Chapter 2.

SOLAR RADIATION

2.1 Solar radiation

One of the basic processes behind the photovoltaic effect, on which the operation of solar cells is based, is generation of the electron-hole pairs due to absorption of visible or other electromagnetic radiation by a semiconductor material. Today we accept that electromagnetic radiation can be described in terms of waves, which are characterized by wavelength (λ) and frequency (ν), or in terms of discrete particles, ***photons***, which are characterized by energy ($h\nu$) expressed in electron volts. The following formulas show the relations between these quantities:

$$\nu = c/\lambda \tag{2.1}$$

$$h\nu = \frac{1}{q}\frac{hc}{\lambda} \tag{2.2}$$

In Eqs. 2.1 and 2.2 c is the speed of light in vacuum (2.998×10^{8} m/s), h is Planck's constant (6.625×10^{-34} Js), and q is the elementary charge (1.602×10^{-19} C). For example, a green light can be characterized by having a wavelength of 0.55×10^{-6} m, frequency of 5.45×10^{14} s^{-1} and energy of 2.25 eV.

Only photons of appropriate energy can be absorbed and generate the electron-hole pairs in the semiconductor material. Therefore, it is important to know the spectral distribution of the solar radiation, i.e. the number of photons of a particular energy as a function of wavelength. Two quantities are used to describe the solar radiation spectrum, namely the ***spectral power density***, $P(\lambda)$, and the ***photon flux density***, $\Phi(\lambda)$. The spectral power density is the incident power of solar radiation per unit area and per unit wavelength [W m^{-2} m^{-1}]. The total power from a radiant source falling on a unit area is also called ***irradiance***. The photon flux density is the number of photons per unit area, per unit time, and per unit wavelength [ph m^{-2} s^{-1} m^{-1}]. The photon flux density is related to the spectral power density by:

$$\Phi(\lambda) = P(\lambda)\frac{\lambda}{hc} \tag{2.3}$$

Each second, the sun releases an enormous amount of radiant energy into the solar system. The temperature at the centre of the sun is high enough to facilitate nuclear reactions, which are assumed to be the source of the sun's energy. The temperature at the centre is of the order of 10^6 degrees but the temperature of the surface layer of the sun, so called ***photosphere***, is about 6000K. The extraterrestrial spectrum of sun's radiant energy can be approximated by that of a black-body radiator at this temperature. The total power density of the solar radiation at the mean earth-sun distance on a plane perpendicular to the direction of the sun, outside the earth's atmosphere, is referred to as the ***solar constant***. Its value is 1353 W/m^2.

The solar radiation is attenuated, when it passes through the earth's atmosphere. Since the spectral distribution of the solar radiation also depends on the attenuation, various solar spectra can be measured at the earth's surface. The degree of attenuation is variable. The most important parameter that determines the solar irradiance under clear sky conditions is the distance that the sunlight has to travel through the atmosphere. This distance is the shortest when the sun is at the zenith, i.e. directly overhead. The ratio of an actual path length of the sunlight to this minimal distance is known as the ***optical air mass***. When the sun is at its zenith the optical air mass is unity and the radiation is described as ***air mass one*** (AM1) radiation. When the sun is at an angle θ to the zenith, the air mass is given by

$$Air\ mass = (\cos\theta)^{-1} \tag{2.4}$$

For example, when the sun is 60 degrees from the zenith, the radiation is described as AM2. The solar radiation spectrum is also a function of air mass. The spectral power density of some commonly used air mass radiation spectra are presented in Figure 2.1. AM0 radiation is the extraterrestrial spectrum of solar radiation outside the earth's atmosphere, which power density is the solar constant. Opposed to the situation outside the earth's atmosphere, terrestrial solar radiation varies both in intensity and spectral distribution depending on the position on the earth and the position of the sun in the sky. In order to allow comparison between the performances of solar cells tested at different locations, a terrestrial solar radiation standard has to be defined and measurements referred to this standard. ***AM1.5 radiation*** serves at present as the standard spectral distribution. It corresponds to an angle of 48.2 degrees between the sun's position and the zenith. The irradiance of the AM1.5 radiation

