Photovoltaic Power Systems (611422)

أنظمة الطاقة الكهروضوئية

Chapter 2 - Solar Radiation

The Sun

As the sun is the only real energy source we have, we need to move to an era in which we start to utilize the energy provided by the sun directly and indirectly to satisfy our energy needs. **The solar energy can be converted into electricity, heat and chemical energy**.

The sun is the energy source for almost all the processes that happen on the surface of our planet.

Wind is a result of temperature difference in the atmosphere induced by solar irradiation**.**

Waves are generated by the wind, **Clouds** and **Rain** are initially formed by the evaporation of water due to sun light. It consists mainly of **hydrogen and helium**. Its structure is sketched in Fig. 2. The mass of the Sun is so large that it contributes to 99.68% of the total mass of the solar system. In the center of the Sun the pressure-temperature conditions are such that nuclear fusion can take place.

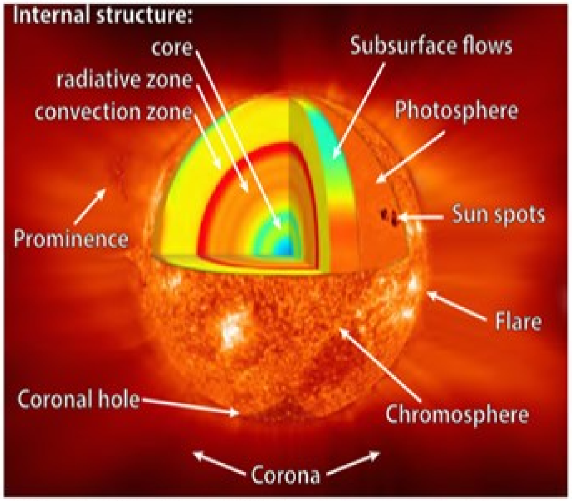


Figure 2: The Sun with its layer structure depicted

Some basic facts of the sun are summarized below.

- **Mean distance from the Earth: 149600000km (the astronomic unit, AU).**
- **Diameter: 1392000 km (10^9 × that of the Earth).**
- **Volume: 1300000×that of the Earth.**
- **Mass: 1.993×10^{27}kg(332000 times that of the Earth).**
- **Density (at its center): $>10^5$ kg m−3 (over 100 times that of water).**
- **Pressure (at its center): over 1 billion atmospheres.**
- **Temperature (at its center): about 15,000,000K .**
- **Temperature (at the surface): 6000K.**
- **Energy radiation: 3.8×10^{23} kW.**
- **The Earth receives: 1.7×10^{14} kW.**

SOLAR POWER

The Sun is a big ball of plasma composed primarily of **hydrogen (92%), helium (8%),** and small amounts of other atoms or elements. **A plasma** is where the electrons are separated from the nuclei because the temperature is so high (kinetic energy of nuclei and electrons is large). The Sun is a stable main sequence star with an estimated age of $4.5 * 10^9$ years and will continue for another 4 to $5 * 10^9$ years before starting the next phase of evolution, the burning of helium. At that point, the Sun will expand and be larger than the orbit of the Earth.

By the process of fusion, protons are converted into helium nuclei plus energy as given in figure 3. In the major nuclear reaction, the proton-proton reaction, via a number of steps four protons react into:

- A helium core (two protons and two neutrons).
- 2 positrons (the anti-particles of electrons).
- 2 neutrinos.
- electromagnetic radiation.

The positrons annihilate with electrons leading to additional radiation.

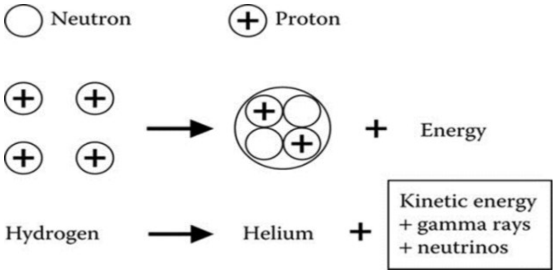


Figure 2: nuclear fusion process.

Protons are converted into helium nuclei, and because the mass of the helium nucleus is less than the mass of the four protons, that difference in mass (for the Sun around 5 * 10^9 kg/s) is converted into energy.

