LAB # 09

To Study and Understand How To Calculate Solar Panel Efficiency, Power and Energy Capacity

Objectives:

- To understand how to calculate the efficiency of a solar panel
- To study and understand how to calculate daily and annual electrical usage using different information sources
- To calculate the power and annual electrical energy consumption of an individual property, household, or facility

Related Theory:

Solar energy exists in two forms that we can use for electrical conversion. One is direct solar to thermal, creating a superheated fluid which can be used to make steam and turn a turbine. There is certain place on the Earth that can use this technology and resource, but they need a lot of direct cloud-free sunlight for many hours per day throughout the year. The other way solar energy can be used is the direct conversion of solar energy to electricity using ***photovoltaics***.

The most common type of photovoltaic we see in the world today are made of the element silicon. The solar cell is the basic unit of a photovoltaic module or panel. A single solar cell produces about a half a volt of electricity and up to about eight amps depending on the type of cell. The solar cell consists of a piece of silicon with contacts or electrodes that are put across the surface and on the back. Often, you'll see many smaller contact is connected together by a few, larger contacts on the cell's surface. Now, a half a volt isn't going to be able to do very much. So, cells are connected in series to create what's called a series string. Thus, increasing the voltage.

The series string is laminated to backing material, sealed in a weatherproof plastic coating, and then a cover glass is placed on top, often with an aluminum frame around the edges. This assembly is called the ***photovoltaic module***. It's also referred to as a solar panel. When designing a photovoltaic system, photovoltaic modules, also known as panels, we put together in what's called a ***photovoltaic array***.

Improvement in Solar Cell Efficiency Over Time:

Over the last 40 years, researchers and manufacturers have made significant efficiency improvements, and developed several types of photovoltaic cells like silicon, CIGS, dye sensitized, and multijunction. The best performing cells become the benchmarks for further improvements. So, how do these different types of cells compare to one another, and how are they improved over time?

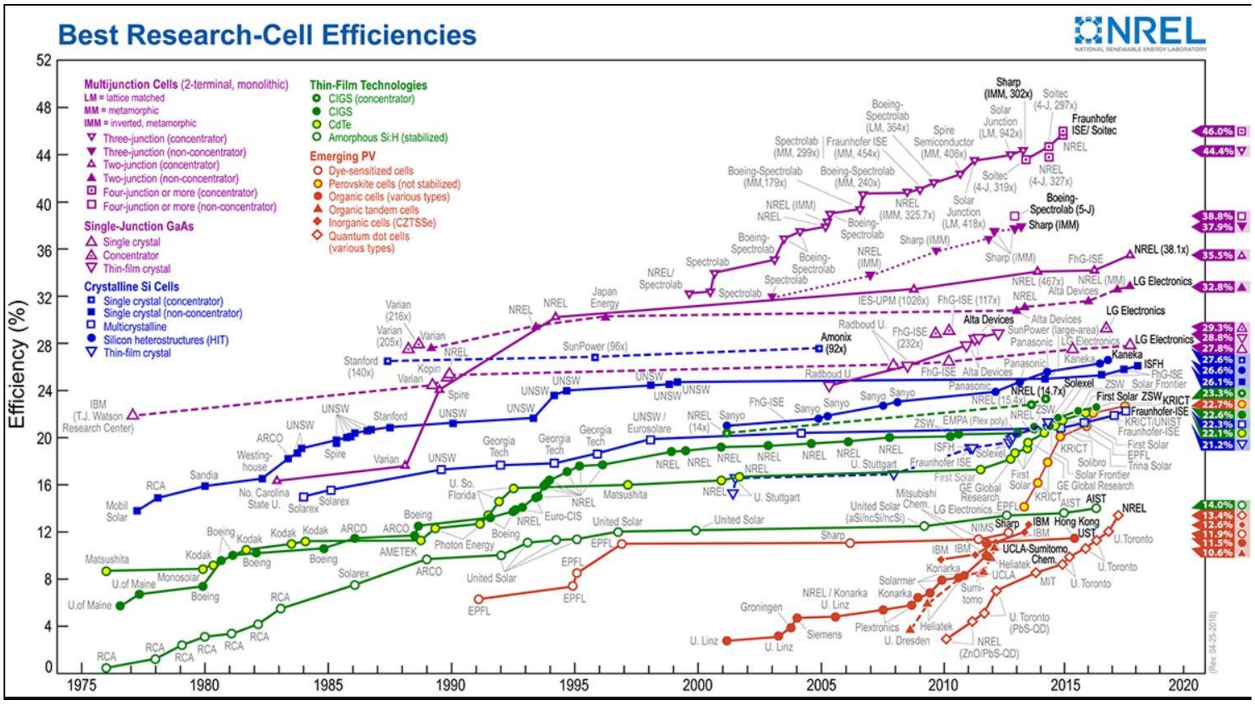
On the graph shown below, we have time on the, from the mid 70's on the X-axis, and the overall cell efficiency on the Y-axis. Silicon efficiency has gone up and remained pretty flat for the last two decades. That's because silicon has essentially reached its maximum and can't get much better. Thin film cells such as CIGS and cadmium telluride have made great improvements over the years, and it became more and more efficient.

