Photovoltaic Cell

1. Introduction

What is solar energy?

The sun has produced energy for billions of years. Solar energy is the sun's rays (solar radiation) that reach the earth. On a bright, sunny day, the sun shines approximately 1,000 watts of energy per square meter of the planet's surface, and if we could collect all of that energy we could easily power our homes and offices for free.

Solar energy can be converted into other forms of energy, such as heat and electricity. **In the 1830s, the British astronomer John Herschel** used a solar thermal collector box (a device that absorbs sunlight to collect heat) to cook food during an expedition to Africa. Today, people use the sun's energy for lots of things.

Solar energy can be Converted into other form of energy?

Solar energy can be converted to ***thermal (or heat) energy*** *and used to*:

- Heat water – for use in homes, buildings, or swimming pools.
- Heat spaces – inside greenhouses, homes, and other buildings.

Solar energy can be converted to electricity in two ways:

Photovoltaic (PV devices) or "solar cells" – change sunlight directly into electricity. The photovoltaic cell was discovered in 1954 by Bell Telephone researchers examining the sensitivity of a properly prepared silicon wafer to sunlight. Beginning in the late 1950s, photovoltaic cells were used to power U.S. space satellites. The success of PV in space generated commercial applications for this technology. The simplest photovoltaic systems power many of the small calculators and wrist watches used everyday. More complicated systems provide electricity to pump water, power communications equipment, and even provide electricity to our homes.

- **Solar Power Plants -** indirectly generate electricity when the heat from solar thermal collectors is used to heat a fluid which produces steam that is used to power generator. Out of the 15 known solar electric generating units operating in the United States at the end of 2006, 10 of these are in California, and 5 in Arizona. No statistics are being collected on solar plants that produce less than 1 megawatt of electricity, so there may be smaller solar plants in a number of other states.

How does a solar panel look?

Photo courtesy DOE/NREL
Photo credit SunLine Transit Agency
Solar panels absorb energy to produce hydrogen at SunLine Transit Agency.

The major disadvantages of solar energy are:

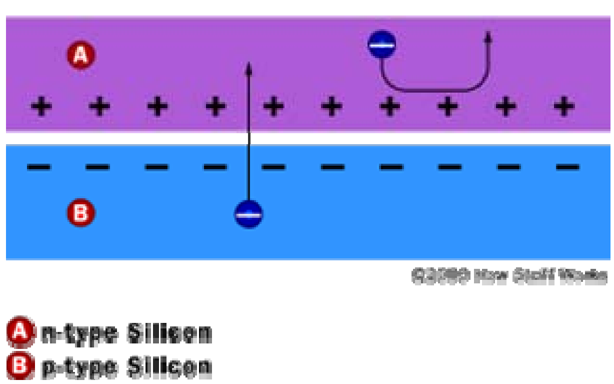
- The amount of sunlight that arrives at the earth's surface is not constant. It depends on location, time of day, time of year, and weather conditions.
- Because the sun doesn't deliver that much energy to any one place at any one time, a large surface area is required to collect the energy at a useful rate.

2. How des the photovoltaic cell work?

A photovoltaic cell, commonly called a solar cell or PV, is the technology used to convert solar energy directly into electrical power. A photovoltaic cell is a non mechanical device usually made from silicon alloys.

Sunlight is composed of photons, or particles of solar energy. These photons contain various amounts of energy corresponding to the different wavelengths of the solar spectrum. When photons strike a photovoltaic cell, they may be reflected, pass right through, or be absorbed. Only the absorbed photons provide energy to generate electricity.

Silicon crystals are all electrically neutral. In n-type Si our extra electrons are balanced out by the extra protons in the phosphorous. In p-type Si missing electrons (holes) were balanced out by the missing protons in the boron. When the holes and electrons mix at the **junction** between N-type and P-type silicon, however, that neutrality is disrupted. Do all the free electrons fill all the free holes? No. If they did, then the whole arrangement wouldn't be very useful. Right at the junction, however, they do mix and form a barrier, making it harder and harder for electrons on the N side to cross to the P side. Eventually, equilibrium is reached, and we have an electric field separating the two sides.