The energy difference is converted into energy according to Einstein's equation:

$$\mathbf{E = m * c^2}$$

That energy is transferred to the surface of the Sun**, The mass of the helium core is 0.635% less than that of four protons; Every second thus, approximately 4 million tons of mass are converted into energy.**

Example: When nucleons come together, the mass of the product is less than the sum of the masses of individual nucleons. (Proton mass = 1.6 7×10^{-27} kg; The actual mass of a helium nucleus is actually 6.64477 x 10 $^{-27}$ Kg). The mass of the helium core is 0.6% less than that of four protons separated; Calculate the energy released from 0.001 μgram of four protons in one day in kWh.

Solution:

$$\mathbf{E = m*c^2} = 0.6 * 10^2 * 1 * 10^{-12} \text{ kg} * (3 * 10^8)^2 = 5.4 * 10^2 \text{ Joules (W. sec).}$$

$$\text{E for one day} = 5.4 * 10^2 * 10^{-3} * 60*60*24 = 4.7 * 10^4 \text{ kWh}$$

The neutrinos hardly interact with matter and thus can leave the solar core without any hinder. Every second, about 6.5 x 1010 per cm^2 pass through the Earth and hence also through our bodies. Neutrinos carry about 2% of the total energy radiated by the Sun. The remainder of the radiation is released as electromagnetic radiation. This tremendous amount of energy is radiated into space in all directions from the surface of the Sun with a power of 3.8 * 10^{23} kW.

The Earth only intercepts a small portion of the Sun's power; however, that is still a large amount. At the top of the atmosphere, the power intercepted by the Earth is 1.73 * 10^{14} kW, equivalent to 1.35 kW/m^2. Remember that this surface is perpendicular (90°) to the Sun. If a surface is at an angle to the Sun, the same amount of energy is spread over a larger area. At the surface of the Earth on a clear day, this solar insolation is around 1.0 to 1.2 kW/m^2 on a surface perpendicular to the Sun from 9 in the morning to 3 in the afternoon, depending on the amount of haze in the atmosphere and on elevation.

Electromagnetic (EM) spectrum

There are two ways of describing nature: **particles and waves. Particles** have mass, are localized in space, and can have charge and other properties, and no two particles can occupy the same space. **Waves** have no mass and are spread out over space; waves obey the principle of superposition, which means that two or more waves can occupy the same space at the same time. Many waves need a **medium to move, for example, water and sound**. however, there is no medium needed for EM waves.

EM waves (Figure 3) travel at the speed of light and are described by their wavelength and frequency, which are related by: $\mathbf{c = \lambda * f}$: where: c is the speed of light in a vacuum, $3 * 10^8$ m/s, λ is the wavelength in m, f is the frequency in hertz, which is the number of cycle/sec.

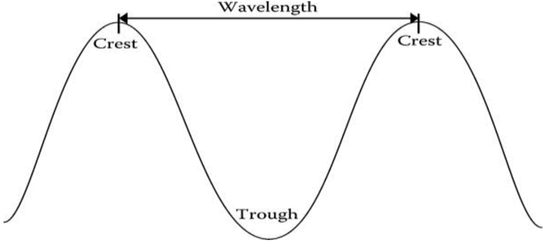


Figure 3: Electromagnetic waves

The EM spectrum (Figure 4 below) is the range of EM radiation from very short wavelengths (high frequency) to very long wavelengths (low frequency). The range of the spectrum that we can see, visible (sometimes referred to as light), is small, with red light ($7 * 10^{-7}$ m) having a longer wavelength than blue light ($4 * 10^{-7}$ m).

