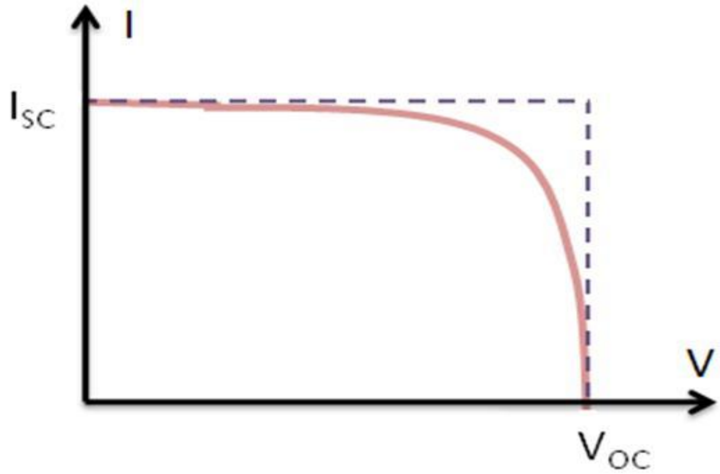
2.4 The parameters of solar cell

In this block we are going to discuss the external parameters that determine the light-to-electricity conversion efficiency of an ideal solar cell.

2.4.1 Open circuit voltage

Let's consider that the terminals of an illuminated solar cell are not connected. This situation is called an open circuit. In open-circuit the solar cell does not produce any current and solely produces a voltage. This voltage is called the open-circuit voltage. The voltage is easily recognized in the I-V plot by the intersection of the I-V curve with the horizontal axis corresponding to a current density equal to zero. We can derive a simple equation for the open-circuit voltage of an ideal solar cell



Under open-circuit conditions the current I is equal to zero.

$$\mathrm{I} = I_{PH} - I_0\left(e^{\frac{q\,V_{OC}}{K_B T}} - 1\right) = 0$$

If we solve this equation we arrive at a simple expression for the open-circuit voltage.

It is linear with the Boltzmann constant times the temperature, divided by the charge of an electron. And it is linear with the natural logarithm of the ratio between photocurrent and the leakage current of a diode plus 1.

$$V_{OC} = \frac{n\,K_B T}{q}\ln\left(\frac{I_{PH}}{I_0} + 1\right)$$

The equation shows that the open-circuit voltage depends on several parameters.

Firstly, the equation shows that if the photocurrent density is increased the open-circuit voltage is increased as well. This means that by increasing the irradiance, or in other words, by shining more light on the solar cell, the open-circuit voltage can be increased.

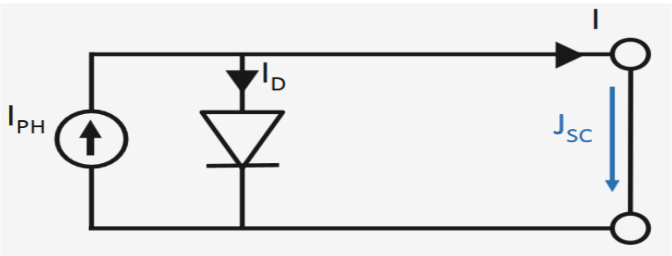
Secondly, the open-circuit voltage depends on the temperature.

Although this equation on first eye suggests that the open-circuit voltage increases with temperature, this is not the case. The leakage current J_0 of the diode strongly depends on the temperature.The higher the temperature, the larger the leakage current and the smaller the open-circuit voltage will be. The open-circuit voltage depends on **other factors**

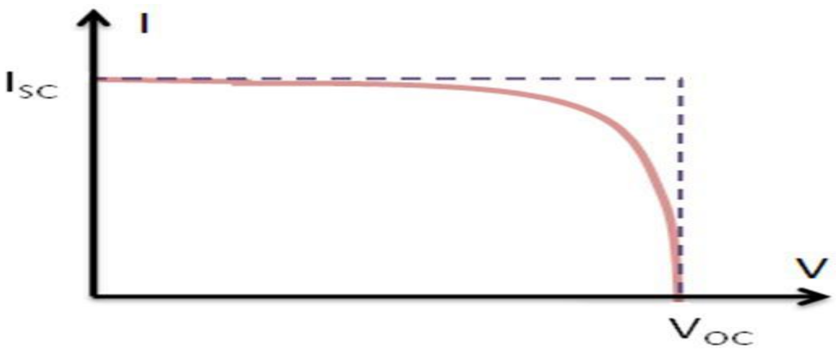
- •The band gap of the absorber material
- •The amount of doping of the doped layers
- •The quality of the material
- •The light generated current density
- •Temperature

