ET3034Tux - 1.6.2 – Solar light 2

We know the shape of the solar spectrum.

How is this spectral shape and irradiance of the solar light affected by the Earth's atmosphere?

Let's consider that the Earth's atmosphere is 8000 km thick.

The irradiance of the solar light arriving at the outer side of the Earth's atmosphere is approximately 1350 watts per square meter.

In this figure the spectral power density of the irradiance arriving at the outer side of the Earth's atmosphere is shown by the yellow region.

This spectrum is called the extraterrestrial spectrum.

Note, that the grey line represents the spectrum of a black body radiator at a temperature of 5800 K.

This demonstrates that Planck's formula gives a reasonable estimate of the solar spectrum as discussed in the previous block.

The red area reflects the spectrum arriving at the Earth surface.

As you can see, a significant fraction of the spectral power density is lost by travelling through the Earth's atmosphere due to scattering at, and absorption by molecules and particles in the atmosphere.

The ultraviolet (UV) part of the spectrum is absorbed by ozone in the atmosphere.

In the infrared, oxygen, water and carbon dioxide absorb light.

They take big bites out of the spectrum.

It means that the total power density arriving at the surface depends on the absorption path length of the light travelling through the atmosphere.

On average, around 20% of the solar irradiation is reflected by clouds, 6% by the molecules in the atmosphere and 4% by the Earth's surface.

So in total 30% is lost due to reflection.

19% of the irradiation is lost due to absorption by clouds, particles and molecules in the atmosphere.

51% of the irradiation is absorbed at the Earth's surface.

As the absorption is a loss mechanism, the path length of the light travelling through the atmosphere determines the amount of scatter and absorption losses.

At the equator the light has the smallest path length through the atmosphere.

However, at high latitudes the sun has a larger path length through the atmosphere.

As a result the absorption and scattering losses are higher at high latitudes.

The path length of light is defined by the optical air mass.

An air mass of 1 corresponds to the smallest possible path length, which is the path length at the equator.

An air mass of 1.5 means that the absorption path length is 1.5 times larger than that at the equator.

The air mass can be calculated by the formula: 1 over the cosine theta, where theta is the latitude in degrees.

An air mass of 1.5 would correspond to the average path length that the light would travel through the atmosphere at a latitude of 48.2 degrees at noon, if we ignore the seasons.

In week 3 we will discuss how to determine the performance of solar cells using solar simulators.

These are lamps which try to simulate the solar spectrum as close as possible.

It has been decided that the standard test conditions (STC) for the solar spectrum has the spectral shape of solar light with a path length of AM1.5 through the atmosphere.

Secondly, the irradiance of this spectrum is 1000 watts per square meter.

As the AM1.5 spectrum is very important to the solar community, I will use it to demonstrate the relation between the spectral power density function, the irradiance, the spectral photon flux and the photon flux.

Here the spectral power density of the AM1.5 spectrum is plotted.

As discussed earlier the irradiance is the integration of the spectral power density function over lambda.

This means that the area below the AM1.5 spectrum in this figure corresponds to the irradiance.

The blue line is the integration of 0 up to lambda and you see that the area below the spectral power density up to 4000 nm is equal to 1000 watts per square meter as expected for the AM1.5 spectrum.

The irradiance tells us something about the power per unit area.

However, we can consider light as a number of photons as well.

The photon flux phi is the amount of photons per time per area.

Similar to irradiance, the photon flux does not contain any spectral information.

For that we define the spectral photon flux, which is the amount of photons per unit area per time per wavelength range.

What is the relation between the spectral power density and the spectral photon flux?

For that we only need the energy of a photon as shown in this equation.

The spectral photon flux at wavelength lambda, is the spectral power density at wavelength lambda divided by the energy of a photon with wavelength lambda.

The photon energy is determined by the product of the Planck's constant and the light velocity divided by the wavelength.

This gives the following relation between P and phi.

So if we integrate the spectral photon flux over lambda we get the photon flux.

In this graph the spectral photon flux is presented.

The area under this graph represents the photon flux.

The blue line shows the photon flux in the AM1.5 spectrum up to the wavelength lambda.

It shows that up to 4000 nm the AM1.5 spectrum has a photon flux of 4.3*10^21 photons per second per square meters.

As we will discuss in the coming two weeks, every photon can result in one collected charge carrier.

This means that the amount of photon flux of the solar spectrum in theory determines the maximum current per area we can generate with a solar cell.

So, the concept that light can be described by quantized packages of energy, as proposed by Einstein, is a very important tool to calculate the maximum possible conversion efficiencies of solar cells.