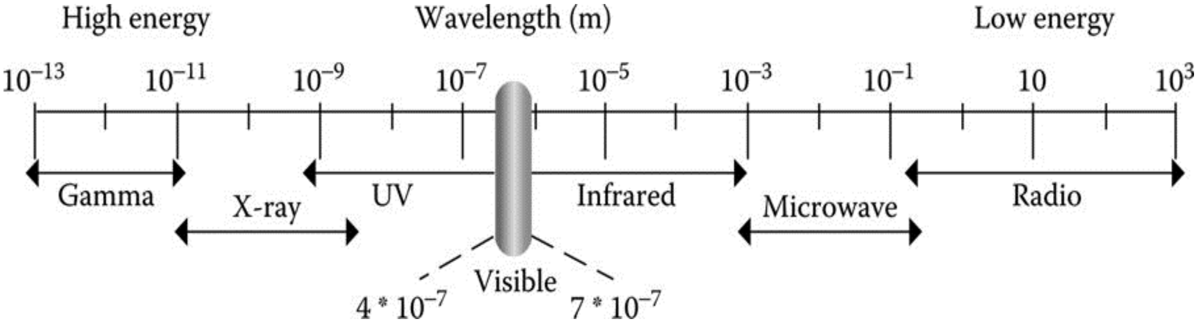


Figure 4: The Electromagnetic spectrum.

At the atomic level, the two ways of describing nature are combined, so EM waves come in units called photons; their energy (E) is given by:

$\mathbf{E = h * f}$ **,** where: h is Planck's constant, $6.6 * 10^{-34}$ kg m^2/s.

$\mathbf{E = h * f = h * c / \lambda}$ has the unit of an energy. Where c is the speed of light ($3x10^8$ m/sec) and f is the frequency of the photons. Light comes in quanta of energy with the size $\mathbf{E_{ph} = h\, f}$

Wave-particle duality

Nowadays, these quanta are called photons. In terms of classical mechanics we could say that light shows the behavior of particles. On the other hand, we have seen that light also shows wave character which becomes obvious when looking at the propagation of light through space or at reflection and refraction at a flat interface It also was discovered that other particles, such as electrons, show wave-like properties. This behavior is called wave-particle duality.

DE Broglie postulated that all matters large or small behaved like wave. The wavelength (λ) of this wave is related to its mass (m) and velocity (v) by:

$\lambda = h/p = h/mv$, where P is the momentum and h is blank constant ($4.12x10^{-12}$ eV . sec or $6.63x10^{-34}$ J. sec).
The relation is valid for all situation and objects including electrons. For the photons the relation becomes:

$\lambda = c/\upsilon$, Where c is the speed of light ($3x10^{8}$ m/sec) and **υ** is the frequency of the photons

Example

Calculate the DE Broglie wave length of: (1) A Tennis ball of mass 0.4 Kg travelling at 0.02m/sec. (2) A dust particle of mass $1x10^{-5}$ Kg travelling at 1m/sec. (3)An electron of mass $9.109x10^{-31}$Kg travelling at $5x10^{5}$m/sec. (4) A photon of frequency $2.5x\ 10^{15}$ Hz.

Solution: (1) For a Tennis ball $\lambda = 6.6x10^{-34}/0.4x0.02 = 8.3x10^{-32}$ m.
(2) For dust particle $\lambda = 6.6x10^{-34}/1x10^{-5}x1 = 6.62x10^{-29}$ m.
(3) For the electron $\lambda = 6.6x10^{-34}/9.1x10^{-31}x5x10^{5} = 1.4x10^{-9}$ m (X-ray).
(4) For the photon $\lambda = C/\upsilon = 3x10^{8}/2.5x10^{15} = 1.2x10^{-7}$m $= 0.12\mu$m (Ultraviolet).

The wavelength of the most common objects will be so small that it is impossible for us to measure this wave like motion. However DE Broglie wave length of electron is almost the same magnitude as wavelength of X-ray, while it is in ultraviolet region for photon.

Blackbody Radiation

A perfect absorber or emitter of EM radiation is a blackbody. The amount of radiation emitted per wavelength (or frequency) depends only on the temperature of the body and not on the type of material or atoms of the body.

So, a blackbody curve can be generated for a specific temperature, with the peak of the curve shifting to shorter wavelengths (larger frequency) for higher temperatures. **A blue flame is hotter than an orange flame.** A higher temperature object emits more radiation at all wavelengths, so the curves are a similar shape, nested within one another (Figure 6). Figure 5 represent Blackbody curve for the Sun (T=5800 K) and a lower-temperature object (T = 3000 K). Notice that the peak of the curve for the Sun is in the visible range, **and it is interesting that our eyes are most sensitive to yellow–green light**. The peak of the curve for the lower-temperature object is in the infrared spectrum.