2.4.2 Short circuit current

If we short-circuit both terminals of the solar cell, the illuminated solar cell will solely produce a current and will produce no voltage. This current density is called the short-circuit current density.



The short-circuit current density can easily be recognized in the I-V curve as well. It is the intersection between the vertical line corresponding to zero voltage and the I-V curve.



We can derive a simple equation for the short-circuit current density of an ideal solar cell using again the expression of the I-V relation.

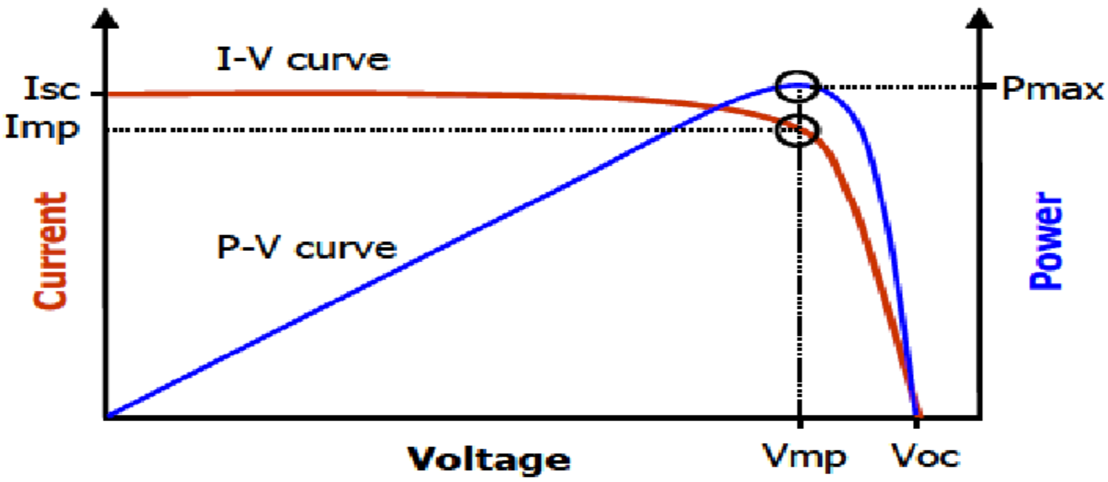
$$I = I_{PH} - I_0\left(e^{\frac{q V_{OC}}{K_B T}} - 1\right)$$

If we take a voltage equal to zero, the short-circuit current density is equal to the photocurrent density. $\{ I = I_{PH} \}$

The short-circuit current density depends on several factors like the incident light intensity

- Incident light intensity (number of photons)
- The spectrum of the incident light
- The optical properties (absorption coefficient)
- The collection probability

2.4.3 Maximum power point



The vertical axis on the right shows the scale of the power density. Note that if the power on this scale is negative, it means that the solar cell is generating power, whereas if the power is positive, it means that the solar cell is consuming or dissipating power. The blue curve shows that the power is varying with the voltage and it shows that the power has a maximum value.

On the I-V curve the black circle point is called the maximum power point and the power generated at this point on the blue line is P_max.

The graph demonstrates that if the solar cell is in open-circuit, which means it only produces an open-circuit voltage and no current, the power is equal to zero. When the solar cell is in short-circuit, which means it only produces a current and no voltage, the power is equal to zero as well. If the voltage is smaller than 0 V, which we call reverse bias, the illuminated solar cell does not generate power but consumes power. Basically, an illuminated solar cell under reverse bias will heat up.

If the voltage is larger than the open-circuit voltage, the illuminated solar cell is dissipating power as well and the solar cell will heat up as well.