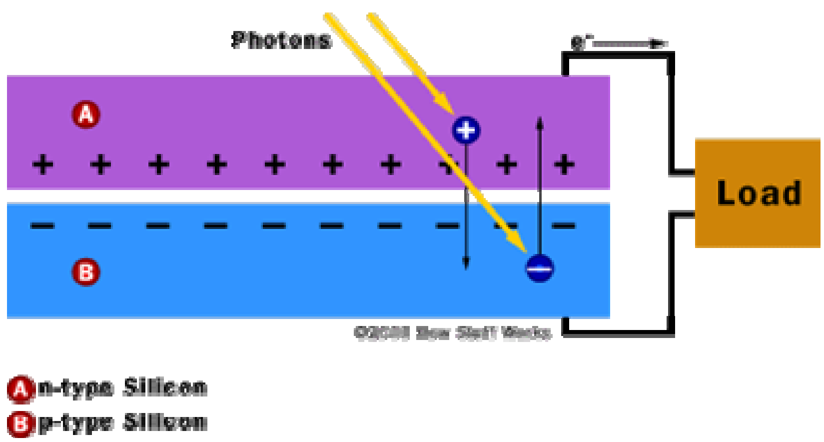
The effect of the electric field in a PV cell

This electric field acts as a diode, allowing (and even pushing) electrons to flow from the P side to the N side, but not the other way around. It's like a hill -- electrons can easily go down the hill (to the N side), but can't climb it (to the P side).

So we've got an electric field acting as a diode in which electrons can only move in one direction.

When light, in the form of photons, hits our solar cell, its energy frees electron-hole pairs.

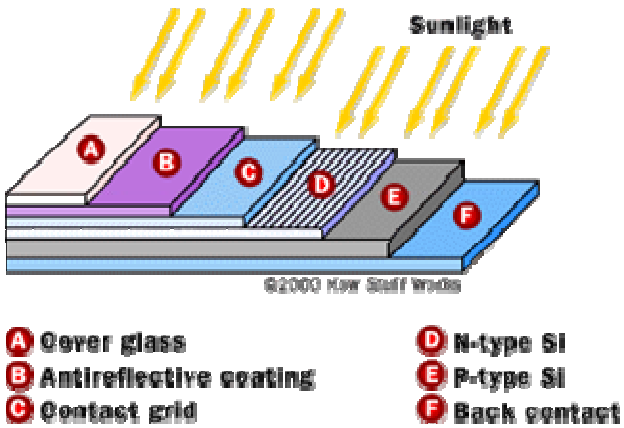
Each photon with enough energy will normally free exactly one electron, and result in a free hole as well. If this happens close enough to the electric field, or if free electron and free hole happen to wander into its range of influence, the field will send the electron to the N side and the hole to the P side. This causes further disruption of electrical neutrality, and if we provide an external current path, electrons will flow through the path to their original side (the P side) to unite with holes that the electric field sent there, doing work for us along the way. The electron flow provides the **current**, and the cell's electric field causes a **voltage**. With both current and voltage, we have **power**, which is the product of the two.



Operation of a PV cell

There are a few more steps left before we can really use our cell. Silicon happens to be a very shiny material, which means that it is very reflective. Photons that are reflected can't be used by the cell. For that reason, an **antireflective coating** is applied to the top of the cell to reduce reflection losses to less than 5 percent.

The final step is the **glass cover plate** that protects the cell from the elements. PV modules are made by connecting several cells (usually 36) in series and parallel to achieve useful levels of voltage and current, and putting them in a sturdy frame complete with a glass cover and positive and negative terminals on the back.