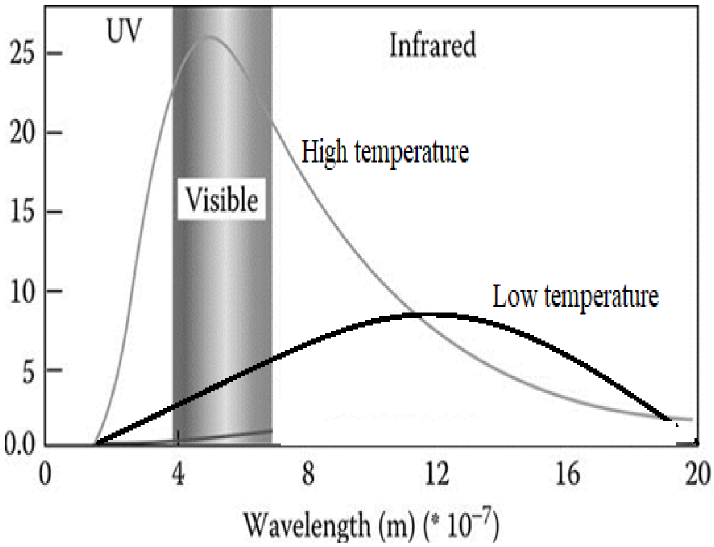


Figure 5 (a) represent Blackbody curve for the Sun (T=5800 K) and a lower-temperature object (T = 3000 K),

The amount of EM radiation from the Sun is primarily in the visible range, and this is absorbed and then converted primarily to thermal energy as shown schematically in figure 7, which has a lower temperature, around 290 K, that radiates at longer wavelengths (peak at $1 * 10^{-5}$ m).

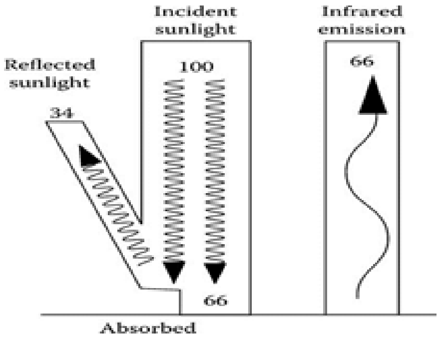


Figure 6: The incident, absorbed, reflected and emitted electromagnetic waves from the surface of the earth.

some is absorbed and **stored in plants through the process of photosynthesis.** Some of the **infrared radiation is emitted to space** (clear skies), **Clear nights are cooler than cloudy nights** because of night time radiation into space, which has a temperature of 3 °K and the rest is absorbed in the atmosphere (Figure below). Of the infrared radiation absorbed in the atmosphere, some is **then reradiated into space, and the rest is reradiated back to Earth**. This absorbed energy drives our weather in terms of evaporation and transportation of heat from the equator the poles. and provides the energy for wind and waves and currents in the ocean. Figure 7 shows transmission and absorption of electromagnetic radiation (kilowatts) and other sources of energy.

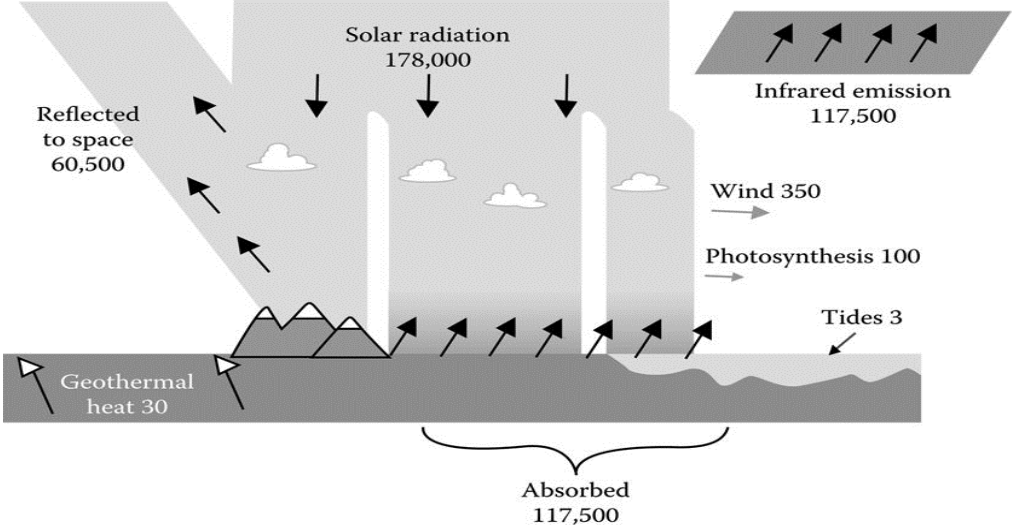


Figure 7: shows transmission and absorption of electromagnetic radiation (kilowatts) and other sources of energy.