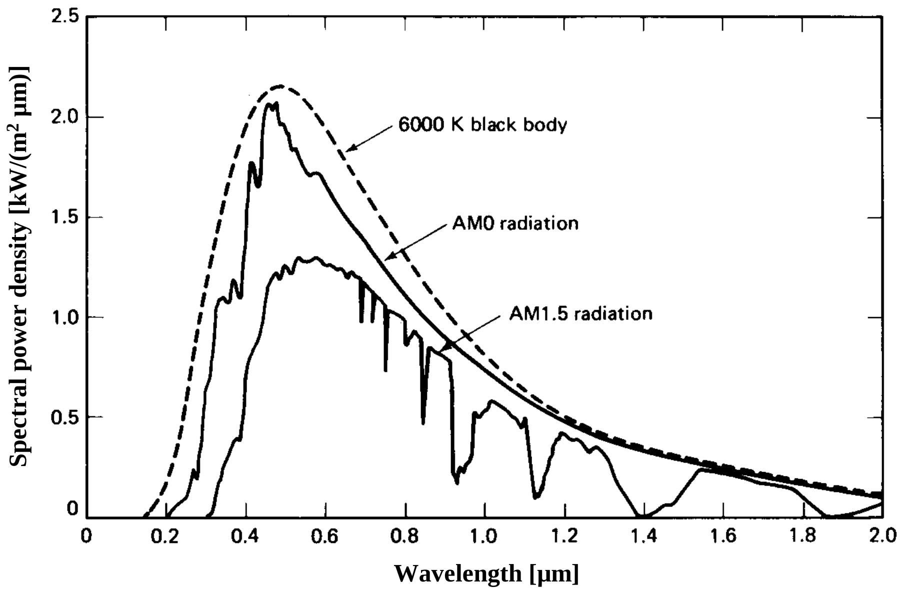

Figure 2.1. Spectral power density of sunlight. The different spectra refer to the black-body radiation at 6000K, the extraterrestrial AM0 radiation and the AM1.5 radiation.

is 827 W/m^2. The value of 1000 W/m^2 was incorporated to become a standard. This value of the irradiance is close to the maximum received at the earth's surface. The peak power of a photovoltaic system is the power generated under this standard AM1.5 (1000 W/m^2) radiation and is expressed in peak watts.

The attenuation of solar radiation is due to scattering and absorption by air molecules, dust particles and/or aerosols in the atmosphere. Especially, steam, oxygen and carbon dioxide (CO_2) cause absorption, which is wavelength-selective and therefore results in gaps in the spectral distribution of solar radiation as apparent in Figure 2.1. Ozone absorbs radiation with wavelengths below 0.3 μm. Depletion of ozone from the atmosphere allows more ultra-violet radiation to reach the earth, with consequent harmful effects upon biological systems. CO_2 molecules contribute to the absorption of solar radiation at wavelengths above 1 μm. By changing the CO_2 content in the atmosphere the absorption of the infrared solar spectrum is influenced, which has consequences for the earth's climate.

The actual amount of solar radiation that reaches a particular place on the earth is extremely variable. In addition to the regular daily and yearly variation due to the apparent motion of the sun, irregular variations are caused by local atmospheric conditions, such as clouds. These conditions particularly influence the direct and diffuse components of solar radiation. The ***direct*** component of solar radiation is that part of the sunlight that directly reaches the earth's surface. Scattering of the sunlight in the atmosphere generates the ***diffuse*** component. A part of the solar radiation that is reflected by the earth's surface, which is called ***albedo***, may be also present in the total solar radiation. We use a term ***global*** radiation to refer to the total solar radiation, which is made up of these three components.

The design an optimal photovoltaic system for a particular location depends on the availability of the solar insolation data at the location. Solar irradiance integrated over a period of time is called ***solar irradiation***. For example, the average annual solar irradiation in The Netherlands is 1000 kWh/ m^2, while in Sahara the average value is 2200 kWh/ m^2.

2.2 The sun

Many people on the Earth are fascinated by the existence of the sun. There are several examples in human history that the sun became an object of worship and people believed that it possessed divine powers. No wonder, the sun is the source of all life on the Earth. The sun is an intensely hot, self-luminous body of gases (mainly hydrogen and helium) at the centre of the solar system. Figure 2.2 shows a photograph of the sun. The sun is a medium-size main-sequence star. Here are some basic technical facts about the sun[1].

Mean distance from the earth:	149 600 000 km (the astronomic unit)
Diameter:	1 392 000 km (109 × that of the earth)
Volume:	1,300,000 times that of the earth
Mass:	1,993 × 10^{27} kg (332 000 times that of the earth)
Density (at its center):	>100 × 10^3 kg m^{-3} (over 100 times that of water)
Pressure (at its center):	over 1 billion atmospheres
Temperature (at its center):	about 15 000 000 degrees Kelvin
Temperature (at the surface):	6 000 degrees Kelvin
Energy radiation:	380 × 10^{21} kW
The Earth receives:	170 × 10^{12} kW

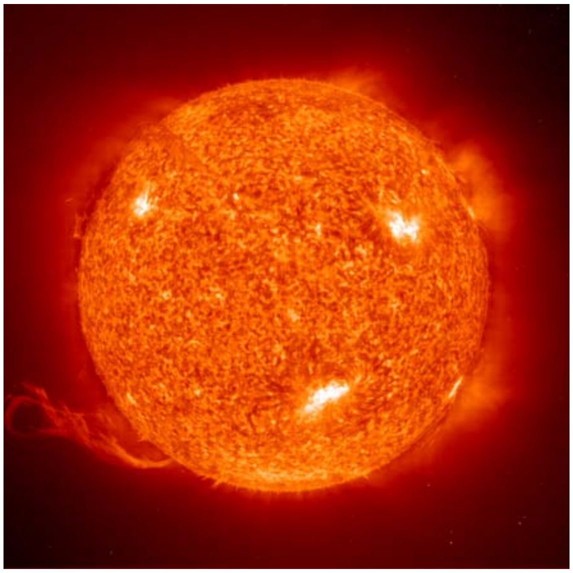

Figure 2.2. A fascinating photograph of the sun.

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