The other method of harnessing solar power: direct conversion to electric power using photovoltaic (PV) panels

The Concentrated Solar Power technology we talked about at the last two classroom session is one method of converting solar power to electric power, but an indirect method, involving two intermediate steps:

- First, solar power is converted to thermal power;
- Next, thermal power is converted to mechanical power, by means of a heat engine (usually, a steam turbine).

And only then the mechanical power is converted to electric power, by means of an electric generator.

In contrast, photovoltaic panels are devices that convert solar power directly to electric current, without any intermediate steps. The panels are made of semiconducting materials, such as silicon (Si), cadmium telluride (CdTe), gallium arsenide (GaAs) – they have been used for making photovoltaic cells for several decades – and quite recently, new technologies have emerged, based on organic compounds, and on the "youngest" group, namely, of semiconductor materials known as "perovskites".

In the past years, I started lecturing about "photovoltaic panels" with a brief (~1 - 1½ class hour) introduction to semiconductor physics. The thing is that the crucial element of all PV cells, no matter of which material they are made of, is something called a *p-n junction*. It's an area which forms when two types of semiconductors, one of *p-type*, and the other of *n-type*, are brought in contact. So, the introduction has to begin with an explanation of the "natural" electronic structure of a semiconductor, and an explanation why such material **does not** conduct electric current. Next, comes an explanation of how this structure can be artificially modified to obtain either an *n-type* material, or a *p-type* one. When modified one way or the other, such materials become conductors – although not as good as metals, which are "canonical conductors", and therefore the prefix *semi-* in the name, which is derived from a Latin word meaning "so-so-", "almost-", or "pretending to be a-". Anyway, poorly but poorly, they **do** conduct electric currents.

Now, one has to explain **how** they do that. And for the *n-type* it is simpler, because in them it's **mobile electrons** which do the job – in a similar way as in metals (there is simply much less electrons in semiconductors than in a metal, and hence their "poorer" conductivity). But with the *p-type* guys things are more tricky, because here the carriers of current are *holes* – micro-objects that are mobile, but, in contrast to electrons they carry a *positive* charge. So, another challenge emerges for the instructor – namely, to explain "what the hell those holes are" – and this is not a completely trivial task, believe me!

Well, only after completing the above task, one can start talking about "what happens, if an *n-type* and a *p-type* meet" – another not-so-trivial task -- and only then, finally, explain why if a *p-n junction* is illuminated by solar light, it will produce an electric current flowing from the "p-type" side of the junction to the "n-type" side.

But after going through all the above explanations in Ph313 courses taught for several consecutive years, I reached a "second thought" – is it really necessary?

Well, I decided that a better approach in the Ph313 course would be to present a much simplified model of what is happening "inside" a solar cell – and then focus the attention on things that are really important for prospective users of PV panels, such as: (a) the efficiency of various types of PV cells, (b) recent progress in research on new types and improving the existing types, (c) marketing issues – what are the current prices, and, especially, the efficiency/price correlations, and (d), very important, what one needs to do with the electricity coming out from the CV panels – before one can start using it, it must be further processed (the output current from a PC cell is not exactly like the current you take from a standard 115V wall outlet!).

So – **a simple-minded theory of semiconductors.** If you are interested in a more serious presentation of the topic, I encourage you to look at this Power Point presentation I used in the Ph313 Course until Spring 2015; the story about electrons and holes in semiconductors in this PPT slide show is based on the famous "parking garage model", authored by William Shockley (a gentleman who was a co-recipient of the Nobel Prize for the invention ot transistors). Also, I encourage you to perform your own search in the Web. For a more ambitious reading, you may try this article from Berkley University.

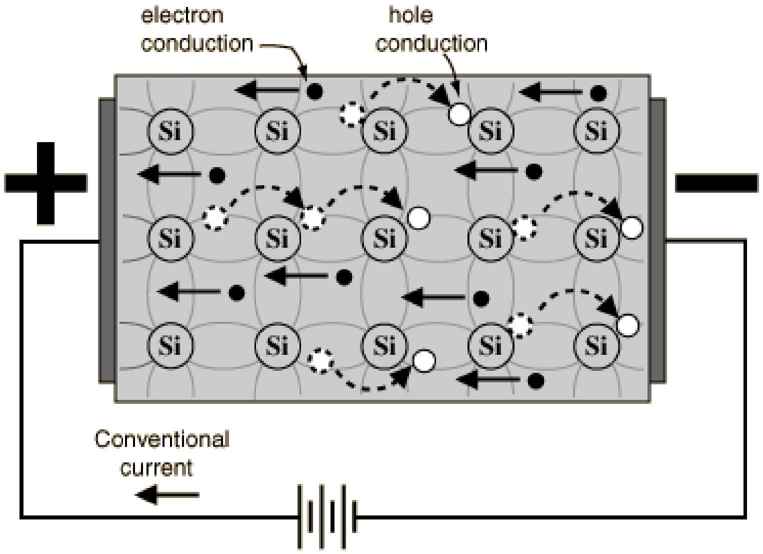
But here is the simple-minded theory (necessarily, to make it simple, we'll need to use some **simplifications** – but I'll try not to drift too far away from the orthodox theory). Let's begin with metals -- in typical metals, which are good conductors of electric current, the electrons occupying the outermost orbits of atoms, leave their "parent" atoms and form an "electron gas" inside the metal – a special gas, called the "Fermi