The atmosphere is transparent to visible and radio wavelengths but absorbs radiation in other wavelengths (Figure 8). Ozone in the upper atmosphere absorbs ultraviolet radiation.

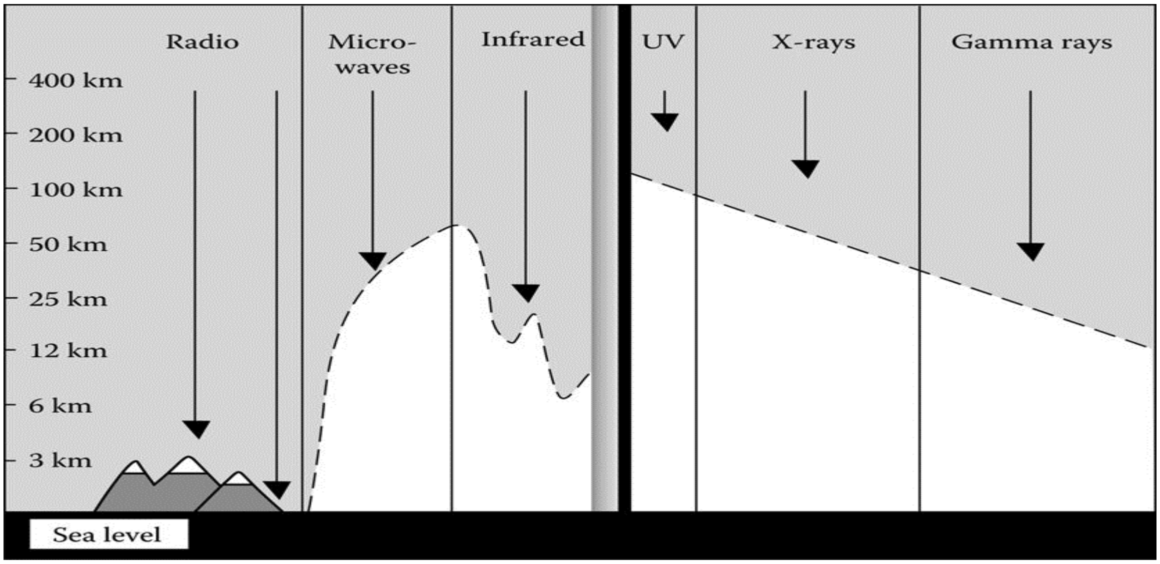


Figure 8: Visible and radio waves reach the surface, while other radiation is absorbed in the atmosphere.

Radiometric properties

Radiometry is the branch of optics concerned with the measurement of light. Since photovoltaics deals with sunlight that is converted into electricity it is very important to discuss how the "amount of energy" of the light can be expressed physically and mathematically. **In solar science, not the total amount of the energy is important, but the amount of energy per unit time (which is known the power- P) is the most important quantity to be known.**

The power that is given by: $\mathbf{P = dE / dt}$

Solar spectra

It is known that only photons of appropriate energy can be absorbed and hence generate electron-hole pairs in a 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 the wavelength λ. **Two quantities are used to describe the solar radiation spectrum, namely the spectral irradiance (L_e (λ), and the spectral photon flux $\Phi_{ph}(\lambda)$.**

For our discussion we assume a surface A that is irradiated by light, (Fig. 9 (a)). For obtaining **the total power that is incident on the surface, we have to integrate over the whole surface.** Further we have to take into account that light is incident from all the different directions, which we parameterize with the spherical coordinates (Θ,ψ). **The polar angle Θ is defined with respect to the normal of the surface element dA and ψ is the azimuth,** as sketched in Fig. 9 (b).