The voltage at the maximum power point is called V_mp and the current at the maximum power point is called I_mp. Which means that maximum power P_max is equal to V_mp*I_mp.

With other words, the shaded area under the maximum power point in a I-V plot represents the power generated.

2.4.4 Fill factor

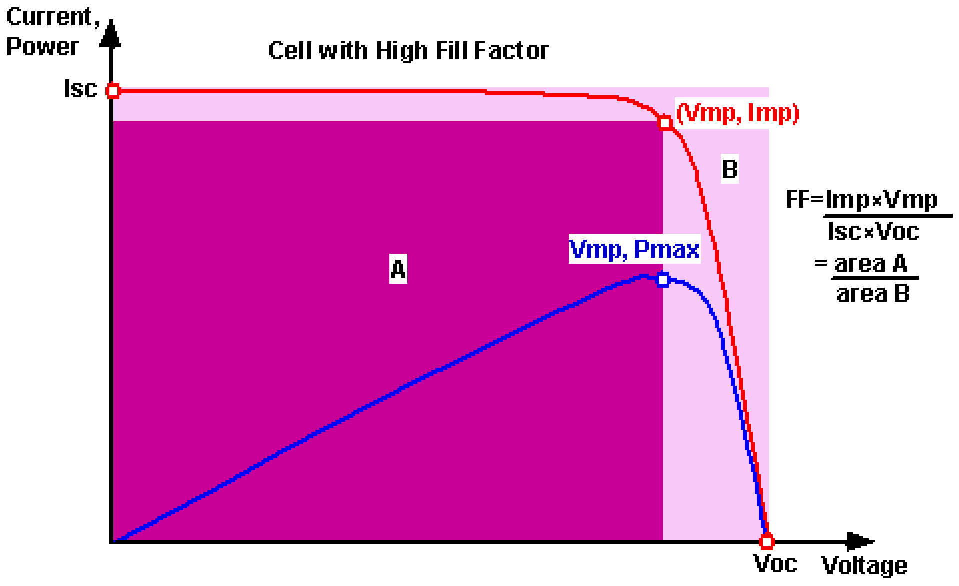
The fill factor is the ratio between the maximum power and the product of the short-circuit current and the open-circuit voltage.

Or the ratio between the product of maximum power point current and the voltage and the product of the short-circuit and the open-circuit voltage.

$$FF = \frac{P_{max}}{V_{OC} I_{sc}} = \frac{V_{mp} I_{mp}}{V_{OC} I_{sc}}$$

The FF can be easily visualized in a I-V curve.

Basically, the FF is the ratio between the area shaded red-yellow and the red area including the shaded red-yellow area. With other words the FF is the ratio between the rectangle with sides V_mp and I_mp, and the area with the sides of the open-circuit voltage and the short-circuit current. This means that we can express the maximum power density as a product of the FF, the open-circuit voltage and the short-circuit current. It implies that it is impossible for a solar cell to have a FF equal to1, in that case the I-V curve should have the shape of a rectangle.