However, there are concerns with toxicity which limits some of their commercialization. Emerging technologies cells like dye-sensitized solar cells, perovskite, and organic cells, are making quick gains, but they are many years from being towards commercialization.

The multijunction cells, show the ***highest efficiencies***, but those cells are mainly in the lab stage, and at this point are prohibitively expensive for commercial purposes. Although there have been some used recently in some highly specialized applications by ***NASA*** for the Dawn space probe in the Mars Rover.

You can see a little more detailed breakdown of the efficiencies of the different types of solar cells over time in the ***National Renewable Energy laboratory's*** graph of solar cell efficiencies, shown below.

In nearly all cases, efficiency improvements are continuous, but cost inefficiency tend to be directly related. Meaning that, ***increased efficiency, typically comes at increased cost***.



Calculating Module Conversion Efficiency:

In a previous discussion, we looked at the maximum efficiencies of laboratory grade photovoltaic cells. We see efficiencies constantly going up and up and up. How is that efficiency calculated and how can we use that to our advantage as we begin to select a photovoltaic module?

Let's begin by looking at how bright the sun really is. If we look at the sun the sky on a general bright sunny day, around mid-latitude on earth, it will be approximately ***1,000 watts per square*** meter. So, we define this value as the ***solar standard***.

We combine that brightness with the standard temperature of ***25 degrees Celsius***, which is around 77 degrees Fahrenheit and another term called air mass to give a definition that combined solar and climactic conditions. The chosen ***air mass*** value is ***1.5***.

There are two fundamental units that we measure for a photovoltaic module to begin to figure out how much power it's producing. One of those units is voltage (***V***) and the other unit is current (***I***). When we take the voltage, that push, and multiply it numerically by the current, the flow, measured in units of Amperes, we get the power which is measured in watts. So, watts are equal to voltage in volts, times current in amps.

P = V x I

Watts = Volts x Amps

If we want to measure the efficiency of a solar panel, we need to know what the power going out is, and divide it by the power going in, which is all based on the same unit of area. That's the ***general*** definition of efficiency.

$$\boldsymbol{Efficiency = \frac{Power\ Out}{Power\ In}}$$

For photovoltaic, we can measure the voltage and the current and multiply them together to get the output power. Then divide that by the area of the module. We then divide by the power of sunlight per square meter to yield the efficiency.

$$\boldsymbol{Efficiency = \frac{Power\ Out \big/ Area\ of\ Module}{Power\ of\ Sunlight \big/ m^2}}$$