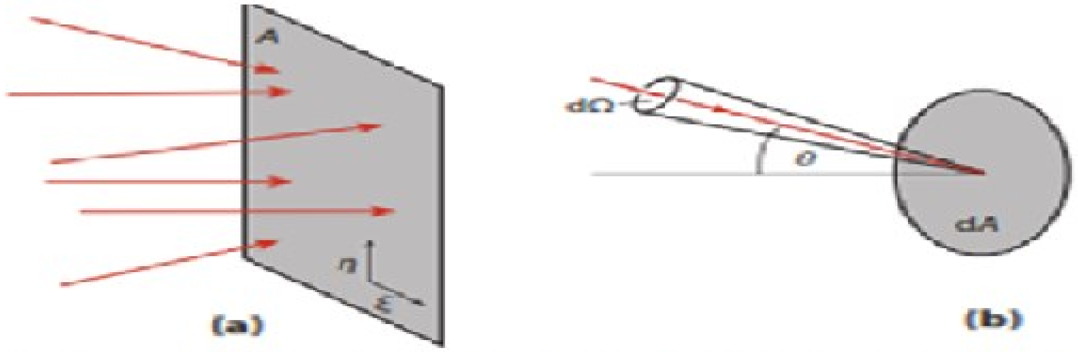


Figure 9 : (a) Illustrating a surface A irradiated by light from various directions and (b) a surface element dA that receives radiation from a solid angle element $d\Omega$ under an angle θ with respect to the surface normal.

Thus, we have to integrate over the hemisphere; from that light can be incident on the surface element dA, as well. We therefore obtain the power P:

$$P = \int_A \int_{2\pi} L_e \cos\theta \, d\Omega \, dA$$

The quantity **L_e is called the radiance** and it is one of the most fundamental radiative properties. Its physical dimension is: **$L_e = W * m^{-2} * sr^{-1}$**

Another very important radiometric property **is the irradiance I_e** that tells us the power density at a certain point (x, h) of the surface. It often also is called the spectral intensity of the light. It is given as the integral of the radiance over the solid angle dΩ:

$$I_e = \int_{2\pi} L_e \cos\theta \, d\Omega$$

Since sunlight consists of a spectrum of different frequencies (or wavelengths), it is useful to use spectral properties. These are given by:

$$P_\nu = \frac{dP}{d\nu}, \qquad P_\lambda = \frac{dP}{d\lambda},$$

$$L_{e\nu} = \frac{dL_e}{d\nu}, \qquad L_{e\lambda} = \frac{dL_e}{d\lambda},$$

As we discussed earlier, the energy of a photon is proportional to its frequency,

$E = h\upsilon = hc/\lambda$.

Thus, the spectral power $P_{\lambda ph}$ is proportional to the spectral photon flow $\varphi_{ph\lambda}$ as follows: $P_\lambda = \varphi_{ph\lambda} (hC/\lambda)$.

Blackbody solar spectrum

If we take a piece of e. g. metal and start heating it up, **it will start to glow, first in reddish color getting more and more yellowish** if we increase temperature even further. **The sun emits electromagnetic radiation that we call thermal radiation** . This what is called Blackbody solar spectrum or solar radiation. The blackbody solar spectrum is illustrated in Fig. 10. **AM1.5** spectrum is included in the Figure. The irradiance at **AM1.5 is I_e (AM1.5) = 1361 $W \cdot m^{-2}$**.