Gas”. If a voltage is applied to such a system, the electrons start drifting in a direction that lowers their potential energy – and this drifting motion is exactly what we call “a current”.

In semiconductors, however the electrons are not so eager to leave their “parent” atoms. They may be **persuaded** to do so by various means – and then they form an “electron gas”, but much less dense than the Fermi gas in typical metals. Less dense, and therefore such a system is not a “conductor”, but only a “semi-conductor”.

Now, about those mysterious “holes”. An atom, as you surely know, consists of a positive nucleus in its center, and of an outside part, consisting of number of electrons. By physicists, this outside part is often called the “electron shell”. Well, imagine that an electron is forced to leave its parent atom. So, the “shell” is now incomplete – one can think of it as a shell in which there is a “hole”.

Good. But such “holes” are connected with their atoms – and atoms in a solid cannot move, so how can they become “carriers” of electric current? Well, the thing is that they can (Yes, we can! – responds a chorus of holes). It’s how it works: suppose that a hole is “punched” in the shell of Atom A. And Atom A’s neighbor is Atom B. Now, an electron from Atom B “jumps” into the hole in Atom A’s shell – so, there is no longer a hole in A’s shell – it has moved to B’s shell. Now, an electron from Atom C jumps into the hole in B’s shell, and plugs it – so the hole has moved to C. And so on, and so on – the hole propagates through a chain of atoms. And such a drift along a chain of atoms is equivalent to a motion of a **positive** charge along the chain.



Now, suppose that a semiconductor is illuminated by solar light. Light, as you of course know, is a stream of particle-like microobjects, called “photons”. We say “particle-like”, because, in contrast to “regular” particles, they do not have mass: a photon is a miniature packet of pure energy. And this energy can be converted to work – and one possible kind of such work is “kicking an electron out of its parent atom”. The photon disappears, and instead, there is a “pair”: (a free electron) + (a hole). It’s called a “photoelectric effect”.

O.K. – but it’s not enough, the free electrons and the holes created by sunlight have to be somehow forced to form an electric current .   And here is where the “p-n junction”, mentioned a moment ago, “enters the stage”. Let me skip the details – if you wish to learn more about a p-n junction, please look at the Web links that are given at the beginning of this text. Here I will use only a “pedagogical analogy”. Consider a glass of carbonated water – if you drop into it a few grain of sand, they will sink, or “travel downwards”, right? But the bubbles of gas, which can be thought of as “holes in the water”, will “travel upwards”. These are the effect of gravitational field in which the glass is “embedded” (as is also everything around it), combined with the Archimedes Law.

The effects of a p-n junction on mobile electrons and on the holes are similar. Here it’s not the gravitational field, but an *electric field* that arises in such junction (physicist often use the terms “built-in field” or “built-I b voltage”). Mobile electrons created by the photoelectric effect will “sink”, i.e., they will move one way, and the holes will travel in the opposite direction. So, if the p-n junction is illuminated by many photons, what is created? – two currents, a current of electrons flowing in one direction, and a current of holes flowing in the opposite direction. All what one needs to do now is to attach wires on both sides of the p-n junction, to collect these currents, and send them away!