Basic structure of a generic silicon PV cell

The performance of a photovoltaic array is dependent upon sunlight. Climate conditions (e.g., clouds, fog) have a significant effect on the amount of solar energy received by a photovoltaic array and, in turn, its performance. Most current technology photovoltaic modules are about 10 percent efficient in converting sunlight. Further research is being conducted to raise this efficiency to 20 percent.

Besides Single-crystal Silicon...

Single-crystal silicon isn't the only material used in PV cells. Polycrystalline silicon is also used in an attempt to cut manufacturing costs, although resulting cells aren't as efficient as single crystal silicon. Amorphous silicon, which has no crystalline structure, is also used, again in an attempt to reduce production costs. Other materials used include gallium arsenide, copper indium diselenide and cadmium telluride. Since different materials have different band gaps, they seem to be "tuned" to different wavelengths, or photons of different energies. One way **efficiency** has been improved is to use two or more layers of different materials with different band gaps. The higher band gap material is on the surface, absorbing high-energy photons while allowing lower-energy photons to be absorbed by the lower band gap material beneath. This technique can result in much higher efficiencies. Such cells, called **multi-junction cells**, can have more than one electric field.

Some advantages of photovoltaic systems are:

1. Conversion from sunlight to electricity is direct, so that bulky mechanical generator systems are unnecessary.
2. PV arrays can be installed quickly and in any size required or allowed.
3. The environmental impact is minimal, requiring no water for system cooling and generating no by-products.

Photovoltaic cells, like batteries, generate direct current (DC) which is generally used for small loads (electronic equipment). When DC from photovoltaic cells is used for commercial applications or sold to electric utilities using the electric grid, it must be converted to alternating current (AC) using inverters, solid state devices that convert DC power to AC.

Energy Loss in a Solar Cell

Visible light is only part of the electromagnetic spectrum. Electromagnetic radiation is not monochromatic -- it is made up of a range of different wavelengths, and therefore energy levels.

Since the light that hits our cell has photons of a wide range of energies, it turns out that some of them won't have enough energy to form an electron-hole pair.

They'll simply pass through the cell as if it were transparent. Still other photons have too much energy. Only a certain amount of energy, measured in electron volts (eV) and defined by our cell material (about 1.1 eV for crystalline silicon), is required to knock an electron loose. We call this the **band gap energy** of a material. If a photon has more energy than the required amount, then the extra energy is lost (unless a photon has twice the required energy, and can create more than one electron-hole pair, but this effect is not significant). These two effects alone account for the loss of around 70 percent of the radiation energy incident on our cell.

Why can't we choose a material with a really low band gap, so we can use more of the photons? Unfortunately, our band gap also determines the strength (voltage) of our electric field, and if it's too low, then what we make up in extra current (by absorbing more photons), we lose by having a small voltage. Remember that power is voltage times current. The optimal band gap, balancing these two effects, is around **1.4 eV** for a cell made from a single material.

We have other losses as well. Our electrons have to flow from one side of the cell to the other through an external circuit. We can cover the bottom with a metal, allowing for good conduction, but if we completely cover the top, then photons can't get through the opaque conductor and we lose all of our current (in some cells, transparent conductors are used on the top surface, but not in all). If we put our contacts only at the sides of our cell, then the electrons have to travel an extremely long distance (for an electron) to reach the contacts. Remember, silicon is a semiconductor -- it's not nearly as good as a metal for transporting current. Its internal resistance (called **series resistance**) is fairly high, and high resistance means high losses. To minimize these losses, our cell is covered by a metallic contact grid that shortens the distance that electrons have to travel while covering only a small part of the cell surface. Even so, some photons are blocked by the grid, which can't be too small or else its own resistance will be too high.

Now that we know how a solar cell operates, let's see what it takes to power a house with the technology

Solar-powering a House

What would you have to do to power your house with solar energy? Although it's not as simple as just slapping some modules on your roof, it's not extremely difficult to do, either.