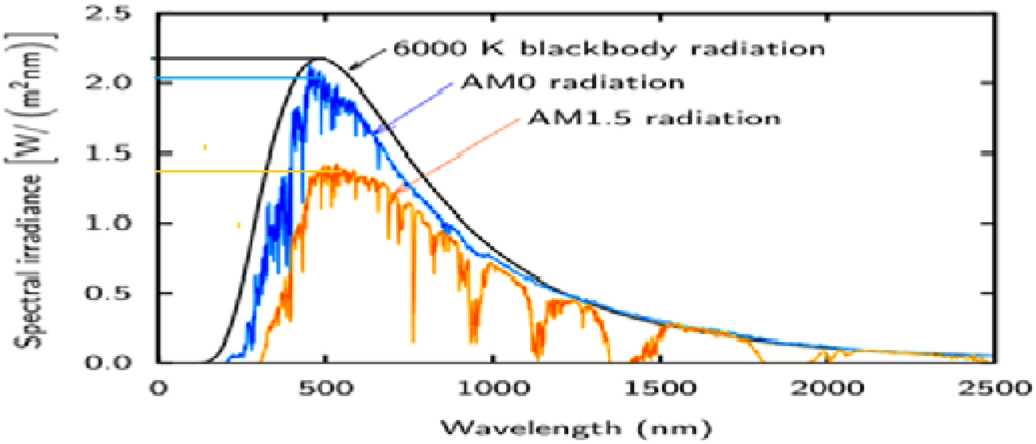


Figure 10 : Different solar spectra: the blackbody spectrum of a blackbody at 6000 K, the extraterrestrial AM0 spectrum and the AM1.5 spectrum.

The spectrum outside the atmosphere of the Earth is already very different. When solar radiation passes through the atmosphere of the Earth, it is attenuated. **The ratio of an actual path length of the sunlight to this minimal distance is known as the optical air mass (AM).** Outside the atmosphere of the earth, It is called the **AM0 (air mass zero)** spectrum, because no (or "zero") atmosphere is traversed. **Depending on the position on the Earth and the position of the Sun in the sky, terrestrial solar radiation varies both in intensity and the spectral distribution.**

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.** When the Sun is at its zenith the optical air mass is unity and the spectrum is called the **air mass 1 (AM1) spectrum**.

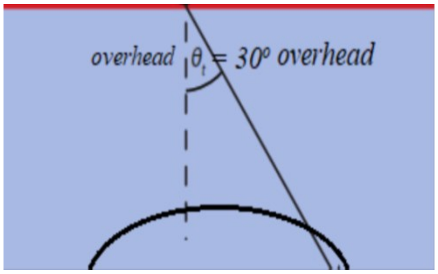
When the Sun is at an angle θ with the zenith, the air mass is given by: **AM =1/ cosθ.**

For example, when the Sun is 60° from the zenith, i.e.30° above the horizon: **AM =1/ cos60 = 2, thus we receive an AM2 spectrum.**

Example1: What is the ratio between the path length of sun light through the atmosphere if the sun directly overhead ($\phi = 0^o$) and when the sun is $\theta = 30^o$ overhead.

Solution. The ratio is = 1/cos30 = 1/0.866/1 = 1.128.

we receive around **1AM.**



Example 2: what is the ratio between the path length of air mass 1.5 and the path length of air mass 2:

$$Ratio = \frac{air\,mass2}{airmass1} = \frac{\cos\emptyset 1}{\cos\emptyset 2} = \frac{2}{1.5} = 1.33$$

Solution: Air mass =1/cos ϕ

The attenuation of solar radiation is due to scattering and absorption by air molecules, dust particles and/or aerosols in the atmosphere. Especially, steam (H_2O), oxygen (O_2) and carbon dioxide (CO_2) cause absorption. Since this absorption is wavelength-selective, it results in gaps in the spectral distribution of solar radiation as apparent in Fig. 8 &10 before. Ozone absorbs radiation with wavelengths below 300 nm (Ultra-violet radiation). 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 in the infrared, which has consequences for our climate.

The spectral radiance

The derivation of Planck for the spectral radiance L_e for the black body totally satisfy Stefan-Boltzmann experimental law for the radiation from the black body:

$$L_e = \sigma T^4$$

$\sigma = 5.67 \times 10^{-8}$ kg s^{-3} K^{-4} is the Stefan-Boltzmann constant. Equation is known as **the Stefan-Boltzmann law**. This law is very important because it tells us that **if the temperature of a body (in K) is doubled, it emits 16 times as much power**. Little temperature variations thus have a large influenced on the total emitted power.

Another important property of blackbody radiation is **Wien's displacement law,** which states that the wavelength of maximal radiance is indirectly proportional to the temperature,

$\lambda_{max} T = b \approx 2.898 * 10^{-3}$ m K. As Shown in figure 11 below.