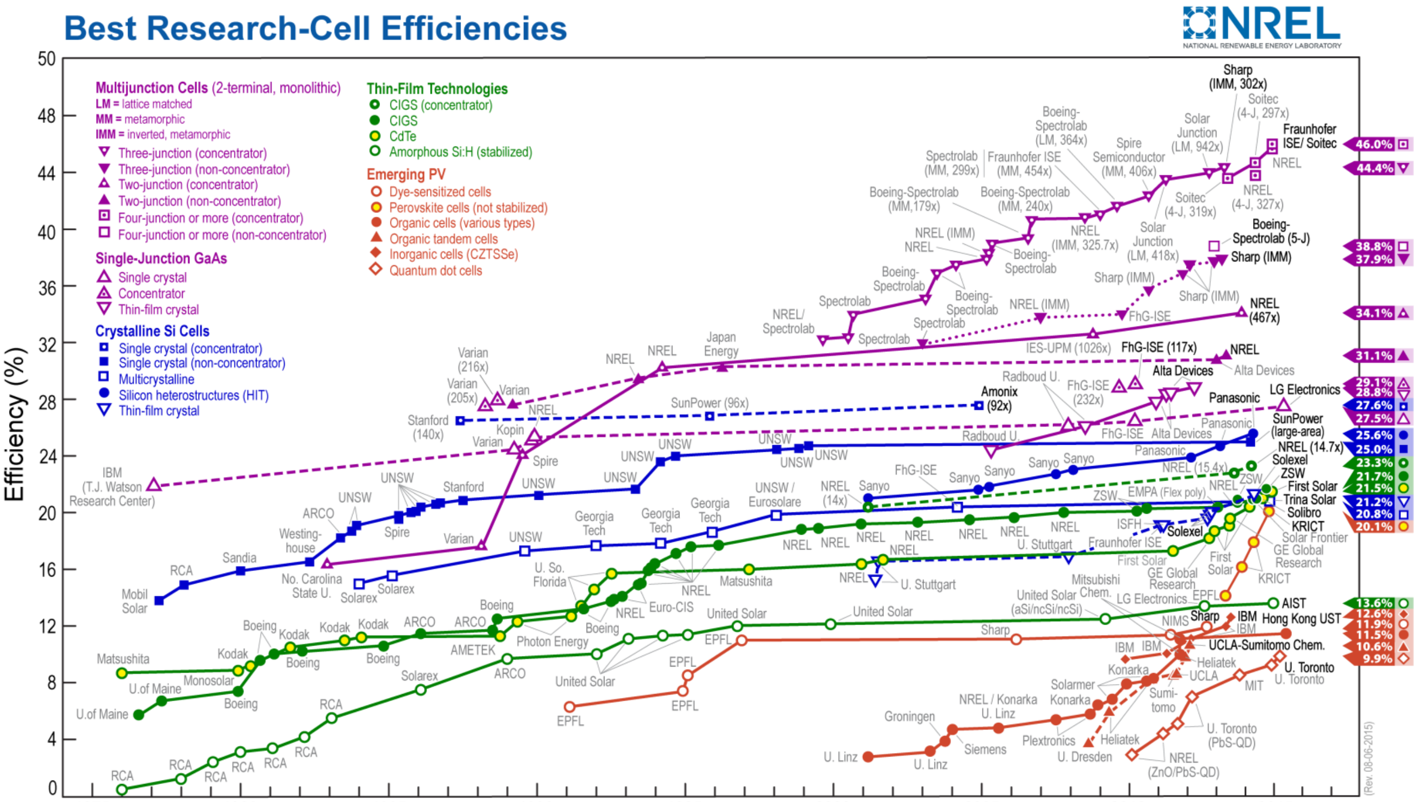
“External parameters” of PV panels, essential for users.

It’s all the story of “what is going on inside a solar cell” I wanted to pass to you. And now, let’s focus on “external properties” of such cells – properties that are important for potential users. One very important property of a PV cell is its efficiency – i.e., how much power of the impinging solar light is converted to electric power.

The most popular PV cells are those made of silicon (Si). The technology is well-established. The main manufacturer of Si PV cells is now China, which has developed a mass-production of reliable panels with efficiency about 15%. The mass-production of anything has always a beneficial effect, i.e., a steady decline of prices. In the case of PV panels, the price is usually expressed in “Dollars per one Watt of output power” unit. The graph in this Wikipedia article illustrates the drop of prices over the period of last 40 years: in 1977 it was $77/Watt, and currently it is as low as $0.30/Watt. However, it's the price of a **single cell**, usually prepared on a Si "wafer" of 2 inch diameter. Such cells have to be combined in larger assemblies to become "panels" – and it adds about $0.16/W – anyway, the net price may be still lower that $0.50/W.

Buying the panels is not all you need for making a "solar roof" in your home – you have to add installation costs. Years ago, in the $76/W period such costs were considerably lower that the price of the panels alone – but the installation costs did not drop about 150 times as panel costs did, and now they are the dominant part of the total cost, about 4 times higher than the panels – which makes the total cost about $2,50/Watt.

Yet, the costs may still keep decreasing, because more and more cells of higher efficiency arrive on the market, or are poised to enter the market in a near future. Better than with words, the progress may be shown by presenting a graph in which the systematic growth of efficiency over years is shown for a number of cell types – the curve for each type is plotted by a different color, and the whole figure looks like a plate of spaghetti:



Well, the graph shows that the situation is still very dynamic and the market may keep changing in a fast rate in the years to come. Therefore, if you think of installing a “solar roof” at some time in the future, it surely would be a good idea to keep observing the tendencies – there is plenty of such info in the Web.