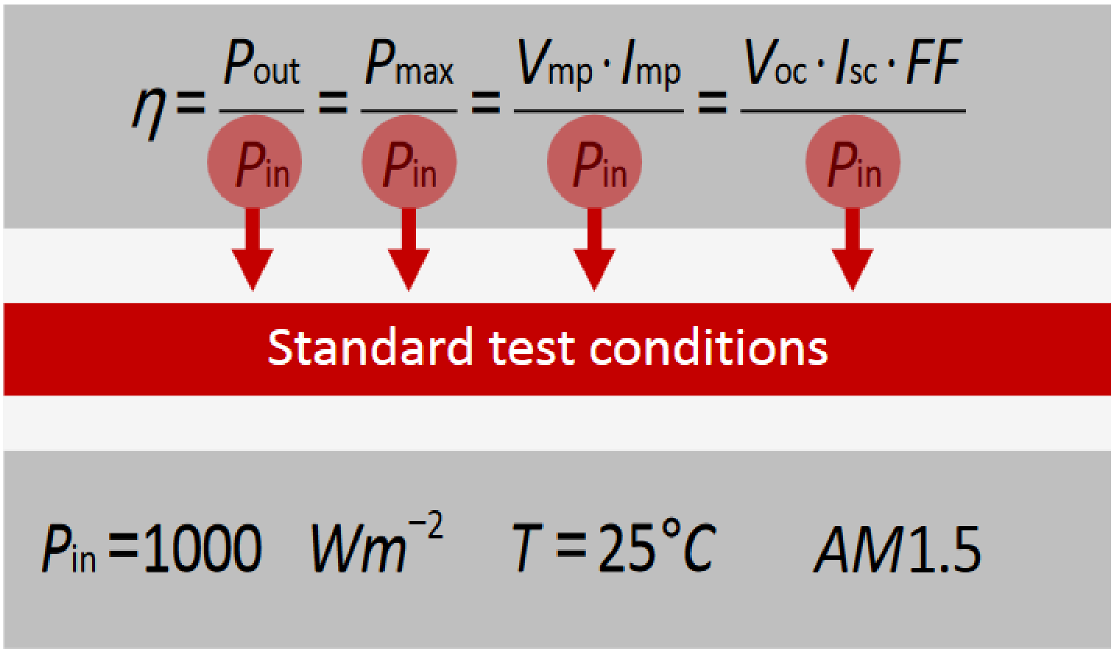


2.4.5 Conversion efficiency

This is the ratio between power coming out of the solar cell P_out and the light power of light incident on the solar cell, or in other words going into the solar cell, P_in. The conversion efficiencies of solar cells are defined in its maximum power point so P_out equals P_max. P_max, as discussed, equals the product of I_mp and V_mp. This product equals to the product of the short-circuit current, the open-circuit voltage and the FF. As a result the conversion efficiency can be expressed in the external parameters of the solar cell: the open-circuit voltage, the short-circuit current density and the fill factor.

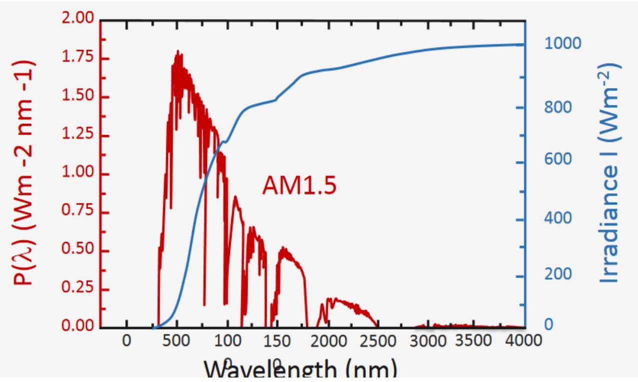
$$\eta = \frac{P_{out}}{P_{in}} = \frac{P_{max}}{P_{in}} = \frac{V_{mp} I_{mp}}{P_{in}} = \frac{V_{OC}.I_{sc}.FF}{P_{in}}$$

To be able to compare the efficiencies of different solar cells, the so-called standard test conditions have been introduced.
The standard test conditions describe the conditions for P_in and the temperature of the solar cell during the I-V measurements.
The temperature of solar cells under standard test conditions is determined to be 25 degrees Celsius.
The solar spectrum has the spectral shape of AM1.5 and a total irradiance of 1000 watts per square meters.



A typical solar spectrum with the shape of AM1.5 is shown here.
On the left vertical axis we show the spectral power density.

The irradiance under standard test conditions has to be equal to 1000 watts per square meters and is given on the right axis.
The blue line represents the irradiance and equals the area under the spectral power density up to the wavelength lambda.
As illustrated, if we integrate over the entire spectral power density
the blue line, corresponding to the irradiation, equals 1000 watts per square meter.

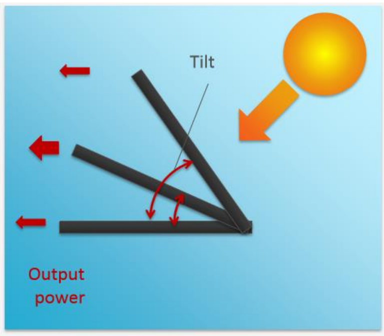


Note, that 1000 watts per square meter equals 100 milliwatts per square centimeter.