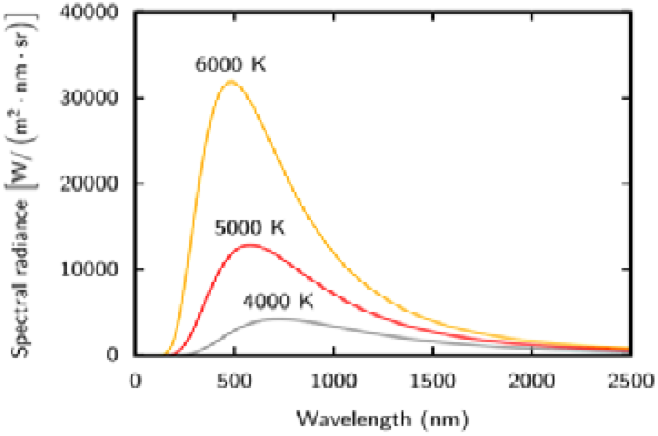


Fig 11: The blackbody spectrum at three different temperatures

The surface temperature of the Sun is about 6000 K. If it would be a perfect black body, it would emit a spectrum which gives the spectral radiance. For calculating the spectral irradiance ($I_{e\lambda}$) a blackbody with the size and position of the Sun would have on Earth, we have to multiply the spectral radiance with the solid angle of the Sun as seen from Earth,

$$I_{e\lambda}^{BB}(T;\lambda) = L_{e\lambda}^{BB}(T;\lambda)\Omega_{\mathrm{Sun}}.$$

$$\Omega_{\mathrm{Sun}} = \pi\left(\frac{R_{\mathrm{Sun}}}{\mathrm{AU} - R_{\mathrm{Earth}}}\right)^2.$$

Where Ω_{sun} is the solid angle of the sun, R_{Sun}= 696 000 km, an astronomical unit AU = 149 600 000 km, and R_{earth} = 6370 km,

Example 3. Calculate the temperature at the surface of the sun. Suppose The irradiance arriving the earth is the value for: (1) AM0; 1350W/m^2. **(2)** Calculate the photon flux density at λ= 0.5nm, suppose h= $6.6*10^{-34}$ J. sec and C= $3*10^8$ m/sec.

Solution: Using R_{Sun} = 696000 km, an astronomical unit AU 149600000 km, and R_{Earth} = 6370 km, we find: (1) The Solid angle (**Ω_{sun}**)

$$\Omega_{\mathrm{Sun}} = \pi\left(\frac{R_{\mathrm{Sun}}}{\mathrm{AU} - R_{\mathrm{Earth}}}\right)^2.$$

$$\mathbf{\Omega_{sun} = 68\ \mu sr}$$

$$\mathbf{I_e=L_e * \Omega}$$
$$\mathbf{L_e= I_e/ \Omega =1350/68\ \mu sr\approx 2x10^7\ W.m^{-2}.sr^{-1}}$$
$$\mathbf{L_e= \sigma * T^4}$$
$$\mathbf{T=(L_e/\sigma)^{1/4}=(2x10^7/5.67\ x\ 10^{-8})^{1/4}= 2149\ {}^oK.}$$
$$\mathbf{(2).\ P_\lambda = \varphi_{ph\lambda}\ (hC/\lambda)}$$
$$\mathbf{\varphi_{ph\lambda} = (P_\lambda\, \lambda\ /\ hC)}$$
$$\mathbf{\varphi_{ph\lambda} = (1.35*0.5*10^{-9})/(6.6*10^{-34}*3*10^8)}$$
$$\mathbf{\varphi_{ph\lambda} = 3.5*10^{19}/m^2}$$

Solar cells and photovoltaic modules are produced by many different companies and laboratories. Further, many different solar cell technologies are investigated and sold. It is therefore of utmost importance to define a reference solar spectrum that allows a comparison of all the different solar cells and PV modules.

The industrial standard is the AM1.5 spectrum, which corresponds to an angle of 48.2°. And corresponds to: Ie (AM1.5) = 1000 W·m^{-2} . It is close to the maximum received at the surface of the Earth. While the “real” AM1.5 spectrum corresponds to a total irradiance of 827 W·m^{-2}.

The power generated by a PV module under these conditions is thus expressed in the unit Watt peak, W_p.

The design of an optimal photovoltaic system for a particular location depends on the availability of the solar insulation 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 Jordan the average value is 2200 kWh/m^2, thus more than twice as high.**