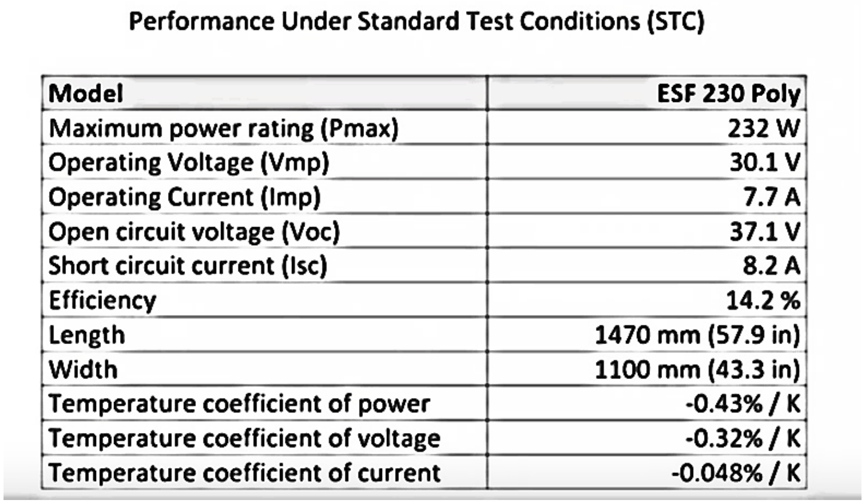
So, how do we know a module's efficiency without having to go out in the field and measure each one independently? Well, manufacturers provide specification sheets for every commercial solar panel they produce.

They'll typically include ***five common terms***. Those terms are always measured under standard test conditions again which is 1,000 watts per square meter, 25-degree air temperature Celsius and AM 1.5 sunlight. The five terms of the voltage at maximum power, which is the voltage being put out by the solar panel, the current at maximum power, which is the current that's being put out under maximum power and the maximum power which is the power of the solar panel which is actually calculation of the voltage and maximum power, multiplied by the current at maximum power.

The other two key terms are the Voc, or open-circuit voltage, which is the maximum voltage that the cell will ever put out, and the Isc, or short circuit current, which is the maximum current the cell will ever put out or the module will ever put out.

If we look at a specification sheet like the one shown below, all the terms are listed; ***Vmp, Imp, Voc, Isc,*** and maximum power or ***Pmax***. Other information that's usually included in the specification sheets are the modules size, weight, the impact loading, the fusing, and a few other electrical guidelines.

So, now that we looked at the specification sheet, and calculate efficiency.



Performance Under Standard Test Conditions (STC)

Model	ESF 230 Poly
Maximum power rating (Pmax)	232 W
Operating Voltage (Vmp)	30.1 V
Operating Current (Imp)	7.7 A
Open circuit voltage (Voc)	37.1 V
Short circuit current (Isc)	8.2 A
Efficiency	14.2 %
Length	1470 mm (57.9 in)
Width	1100 mm (43.3 in)
Temperature coefficient of power	-0.43% / K
Temperature coefficient of voltage	-0.32% / K
Temperature coefficient of current	-0.048% / K

Efficiency Calculations:

Calculating Power and Energy:

Let’s look at an electrical input of any appliance. It either has a power rating listed as some number with a ***W*** next to it, or a ***current*** and ***voltage*** rating. But what do those mean, and how do we assess what they mean for electrical needs? And how do we determine the appropriate solar panel system that would fit the needs of a specific device or maybe a whole building.

Let's start by looking at the unit of power. ***Power*** is typically defined in watts or kilowatts. Power is the rate of doing work or rate at which energy is used, produced, or transferred.

$$\mathbf{P = \frac{W}{t} = V \times I}$$

As an example, we might look at a clothes dryer which operates at 220 volts and 8 amps. So, we can calculate the power by:

$$P = 220V \times 8A = 1760 \text{ watts}$$

Another one will be a photovoltaic panel, which operates on outputs 40 volts at 5 amps. So, Power will be:

If the PV system produces 1,300 watts, and outputs 224 volts, then current will be:

Now let's look at what power has to do with ***energy***. As we just saw, power is defined as energy divided by time. So, energy is power multiplied by time. Energy includes how long a device is being used or how long it's producing power.

