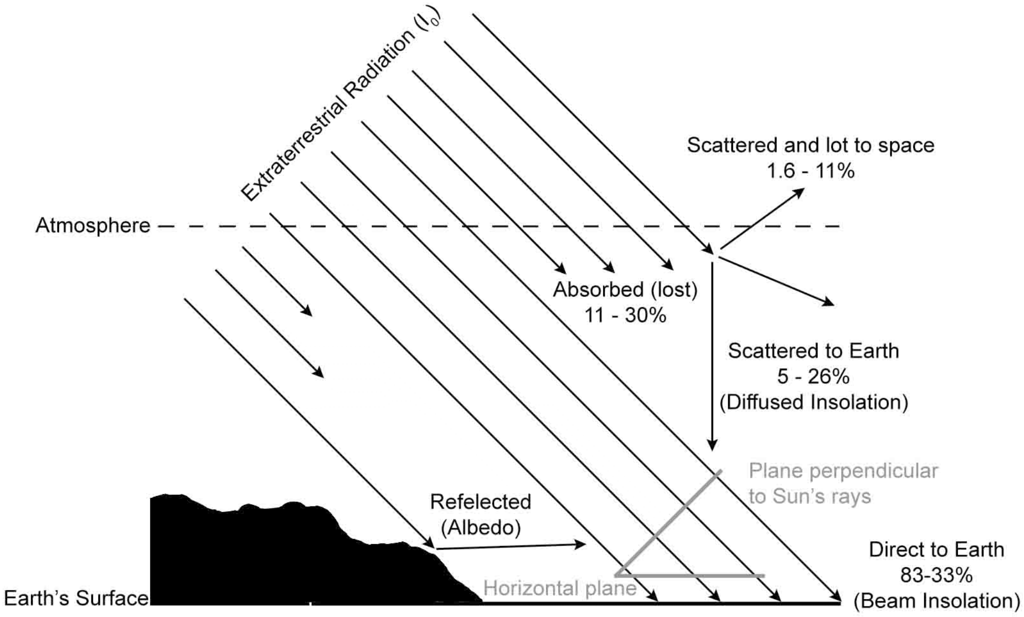


Figure 2.6: The effect of the atmosphere on the solar radiation reaching the Earth's Surface.

The fraction of the total solar radiant energy reflected back to space from clouds, scattering and reflection from the Earth's surface is called the albedo of the Earth-atmosphere system and is roughly 0.3 for the Earth as a whole. Figure 2.6 shows that a plane on the Earth's surface receives:

- *Beam (or direct) radiation* – coming straight through the atmosphere to hit the plane (very directional);
- *Diffused radiation* – scattered in all direction in the atmosphere and then some arrives at the plane on the Earth's surface (not directional);
- *Reflected radiation* – beam and diffused radiation that hits the Earth's surface and is reflected onto the plane.

The amount of energy reflected, scattered and absorbed depends on the amount of atmosphere that the incident radiation travels through as well as the levels of dust particles and water vapour present in the atmosphere. The latter is difficult to judge but the distance travelled through the atmosphere by incident radiation depends on the angle of the Sun (figure 2.7).

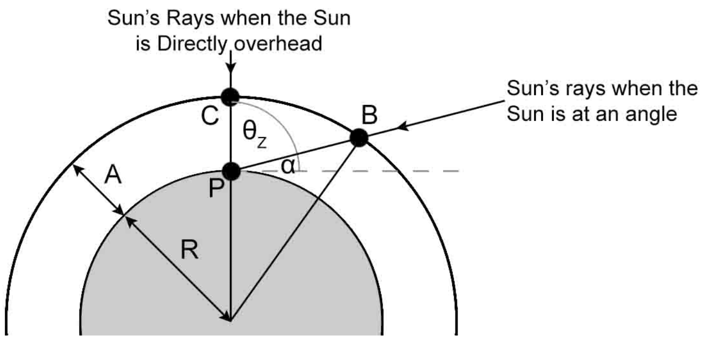


Figure 2.7: The distance travelled through the atmosphere by the Sun's rays.