2.4.6 solar irradiance

Even though so many technological advancements are being made at the cell level to improve efficiency (as discussed), there is still a lot to be done at the PV system level to ensure a healthy PV yield. Getting a good module (in terms of efficiency and output sensitivity) is winning only half the battle, what matters ultimately is the yield of the PV system.
So the question is: What else can you do to increase the yield of your PV system at the system level?
Of course, MPP tracking is a valuable tool to ensure that the PV module always operates at the MPP on an I-V curve, under a given set of irradiance and temperature.
But how do we improve the amount of light falling on the PV module, at the system level? The simplest way of doing that is by playing with the orientation and tilt of the module. What do we mean by orientation and tilt? Tilt is the degree of freedom that defines the elevation or the pitch of the solar module with respect to the horizontal.

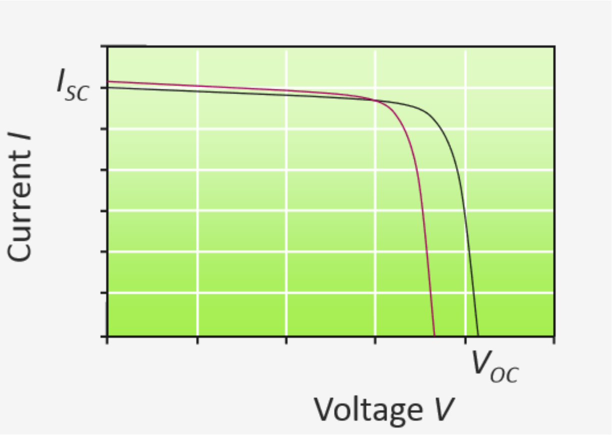
Of course, this stems from the basic fact that in order to get maximum energy from the sun at any instant, the plane of the solar panel (or the plane of array, as sometimes called) should be perpendicular to the direct rays of the sun at that instant. The amount of solar energy falling on the Earth is dependent on astronomical factors like the tilt of the Earth's axis and the near-spherical shape of the Earth.



In general, all other parameters being unchanged, higher the irradiance, greater the output power generated

2.4.7 Cell temperature

In this block I would like to discuss with you the effect of a parameter of great importance: the temperature. First, I'd like to answer the simple question, is a greater temperature better for the PV output? Or is PV output independent of the temperature changes?



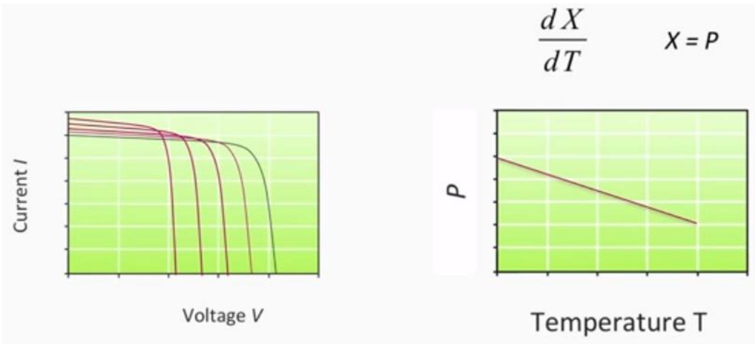
In this graph you see the I-V curve of a PV module at a given irradiance and temperature as shown in black curve. if the temperature increases while the irradiance is constant we see an I-V curve that looks like the red curve.

So we see that while the current has very minutely increased, there is a significant drop in voltage. This means that the overall power output has decreased. On the other hand, if the temperature were to decrease with respect to the original conditions while the irradiance were constant, the PV output would show an increase. The minute increase in current with temperature can be explained with the fact that carrier concentration and mobility increase in the semiconductor with temperature. This is consistent with our basic understanding that a semiconductor, unlike a regular conductor, exhibits better conductivity with increasing temperature and is a perfect insulator at absolute temperature of 0 K. The decreasing effect on voltage can be explained from this form of the basic diode equation seen earlier.