The average annual solar irradiance on Earth varies depending on the location as you can see in this figure.

A useful tool in expressing the local solar irradiance is sun hours.

1 sun hour equals the energy of 1 kWh per square meters.

Or with other words, an Earth surface that is exposed for 1 hour to standard test conditions irradiance of 1000 watts per square meter.

Why is this a handy unit?

It is related to the fact that the performance of solar modules is quantified under standard test conditions.

If a module has a power of 100 watt-peak, it means that the module delivers under AM1.5 solar irradiance of 1000 watts per square meter, 100 watts.

The addition peak means, the maximum power a solar module can deliver under standard test conditions.

How do we calculate the average energy yield of a solar module?

Let's take again a module of 100 watt-peak.

In the Netherlands the annual average solar irradiance is 2.7 sun hours per day.

It means that a module in the Netherlands delivers 100 watt-peak times 2.7 sun hours is 270 Wh per day.

This equals 98.6 kWh per year.

In sunnier places like Spain, common irradiance can be around 4.2 sun hours per day.

This means that the same 100 watt-peak will deliver on average 420 Wh per day in Spain.

On a day with a clear sky the irradiance reaching the Earth's surface is typically in the range from 700 to 1,300 watts per square meter at local solar noon, depending on the latitude, altitude and time of year.

On a cloudy day the spectral composition of light is different from that of light on a clear day.

Namely on a cloudy day, represented by the black line, the relative amount of ultraviolet (UV) is less and the relative amount of infrared (IR) light is higher.

That happens because the shorter wavelengths scatter more strongly.

Up to now we have only considered the light coming from the sun and directly incident on the earth surface.

However, as mentioned earlier 26% of the light is scattered in the atmosphere.

This means that light falls under various broad angles on a horizontal surface.

The amount of solar radiation that falls on a horizontal surface is characterized by Global Horizontal Irradiance (GHI) - it is the energy that comes from all directions, indicated by the dark blue line.

It consists of direct normal radiation from the sun, indicated in green, and the diffuse radiation from the sky, indicated in red.

In weeks 7 and 8 we will talk about PV systems.

You have to realize that the response of a PV system differs between diffuse light and direct light.

This week, I would like to show how we can measure the irradiance of direct light and diffuse light.

For that we use a pyranometer and you often see these tools installed next to a PV system.

These are instruments used to measure the heating power of radiation.

Pyranometers have a field of view equal to a complete hemisphere and is sensitive to the full spectrum of solar radiation in the range of 300 nm to 3000 nm and has a flat spectral response in the whole range.

It allows to measure the radiation very precisely independent of the wavelength of light.

It measures the thermal effect of the radiation.

The pyranometer consists of a black thermopile detector that absorbs light in the whole spectral range.

When light is absorbed the black surface of the detector heats up and the increase in the temperature is proportional to the amount of radiation.

This temperature difference is transformed into an electrical signal by the thermopile and can be easily measured.

The special hemispherical glass dome has the function of a spectral filter.

It limits the spectral response from 300 to 2800 nm, cutting off the part above 2800 nm, while preserving the 180 degree field of view.

Direct radiation from the sun is measured using a pyrheliometer.

A pyrheliometer has the same principle as a pyranometer - it also uses a black absorber and thermopile detector to measure the amount of radiation.

But it only can see the sun as its field of view is limited to 5 degrees as you see in this movie.

To keep the pyrheliometer pointed continuously at the center of the sun, the instrument must be mounted on a high accuracy automatic sun tracker.

In accurate measurement stations diffuse radiation (DHI) is measured by fitting a pyranometer on top of the sun tracker and a shading assembly that moves with the tracker to always block the direct beam radiation from reaching the pyranometer as you can see in this movie.

A typical clear day data would look like this.

The direct light in green is dominant over the diffuse light in red.

In next example the morning was clear until 9am when some clouds passed overhead.

The direct radiation decreased intermittently and the diffused component increased.

By 1PM the clouds completely eclipsed the sun and all radiation was diffused.

The green line is nearly zero and the blue line and red line coincide.

Summarized, I hope that I have given you some general insights into solar energy this week.

In the last two blocks we have discussed the various properties of solar light that will be important to understand the various concepts on which solar energy technologies are based.

So, let's start using the solar light.

Next week, I will discuss the fundamental properties of semiconductor materials.

We will answer questions like: What is the band gap of a semiconductor?

How do we excite charge carriers and what are the transport mechanisms of charge carriers in semiconductor materials?

How do we use semiconductor materials to make photovoltaic devices?

See you next week!