If the panels are already on the roof, what next?

Electricity from PV panels cannot be used right away, because it is not compatible with the installation at home and with the “needs” of all appliances. The output from a panel system is a “direct current” (DC)– it means that one terminal will always be the “positive”, or “the plus” one, and the other will always be the “negative”, or “the minus” one. In addition, the voltage may change, depending on the amount of impinging sunlight.

In contrast, the “standard product” the utility company delivers to home installations is **alternating current** (AC). In a wall outlet, the polarity changes 120 times per second: if a “slot” in the wall outlet is a “plus” at one moment, it will become a “minus” after 1/120 second, and a “plus” again after another 1/120 second. Why it is so? OK, this is the later Dr. Nicola Tesla who has to be “blamed” for it! He waged a long war with Thomas Edison, who preferred direct current in home installations. Edison was a genius, no doubt – but even geniuses make mistakes. It is very difficult to send DC power over large distances, whereas AC power is very well suited for this purpose. If Edison’s vision prevailed, we would not have the nationwide power grid today. And wahat are the benefits of such a grid? – there will be a special lecture hour on this topic toward the end of our course.

As follows from the above, there should be a component that convert the DC output of varying voltage from PV panels to 60 Hz AC power with constasnt voltage of 115 V. Then the “solar roof” can work in parallel with the home installation. In times when there is plenty of sunshine, the home installation will be fed by the PV system – and when there is no sunlight, the installation will drag power from the normal utility company delivery system. It’s also possible that if there is “too much” sunshine than needed for satisfying all needs at home (such as the refrigerator, A/C system, laundy machine, home computers, TV sets, etc.), the “surlplus” may be sent back to the utility company grid, and the company may pay for such power. The “gizmo” that one needs for making the output from the PV panels compatible with the standard home installation is called an “inverter”. Forty years ago, when first PV panels started emerging at roofs, an inverter was a huge and very hefty device -- with a mass of about 20 kg for every kW of converted power. Also, the price was pretty hefty. Fortunately, due to the progress in electronics, such gizmos have become much lighter and much less expensive – below, there is a picture from the Web, showing a modern 5 kW inverter :

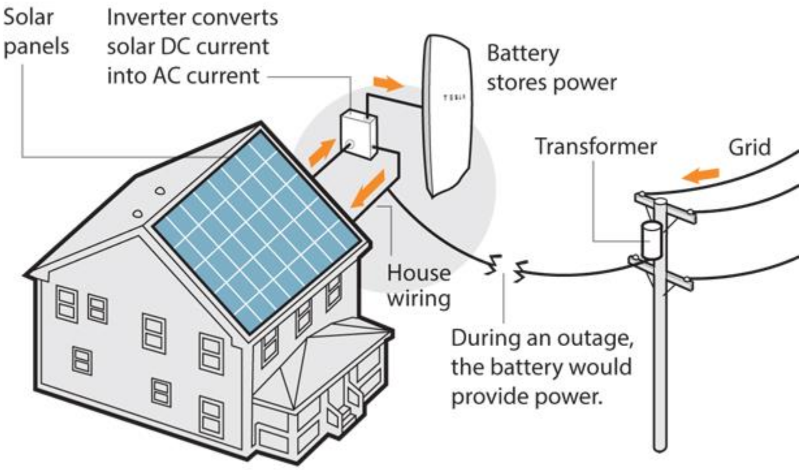
Its weight is only about 7 kg, and its sale price is advertised as $399.

If the home sunroof generates more power, than needed, selling the “surplus” to the utility company is one option – but what more and more people do now is “storing” such surplus in a battery. The power from the battery may be then used after the sunset. There is a variety of battery types one can use – old-fashioned lead-acid batteries perform pretty well (one should remember, though, that standard car batteries cannot be used for this purpose – one needs special “deep-discharge” batteries which are 2-3 times more expensive than car batteries). Elon Musk’s “Tesla” company now offers a choice of very modern Lithium-ion super-duper storage batteries called “Power-Wall”, capable of storing 5-10 kWh of energy.

Below, there is a scheme of an installation utilizing a storage battery. It’s a good non-nonsense picture – I would only add one small orange-colored arrow pointing to the **right,** above the cable connecting the “House wiring” with the “Transformer” -- to indicate that such a system may also be capable of sending power back to the grid.

How Powerwall will work

Tesla introduced a new battery system that can draw power from home solar panels or the grid to use during electrical outages. The battery is the size of a suitcase and can be mounted to an indoor or outdoor wall. It holds up to 10 kilowatt-hours of energy, about one-third of what the average U.S household uses per day.



Sources: SolarCity, Tesla, U.S. Energy Information Administration, staff reports
THE WASHINGTON POST

About storage batteries, we will have a longer session on them later in the course.