First of all, not every roof has the correct **orientation** or **angle of inclination** to take advantage of the sun's energy. Non-tracking PV systems in the Northern Hemisphere should point toward true south (this is the orientation). They should be inclined at an angle equal to the area's latitude to absorb the maximum amount of energy year-round. A different orientation and/or inclination could be used if you want to maximize energy production for the morning or afternoon, and/or the summer or winter. Of course, the modules should never be shaded by nearby trees or buildings, no matter the time of day or the time of year. **In a PV module, even if just one of its 36 cells is shaded, power production will be reduced by more than half.**

If you have a house with an unshaded, south-facing roof, you need to decide what size system you need. This is complicated by the facts that your electricity production depends on the weather, which is never completely predictable, and that your electricity demand will also vary. These hurdles are fairly easy to clear. **Meteorological data** gives average monthly sunlight levels for different geographical areas. This takes into account rainfall and cloudy days, as well as altitude, humidity, and other more subtle factors. You should design for the worst month, so that you'll have enough electricity all year. With that data, and knowing your average household demand (your utility bill conveniently lets you know how much energy you use every month),there are simple methods you can use to determine just how many PV modules you'll need. You'll also need to decide on a system voltage, which you can control by deciding how many modules to wire in series.

You may have already guessed a couple of problems that we'll have to solve. First, what do we do when the sun isn't shining?

Solving Solar-power Issues

Certainly, no one would accept only having electricity during the day, and then only on clear days, if they have a choice. We need **energy storage** -- batteries. Unfortunately, batteries add a lot of cost and maintenance to the PV system. Currently, however, it's a necessity if you want to be completely independent. One way around the problem is to connect your house to the utility grid, buying power when you need it and selling to them when you produce more than you need. This way, the utility acts as a practically infinite storage system. The utility has to agree, of course, and in most cases will buy power from you at a much lower price than their own selling price. You will also need special equipment to make sure that the power you sell to your utility is synchronous with theirs -- that it shares the same sinusoidal waveform and frequency. Safety is an issue as well. The utility has to make sure that if there's a power outage in your neighborhood, your PV system won't try to feed electricity into lines that a lineman may think is dead. This is called **islanding**.

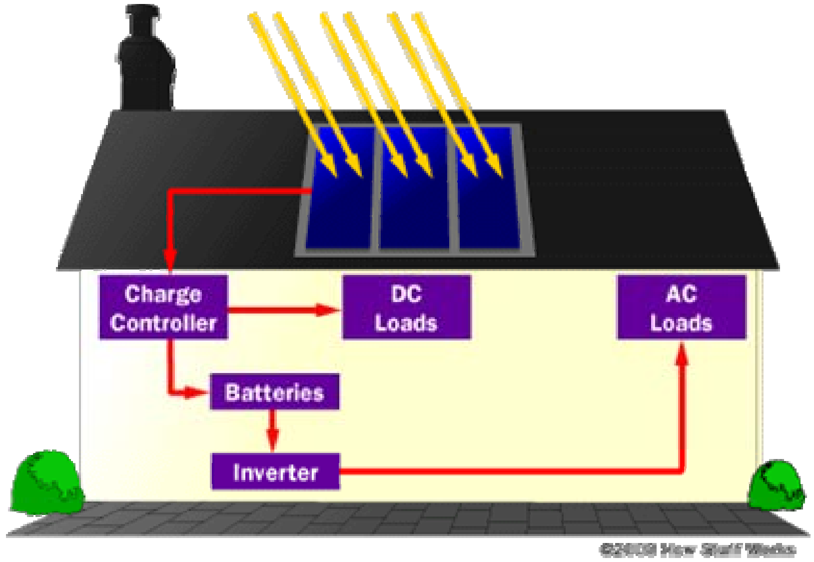
If you decide to use batteries, keep in mind that they will have to be maintained, and then replaced after a certain number of years. The PV modules should last 20 years or more, but batteries just don't have that kind of useful life. Batteries in PV systems can also be very dangerous because of the energy they store and the acidic electrolytes they contain, so you'll need a well-ventilated, non-metallic enclosure for them.