Energy = Power x time

There are many units for energy, such as watt hours, kilowatt hours, Btu’s, which stand for British thermal units, Joules, and calories.

Energy for electricity is typically measured in ***kilowatt hours*** or ***watt hours*** when being consumed or produced. Coincidentally, sunlight energy also measured in kilowatt-hours, or watt-hours. Knowing this, we can compare the Sun's energy output to photovoltaic energy and electrical load, or the demand, using this common unit of kilowatt-hours or watt-hours. It's a direct comparison.

So how do we use that energy value? Well, again since energy is just power multiplied by time, we can look at everyday appliances, like say a hairdryer or a light bulb.

Let's assume, a hairdryer might use 1,100 watts and it's on for 15 minutes per day or one quarter of an hour using that 1,100 watts for about 180 days per year. So,

$$P = 1100W$$

$$t = 0.25h$$

$$\text{Energy (E)} = \text{Power (P)} \times \text{Time (t)}$$

$$E = 1100W \times 0.25h = 275 \text{ watt-hours per day}$$

For annual use,

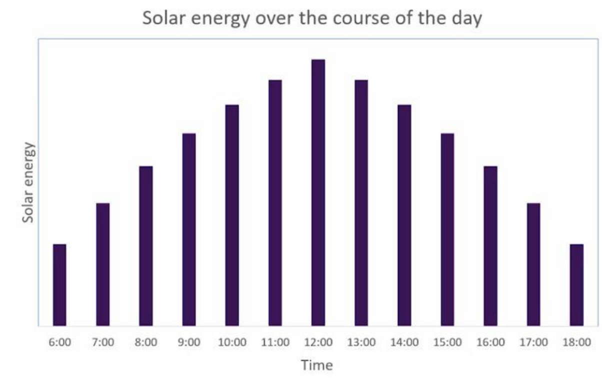
$$E = 275 \text{ Wh} \times 180\text{d} = 49{,}500 \text{ Wh per year}$$

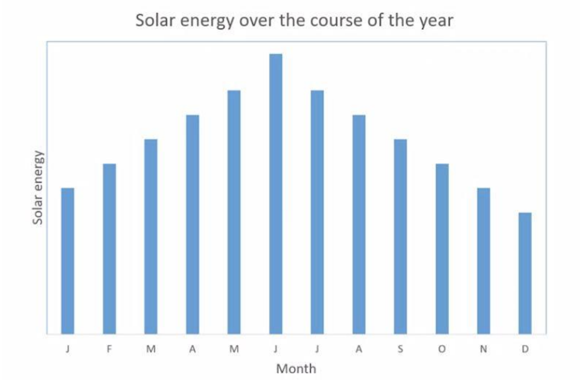
Or

$$E = 49.5 \text{ KWh per year}$$

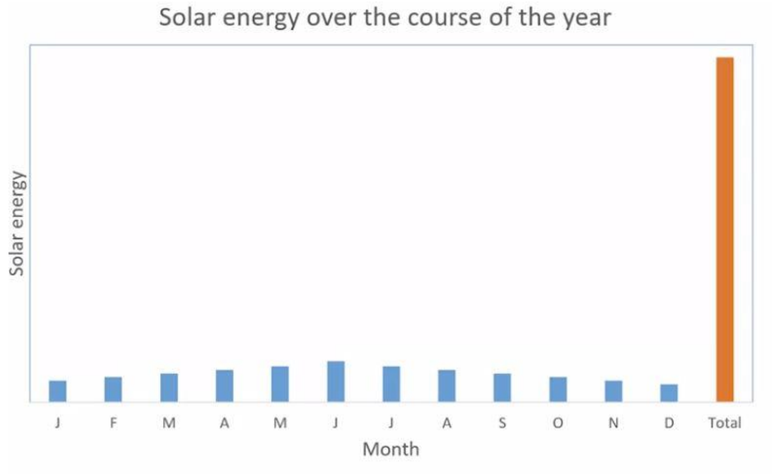
Now calculate for another one, If we take a 60-watt light bulb and use it for four hours a day and 345 days per year.