$$V_{OC} = \frac{n\, K_B T}{q} \ln(\frac{I_{PH}}{I_0} + 1)$$

While the temperature affects the various terms in the equation, the net effect of temperature is that it decreases the Voc linearly. The drop in open-circuit voltage with temperature is mainly related to the increase in the leakage current of the photodiode I_0 in the dark with temperature. The I_0 strongly depends on the temperature. We have dedicated one of the exercises this week to this effect. The magnitude of reduction varies inversely with Voc. This means that cells with higher Voc are less affected by the temperature than cells with lower Voc. This means that a solar cell based on c-Si with a Voc of 0.65 V will be more affected than the a-Si with a Voc of 0.85 V. So now you have an idea of the effect of temperature on the PV output. But how do we quantify this effect? If the temperature of the PV module were to increase by 10°C, how would the output be affected? Well, the PV module manufacturers include what are known as the temperature coefficients in the datasheets of the commercial modules.

Temperature coefficient $\frac{dX}{dT}$ is nothing but the rate of change of a parameter(X) with a temperature. For instance, the temperature coefficient of voltage is the rate of change of the voltage with temperature.



Similarly, temperature coefficient of power is the rate of change of the output power with temperature. A typical datasheet of a commercial PV module specifies temperature coefficients for the power, Voc and Isc under STC conditions.

Temperature characteristics	240
Temperature coefficient of Pmax [%/°C]	-0.30
Temperature coefficient of Voc [V/°C]	-0.131
Temperature coefficient of Isc [mA/°C]	1.76

Given these coefficients, how do we calculate the PV output with respect to the temperature change? We can use this simple equation.

$$X(T) = X_{STC} + \frac{dX}{dT}(T - T_{STC}) \qquad\qquad X = V_{OC}, P, I_{sc}$$

The term dX/dT denotes the temperature coefficient of the particular parameter. The reference temperature taken for this calculation is the STC temperature, i.e. 25°C.

Let's take a look at an example. If the maximum power output of a PV module under STC is 250 W, and the temperature coefficient of power is -2 W/°C, then the module's power output at a temperature of 30°C can be calculated as follows:

P = 250 W + (-2 W/°C) *(30-25) °C = 240 W.

As you can see, the sign of the temperature coefficient determines if the parameter is increasing or decreasing with temperature.

Now, we must be careful while making these calculations. In the previous example, when we said that the temperature was 30°C, did we mean the PV module's temperature? Or the ambient temperature? or Should the two be the same?

As it turns out, the module temperature or the cell temperature, the popular term in literature, can be quite different from the ambient temperature. Let's see why there should be a difference between the module temperature and the ambient temperature. There could be several factors impacting the heat flow in and out of the modules. Encapsulation of the solar cells is a major factor in increasing the operating temperature of the PV module. The eventual operating temperature of a module will be a result of the thermal equilibrium between the heat generated by the PV module, the heat lost to the surrounding environment. The heat exchange with the environment in turn could depend on several factors like: ambient temperature, wind, heat transfer coefficients between the module and the environment, and the thermal conductivity of the module's body. Then how do we estimate the module temperature based on the ambient temperature if we have to account for so many factors?

Fortunately there is a model provided in literature that gives a reasonable estimate of the module temperature as a function of the ambient temperature.

$$T_{cell} = T_{ambient} + G * \frac{(NOCT - 20)}{800\ W/m^2}$$

This model is sometimes called the NOCT model, due to the use of the ***Nominal Operating Cell Temperature***, or NOCT of the PV cell or module.

NOCT is the temperature attained by the PV cell under an irradiance of 800 W/m², with a nominal wind speed of 1 m/s and an ambient temperature of 20°C. Here, G is the irradiance at the instant when the ambient temperature is T_ambient. The model gives the corresponding cell temperature as T_cell. As can be seen from this equation, the cell temperature is not only a function of the ambient temperature but also of the irradiance. This makes things interesting, because if we consider the irradiance and temperature changes over a calendar year, we would see an effect of both irradiance and temperature across the seasons.

This can be seen in the graph shown, which has been made using the actual ambient temperature and irradiance data as seen in the Netherlands in the year 2012. The corresponding cell temperatures have been calculated using the NOCT model.
This graph outlines the main inferences from the NOCT model.