Although several different kinds of batteries are commonly used, the one characteristic they should all have in common is that they are **deep-cycle batteries**. Unlike your car battery, which is a shallow-cycle battery, deep-cycle batteries can discharge more of their stored energy while still maintaining long life. Car batteries discharge a large current for a very short time -- to start your car -- and are then immediately recharged as you drive. PV batteries generally have to discharge a smaller current for a longer period (such as all night), while being charged during the day.

The most commonly used deep-cycle batteries are **lead-acid** batteries (both sealed and vented) and **nickel-cadmium** batteries. Nickel-cadmium batteries are more expensive, but last longer and can be discharged more completely without harm. Even deep-cycle lead-acid batteries can't be discharged 100 percent without seriously shortening battery life, and generally, PV systems are designed to discharge lead-acid batteries no more than 40 percent or 50 percent.

Also, the use of batteries requires the installation of another component called a **charge controller**. Batteries last a lot longer if care is taken so that they aren't overcharged or drained too much. That's what a charge controller does. Once the batteries are fully charged, the charge controller doesn't let current from the PV modules continue to flow into them. Similarly, once the batteries have been drained to a certain predetermined level, controlled by measuring battery voltage, many charge controllers will not allow more current to be drained from the batteries until they have been recharged. The use of a charge controller is essential for long battery life.

The other problem besides energy storage is that the electricity generated by your PV modules, and extracted from your batteries if you choose to use them, is not in the form that's used by the electrical appliances in your house. The electricity generated by a solar system is direct current, while the electricity supplied by your utility (and the kind that every appliance in your house uses) is alternating current. You will need an **inverter**, a device that converts DC to AC. Most large inverters will also allow you to automatically control how your system works. Some PV modules, called **AC modules**, actually have an inverter already built into each module, eliminating the need for a large, central inverter, and simplifying wiring issues.



General schematic of a residential PV system with battery storage

Throw in the mounting hardware, wiring, junction boxes, grounding equipment, overcurrent protection, DC and AC disconnects and other accessories and you have yourself a system. Electrical codes must be followed (there's a section in the National Electrical Code just for PV), and it's highly recommended that the installation be done by a licensed electrician who has experience with PV systems. Once installed, a PV system requires very little maintenance (especially if no batteries are used), and will provide electricity cleanly and quietly for 20 years or more.

If photovoltaics are such a wonderful source of free energy, then why doesn't the whole world run on solar power?

Solar-power Costs

Some people have a flawed concept of solar energy. While it's true that sunlight is free, the electricity generated by PV systems is not. As you can see from our discussion of a household PV system, quite a bit of hardware is needed. Currently, an installed PV system will cost somewhere around **$9 per peak Watt**. To give you an idea of how much a house system would cost, let's consider the Solar House -- a model residential home in Raleigh, North Carolina, with a

PV system set up by the North Carolina Solar Center to demonstrate the technology. It's a fairly small home, and it is estimated that its 3.6-kW PV system covers about half of the total electricity needs (this system doesn't use batteries -- it's connected to the grid). Even so, at $9 per Watt, this installed system would cost you around $32,000.

That's why PV is usually used in remote areas, far from a conventional source of electricity. Right now, it simply can't compete with the utilities. Costs are coming down as research is being done, however. Researchers are confident that PV will one day be cost effective in urban areas as well as remote ones. Part of the problem is that manufacturing needs to be done on a large scale to reduce costs as much as possible. That kind of demand for PV, however, won't exist until prices fall to competitive levels. It's a Catch-22 situation. Even so, demand and module efficiencies are constantly rising, prices are falling, and the world is becoming increasingly aware of environmental concerns associated with conventional power sources, making photovoltaics a technology with a bright future