The distance travelled through the atmosphere by the Sun's rays incident on the Earth is accounted for by a quantity called *air mass* (AM).

$$\text{air mass} = \frac{\text{path length travelled}}{\text{verticle depth of the atmosphere}}$$

$$\text{AM} = \frac{\text{BP}}{\text{CP}} = \left[\left(\frac{R}{H}\cos\theta_Z\right)^2 + 2\frac{R}{H} + 1\right]^{1/2} - \left(\frac{R}{H}\right)\cos\theta_Z \qquad (2.3)$$

Where:
R = the radius of the Earth, taken to be 6370 km;
H = thickness of atmosphere, taken to be 7991 km (although it is considerably thicker at the equator than the poles).

For angles of $\theta_Z < 70°$:

$$\text{AM} \approx \frac{1}{\cos\theta_Z} = \sec\theta_Z \qquad (2.4)$$

Therefore outside the Earth's atmosphere AM = 0, when the Sun is directly overhead $\theta_Z = 0$, AM = 1 and when the $\theta_Z = 60°$ AM = 2. AM is normally taken to be an average of 1.5 for a clear sunny day and this value is used for the calibration of solar cells.

2.6. Rough Estimates Of The Solar Energy Available At The Earth's Surface

The solar constant is the average extraterrestrial insolation at the edge of the atmosphere:

$$I_{SC} = 1367 \text{ W/m}^2$$

The Earth presents a disc of area πR^2 to the Sun, therefore the total amount of extraterrestrial insolation incident on the Earth is $I_{SC} \times \pi R^2$. This value is then divided by half the surface areas of the Earth, $4\pi R^2/2$, which gives 684 W/m^2, the average insolation incident on unit area of the Earth facing the Sun (figure 2.8). Note that solar panels are calibrated assuming that there is 1000 W/m^2 available.

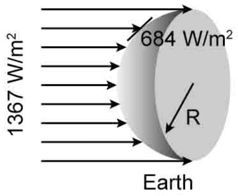


Figure 2.8

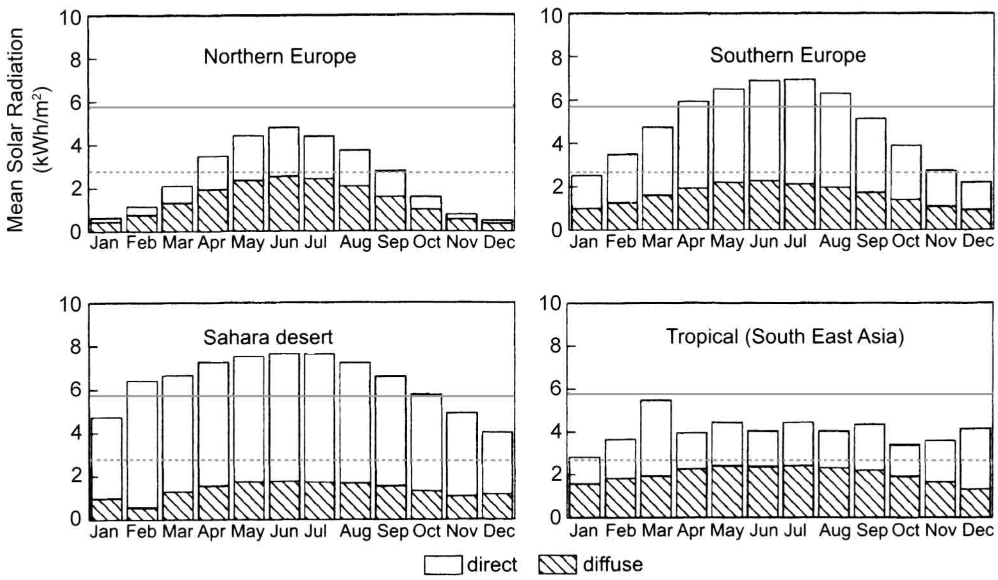
A rough estimate of the irradiation incident per unit area (H) of the Earth's surface can be made if we assume that 30% of the Sun's energy is lost in the atmosphere and that the a day is an average of 12 hours long at any location.

$$H = 0.7 \times 684 \times 12 = 5.75 \text{kWh / day}$$

Or if we assume that the Sun is only at an appreciable strength for an average 6 hours in the day (as is likely in more northerly latitudes):

$$H = 0.7 \times 684 \times 6 = 2.88 \text{kWh / day}$$

Figure 2.9 shows the yearly profile of mean solar radiation for different locations around the world. The solid grey line show the value of 5.75 kWh/day and the dashed grey line shows 2.88 kWh/day.



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