The power tells us about the ***instantaneous*** consumption, and the energy tells us how long that electricity is being used or produced. A solar module can produce a specific amount of power based on sunlight levels and that amount of *power varies constantly based upon weather*, and seasons, and day or night cycles.


Solar energy over the course of the day


Solar energy over the course of the year

Because that power level varies the only way to know how much electricity is produced during a year is to calculate the sunlight power over time. That's energy, energy values can be summed over a time period to get the total energy used or produced. This helps us *compare the energy demand to the energy production.*



Based on the above discussion, Calculate annual energy produced by the photovoltaic module that generates 38 volts and 5.68 amps under full sunlight conditions. It does this for an average of four hours per day for a whole year.

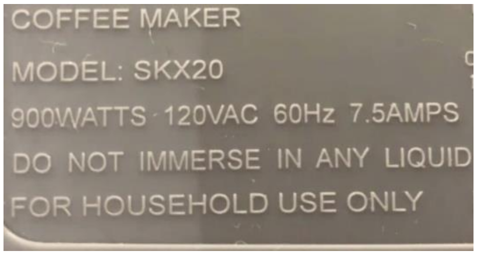
Measuring Appliances Power and Energy:

Let's now check appliances power consumption in real time. We have plugged a light bulb into a watt meter, which shows the system voltage is approximately 120 volts. But since it's **off**, there is no current or zero amps. Once we turn **on** the light bulb, the current measures 0.509 amps. It also tells me that the wattage of the system is 67.7 watts, which is close to the calculated value within the error.

Then we use the same meter to compare three different light bulbs: in **incandescent**, a **compact fluorescent**, and an **LED**. We can see in real time that for almost the same equivalent brightness, the incandescent bulb uses **67 watts**, the compact fluorescent uses **19.5 watts**, and the LED uses **8.5 watts**. This also illustrates how switching to more efficient devices can reduce the overall energy consumption.

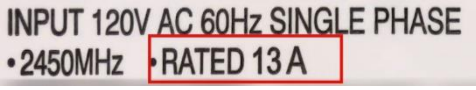
Let's take another example of a **coffee maker**, that is typically high-powered device, and the label indicates that it consumes 7.5 amps when in use, plugged into our watt meter.

So, In real time, its approximately use about 0.5 watts in **off** condition (switch plugged in). But as soon as we turn **on** the power, it goes up to 873 watts, 120-volt operating system voltage times 7.5 amperes equal 900 watts. So, the coffee pot is operating near its maximum rating.



COFFEE MAKER
MODEL: SKX20
900WATTS 120VAC 60Hz 7.5AMPS
DO NOT IMMERSE IN ANY LIQUID
FOR HOUSEHOLD USE ONLY

Similarly, a **microwave**, which is rated at 13 amps, has some background power about 1.5 watts, and then goes much higher to 1,691 watts when in use.



INPUT 120V AC 60Hz SINGLE PHASE
•2450MHz •RATED 13 A

Finally, **refrigerator** is a bit more tricky because while there's an amperage rating on the refrigerator, it cycles **on** and **off** with the **compressor**, as well as when the **light** goes **on** and **off** with the **door open**. So, it goes very low when the light is off, and then it goes slightly higher when the incandescent **light bulb** turns on and the doors open to **94.5 watts**. The power then goes much higher to **880 watts** at the peak power with the **compressor running**. So, the power consumption is very variable.

In this case, an instantaneous power measurement like we did before is not very informative because consumption ***fluctuate*** so much. In situations like these, finding published annual energy consumption data from the manufacturer or a third-party site like ***Energy Star*** (www.energystar.gov), would be more accurate.

Calculations From Web Sources:

List and show at least 10 items (Home and Commercial) from energy star website with screenshots.

Conclusion and Comments: