Solar Power and Photovoltaics Explained

Solar Energy Solutions for the Future

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SOLAR POWER

Photovoltaic (PV) technology makes use of the abundant energy in the sun, and it has little impact on our environment. Photovoltaics can be used in a wide range of products, from small consumer items to large commercial solar electric systems.

PV Physics

What do we mean by *photovoltaics*? First used in about 1890, the word has two parts: *photo*, derived from the Greek word for light, and *volt*, relating to electricity pioneer Alessandro Volta. So, *photovoltaics* could literally be translated as *light-electricity*. And that's what photovoltaic (PV) materials and devices do — they convert light energy into electrical energy (Photoelectric Effect), as French physicist Edmond Becquerel discovered as early as 1839.

Commonly known as *solar cells*, individual PV cells are electricity-producing devices made of semiconductor materials. PV cells come in many sizes and shapes — from smaller than a postage stamp to several inches across. They are often connected together to form PV *modules* that may be up to several feet long and a few feet wide. Modules, in turn, can be combined and connected to form PV *arrays* of different sizes and power output.

The size of an array depends on several factors, such as the amount of sunlight available in a particular location and the needs of the consumer. The modules of the array make up the major part of a PV *system*, which can also include electrical connections, mounting hardware, power-conditioning equipment, and batteries that store solar energy for use when the sun isn't shining.

Did you know that PV systems are already an important part of our lives? Simple PV systems provide power for many small consumer items, such as calculators and wristwatches. More complicated systems provide power for communications satellites, water pumps, and the lights, appliances, and machines in some people's homes and workplaces. Many road and traffic signs along highways are now powered by PV. In many cases, PV power is the least expensive form of electricity for performing these tasks.

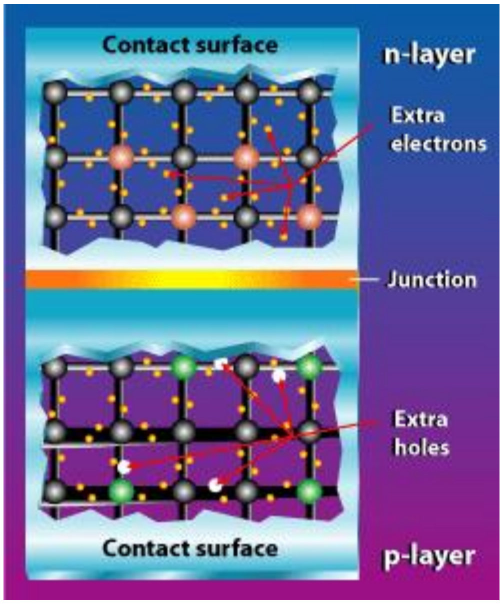
The Photoelectric Effect

To broaden their scientific perspective on a new generation of silicon PV devices, the U.S. Department of Energy's National Renewable Energy Laboratory has pioneered a new class of materials — **microcrystalline silicon alloys** — which may have application in the photovoltaic and microelectronics industries. To date, the scientists have deposited and characterized 50 microcrystalline silicon films.

In 1839, Edmond Becquerel discovered the process of using sunlight to produce an electric current in a solid material. But it took more than another century to truly understand this process. Scientists eventually learned that the photoelectric or photovoltaic (PV) effect caused certain materials to convert light energy into electrical energy at the atomic level.

The photoelectric effect is the basic physical process by which a PV cell converts sunlight into electricity. When light shines on a PV cell, it may be reflected, absorbed, or pass right through. But only the absorbed light generates electricity.

The energy of the absorbed light is transferred to electrons in the atoms of the PV cell. With their newfound energy, these electrons escape from their normal positions in the atoms of the semiconductor PV material and become part of the electrical flow, or current, in an electrical circuit. A special electrical property of the PV cell—what we call a "built-in electric field"—provides the force, or voltage, needed to drive the current through an external "load," such as a light bulb.



To induce the built-in electric field within a PV cell, two layers of somewhat differing semiconductor materials are placed in contact with one another. One layer is an "n-type" semiconductor with an abundance of electrons, which have a negative electrical charge. The other layer is a "p-type" semiconductor with an abundance of "holes," which have a positive electrical charge.

Although both materials are electrically neutral, n-type silicon has excess electrons and p-type silicon has excess holes. Sandwiching these together creates a p/n junction at their interface, thereby creating an electric field.

When n- and p-type silicon come into contact, excess electrons move from the n-type side to the p-type side. The result is a buildup of positive charge along the n-type side of the interface and a buildup of negative charge along the p-type side.

Because of the flow of electrons and holes, the two semiconductors behave like a battery, creating an electric field at the surface where they meet—what we call the **p/n junction**.

The electrical field causes the electrons to move from the semiconductor toward the negative surface, where they become available to the electrical circuit. At the same time, the holes move in the opposite direction, toward the positive surface, where they await incoming electrons.

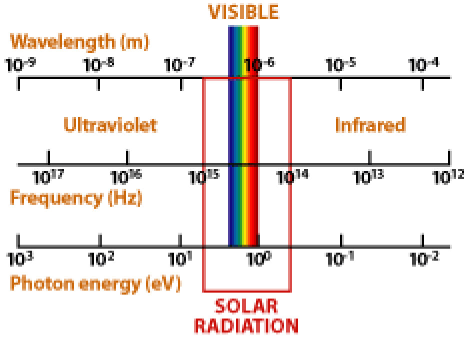
How do we make the p-type ("positive") and n-type ("negative") silicon materials that will eventually become the photovoltaic (PV) cells that produce solar electricity? Most commonly, we add an element to the silicon that either *has* an extra electron or *lacks* an electron. This process of adding another element is called doping.

Light and the PV Cell

We've looked at how to construct a solar cell using crystalline silicon. And we've used this basic type of cell to explain the photoelectric effect, which is the phenomenon operating at the heart of a solar cell. Here, we want to take a look at sunlight, the energy source actually used by solar cells. A brief discussion of several terms will help us better understand aspects of light's interaction with solar cells.

Wavelength, Frequency, and Energy

The energy from the sun is vital to life on Earth. It determines the Earth's surface temperature and supplies virtually all the energy that drives natural global systems and cycles. Some other stars are enormous sources of energy in the form of X-rays and radio signals, but our sun releases the majority of its energy as visible light. However, visible light represents only a fraction of the total spectrum of radiation. Specifically, infrared and ultraviolet rays are also significant parts of the solar spectrum.



The sun emits almost all of its energy in a range of wavelengths from about $2x10^{-7}$ to $4x10^{-6}$ meters. Most of this energy is in the visible light region. Each wavelength corresponds to a frequency and an energy: the shorter the wavelength, the higher the frequency and the greater the energy (which is expressed in electron-volts, or eV). Red light is at the low-energy end of the visible spectrum and violet light is at the high-energy end, where it has half again as much energy as red light. In the invisible portions of the spectrum, radiation in the ultraviolet region, which causes the skin to tan, has more energy than that in the visible region. Likewise, radiation in the infrared region, which we feel as heat, has less energy than the radiation in the visible region.

Solar cells respond differently to the different wavelengths, or colors, of light. For example, crystalline silicon can use the entire visible spectrum, plus some part of the infrared spectrum. But energy in part of the infrared spectrum, as well as longer-wavelength radiation, is too low to produce current flow. Higher-energy radiation can produce current flow, but much of this energy is likewise not usable. In summary, light that is too high or low in energy is not usable by a cell to produce electricity. Rather, it is transformed into heat.

Air Mass

The sun is continually releasing an enormous amount of radiant energy into the solar system. The Earth receives a tiny fraction of this energy; yet, an average of 1367 watts (W) reaches each square meter (m^2) of the outer edge of the Earth's atmosphere. The atmosphere absorbs and reflects some of this radiation, including most X-rays and ultraviolet rays. Still, the amount of the sun's energy that reaches the surface of the Earth every hour is greater than the total amount of energy that the world's human population uses in a year.

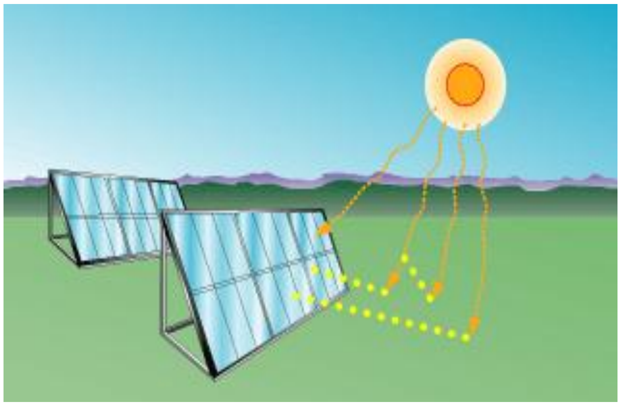
How much energy does light lose in traveling from the edge of the atmosphere to the surface of the Earth? This energy loss depends on the thickness of the atmosphere that the sun's energy must pass through. The radiation that reaches sea level at high noon in a clear sky is 1000 W/m^2 and is described as "air mass 1" (or AM1) radiation. As the sun moves lower in the sky, the light passes through a greater thickness (or longer path) of air, losing more energy. Because the sun is overhead for only a short time, the air mass is normally greater than one—that is, the available energy is less than 1000 W/m^2.

Scientists have given a name to the standard spectrum of sunlight at the Earth's surface: AM1.5G (where G stands for "global" and includes both direct and diffuse radiation, described next) or AM1.5D (which includes direct radiation only). The number "1.5" indicates that the length of the path of light through the atmosphere is 1.5 times that of the shorter path when the sun is directly overhead.

The standard spectrum outside the Earth's atmosphere is called AM0, with no light passing through the atmosphere. AM0 is typically used to predict the expected performance of PV cells in space. The intensity of AM1.5D radiation is approximated by reducing the AM0 spectrum by 28%, where 18% is absorbed and 10% is scattered. The global spectrum is 10% greater than the direct spectrum. These calculations give about 970 W/m^2 for AM1.5G. However, the standard AM1.5G spectrum is "normalized" to give 1000 W/m^2, because of inherent variations in incident solar radiation.

Direct and Diffuse Light

As we have noted, the Earth's atmosphere and cloud cover absorb, reflect, and scatter some of the solar radiation entering the atmosphere. Nonetheless, an enormous amount of the sun's energy reaches the Earth's surface and can therefore be used to produce PV electricity. Some of this radiation is direct and some is diffuse, and the distinction is important because some PV systems (flat-plate systems) can use both forms of light, but concentrator systems can only use direct light.



Flat-plate collectors, which typically contain a large number of solar cells mounted on a rigid, flat surface, can make use of both direct sunlight and the diffuse sunlight reflected from clouds, the ground, and nearby objects.

- Direct light consists of radiation that comes straight from the sun, without reflecting off of clouds, dust, the ground, or other objects. Scientists also talk about direct-normal radiation, referring to the portion of sunlight that comes directly from the sun and strikes the plane of a PV module at a 90-degree angle.
- Diffuse light is sunlight that is reflected off of clouds, the ground, or other objects. It obviously takes a longer path than a direct light ray to reach a module. Diffuse light cannot be focused by the optics of a concentrator PV system.
- Global radiation refers to the total radiation that strikes a horizontal surface. Global sunlight is composed of direct-normal and diffuse components of sunlight. Additionally, diffuse and direct-normal sunlight generally have different energy spectra or distributions of color.

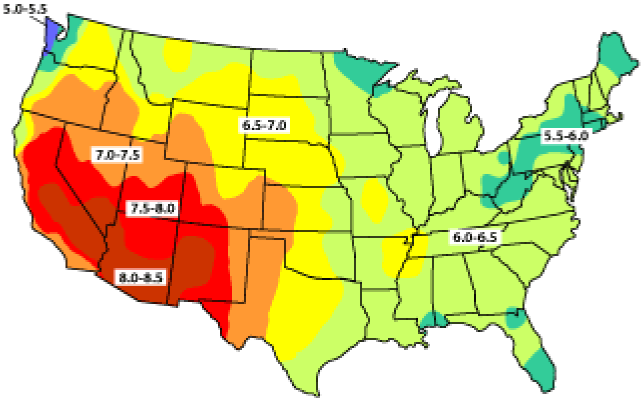
Insolation

The actual amount of sunlight falling on a specific geographical location is known as insolation—or "incident solar radiation." Insolation values for a specific site are sometimes difficult to obtain. Weather stations that measure solar radiation components are located far apart and may not carry specific insolation data for a given site. Furthermore, the information most generally available is the average daily total—or global—radiation on a horizontal surface. To learn more about solar and other resource data, please visit the following Web sites:

Renewable Resource Data Center (RReDC)
The RReDC provides information on several types of renewable energy resources in the United States, in the form of publications, data, and maps.

NASA's Surface Meteorology and Solar Energy Data
This is a renewable energy resource web site sponsored by NASA's Earth Science Enterprise Program that contains over 200 satellite-derived meteorological and solar energy parameters, monthly averaged from 10 years of data, and data tables for a particular location.

When sunlight reaches the Earth, it is distributed unevenly in different regions. Not surprisingly, the areas near the Equator receive more solar radiation than anywhere else on the Earth. Sunlight varies with the seasons, as the rotational axis of the Earth shifts to lengthen and shorten days with the changing seasons. For example, the amount of solar energy falling per square meter on Yuma, Arizona, in June is typically about nine times greater than that falling on Caribou, Maine, in December. The quantity of sunlight reaching any region is also affected by the time of day, the climate (especially the cloud cover, which scatters the sun's rays), and the air pollution in that region. Likewise, these climatic factors all affect the amount of solar energy that is available to PV systems.



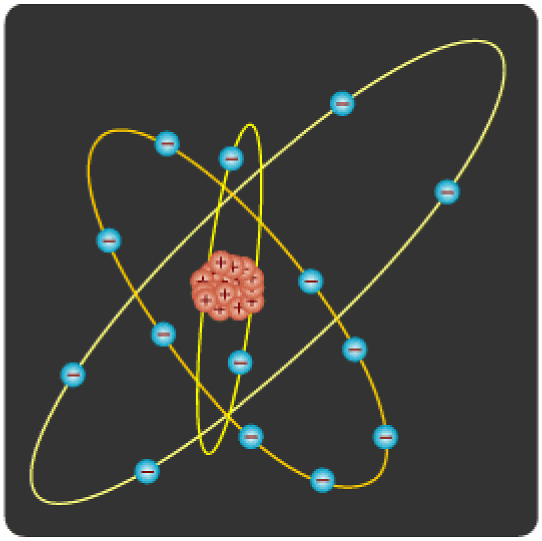
Although the quantity of solar radiation striking the Earth varies by region, season, time of day, climate, and air pollution, the yearly amount of energy striking almost any part of the Earth is vast. Shown is the average radiation received on a horizontal surface across the continental United States in the month of June. Units are in kWh/m^2.

The Crystalline Silicon Solar Cell

PV cells can be made of many different semiconductors. But we'll use crystalline silicon as an example, for three reasons. First, crystalline silicon was the material used in the earliest successful PV devices. Second, and more important, it's still the most widely used PV material. And third, although other PV materials and designs exploit the photoelectric effect in slightly different ways, if you know how the effect works in crystalline silicon, then you'll have a basic understanding of how it works in all PV devices.

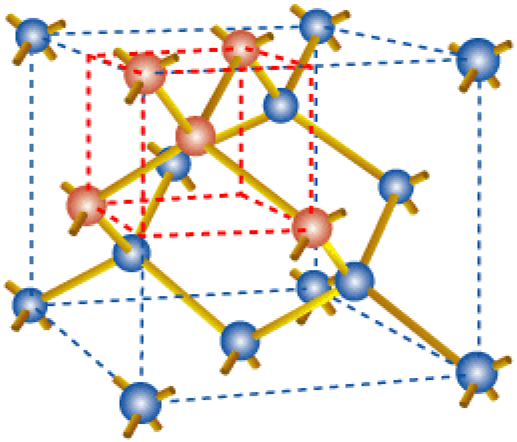
An Atomic Description of Silicon

All matter is composed of atoms, which are made up of positively charged protons, negatively charged electrons, and neutral neutrons. Protons and neutrons, which are about the same size, are in the close-packed, central nucleus of the atom. The much lighter electrons orbit the nucleus. Although atoms are built of oppositely charged particles, their overall charge is neutral because they contain an equal number of positive protons and negative electrons whose charges offset one another.



As depicted in this simplified diagram, silicon has 14 electrons. The four electrons that orbit the nucleus in the outermost "valence" energy level are given to, accepted from, or shared with other atoms.

Electrons orbit at different distances from the nucleus, depending on their energy level. For example, an electron with less energy orbits close to the nucleus, whereas one with greater energy orbits farther away. The higher energy electrons farthest from the nucleus are the ones that interact with neighboring atoms to form solid structures.



In the basic unit of a crystalline silicon solid, a silicon atom shares each of its four valence electrons with each of four neighboring atoms.

A silicon atom has 14 electrons, but their natural orbital arrangement allows only the outermost four electrons to be given to, accepted from, or shared with other atoms. These outermost four electrons, called *valence* electrons, play a very important role in the photoelectric effect.

Large numbers of silicon atoms bond with each other by means of their valence electrons to form a crystal. In a crystalline solid, each silicon atom normally shares one of its four valence electrons in a covalent bond with each of four neighboring silicon atoms. The solid thus consists of basic units of five silicon atoms: the original atom plus the four other atoms with which it shares valence electrons.

The solid silicon crystal is thus made up of a regular series of units of five silicon atoms. This regular, fixed arrangement of silicon atoms is known as the *crystal lattice*.

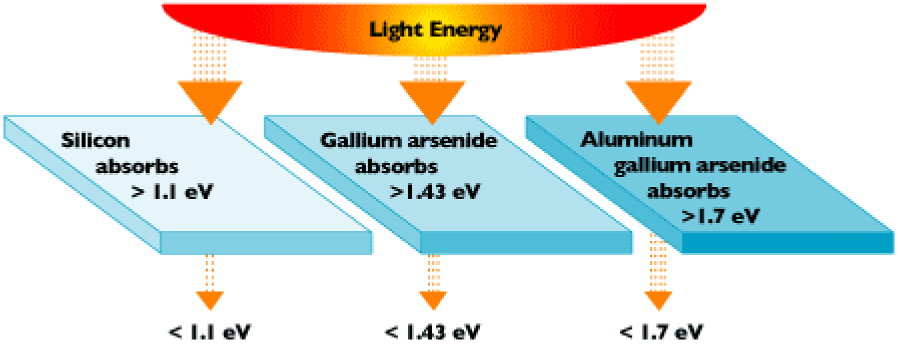
Bandgap Energies of Semiconductors and Light

When light shines on crystalline silicon, electrons within the crystal lattice may be freed. But not all photons — as packets of light energy are called — are created equal. Only photons with a certain level of energy can free electrons in the semiconductor material from their atomic bonds to produce an electric current.

This level of energy, known as the "bandgap energy," is the amount of energy required to dislodge an electron from its covalent bond and allow it to become part of an electrical circuit. To free an electron, the energy of a photon must be at least as great as the bandgap energy. However, photons with more energy than the bandgap energy will expend that extra amount as heat when freeing electrons. So, it's important for a PV cell to be "tuned"—through slight modifications to the silicon's molecular structure—to optimize the photon energy. A key to obtaining an efficient PV cell is to convert as much sunlight as possible into electricity.

Crystalline silicon has a bandgap energy of 1.1 electron-volts (eV). (An electron-volt is equal to the energy gained by an electron when it passes through a potential of 1 volt in a vacuum.) The bandgap energies of other effective PV semiconductors range from 1.0 to 1.6 eV. In this range, electrons can be freed without creating extra heat.

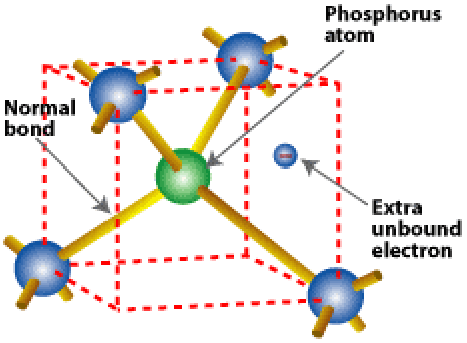
The photon energy of light varies according to the different wavelengths of the light. The entire spectrum of sunlight, from infrared to ultraviolet, covers a range of about 0.5 eV to about 2.9 eV. For example, red light has an energy of about 1.7 eV, and blue light has an energy of about 2.7 eV. Most PV cells cannot use about 55% of the energy of sunlight, because this energy is either below the bandgap of the material or carries excess energy.



Different PV materials have different energy band gaps. Photons with energy equal to the band gap energy are absorbed to create free electrons. Photons with less energy than the band gap energy pass through the material.

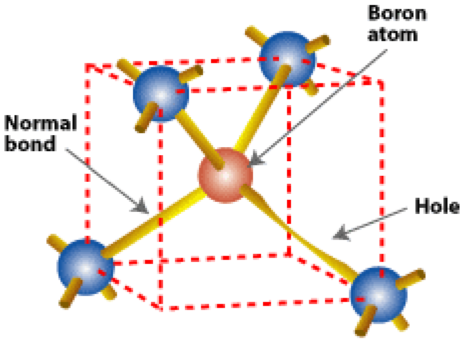
Doping Silicon to Create n-Type and p-Type Silicon

In a crystalline silicon cell, we need to contact p-type silicon with n-type silicon to create the built-in electrical field. The process of doping, which creates these materials, introduces an atom of another element into the silicon crystal to alter its electrical properties. The "dopant," which is the introduced element, has either three or five valence electrons—which is one less or one more that silicon's four.



Substituting a phosphorus atom (with five valence electrons) for a silicon atom in a silicon crystal leaves an extra, unbonded electron that is relatively free to move around the crystal.

Phosphorus atoms, which have five valence electrons, are used in doping n-type silicon, because phosphorus provides its fifth free electron. A phosphorus atom occupies the same place in the crystal lattice formerly occupied by the silicon atom it replaced. Four of its valence electrons take over the bonding responsibilities of the four silicon valence electrons that they replaced. But the fifth valence electron remains free, having no bonding responsibilities. When phosphorus atoms are substituted for silicon in a crystal, many free electrons become available.



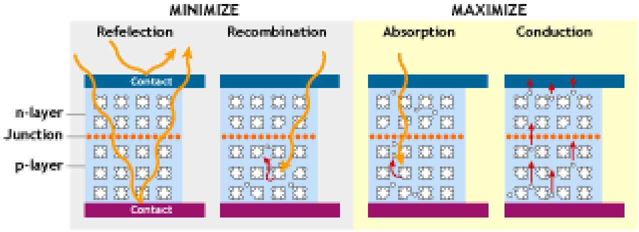
Substituting a boron atom (with three valence electrons) for a silicon atom in a silicon crystal leaves a hole (a bond missing an electron) that is relatively free to move around the crystal.

The most common method of doping is to coat a layer of silicon material with phosphorus and then heat the surface. This allows the phosphorus atoms to diffuse into the silicon. The temperature is then reduced so the rate of diffusion drops to zero. Other methods of introducing phosphorus into silicon include gaseous diffusion, a liquid dopant spray-on process, and a technique where phosphorus ions are precisely driven into the surface of the silicon.

The n-type silicon doped with phosphorus cannot form an electric field by itself. We also need p-type silicon. Boron, which has only three valence electrons, is used for doping p-type silicon. Boron is introduced during silicon processing when the silicon is purified for use in PV devices. When a boron atom takes a position in the crystal lattice formerly occupied by a silicon atom, a bond will be missing an electron. In other words, there is an extra positively charged hole.

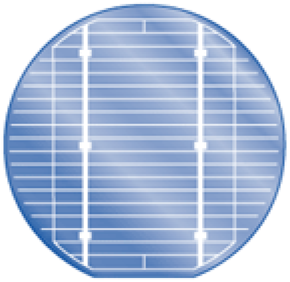
Absorption and Conduction

In a PV cell, photons are absorbed in the p-layer. And it's very important to "tune" this layer to the properties of incoming photons to absorb as many as possible, and thus, to free up as many electrons as possible. Another challenge is to keep the electrons from meeting up with holes and recombining with them before they can escape from the PV cell. To do all this, we design the material to free the electrons as close to the junction as possible, so that the electric field can help send the free electrons through the conduction layer (the n-layer) and out into the electrical circuit. By optimizing all these characteristics, we improve the PV cell's conversion efficiency, which is how much of the light energy is converted into electrical energy by the cell.



To make an efficient solar cell, we try to maximize absorption, minimize reflection and recombination, and thus maximize conduction.

Electrical Contacts



Grid contacts on the top surface of a typical cell are designed to have many thin, conductive fingers spreading to every part of the cell's surface.

Electrical contacts are essential to a photovoltaic (PV) cell because they bridge the connection between the semiconductor material and the external electrical load, such as a light bulb.

The back contact of a cell — on the side away from the incoming sunlight — is relatively simple. It usually consists of a layer of aluminum or molybdenum metal. But the front contact — on the side facing the sun — is more complicated. When sunlight shines on the PV cell, a current of electrons flows all over its surface. If we attach contacts only at the edges of the cell, it will not work well because of the great electrical resistance of the top semiconductor layer. Only a small number of electrons would make it to the contact.

To collect the most current, we must place contacts across the entire surface of a PV cell. This is normally done with a "grid" of metal strips or "fingers." However, placing a large grid, which is opaque, on the top of the cell shades active parts of the cell from the sun. The cell's conversion efficiency is thus significantly reduced. To improve the conversion efficiency, we must minimize these shading effects.

Another challenge in cell design is to minimize the electrical resistance losses when applying grid contacts to the solar cell material. These losses are related to the solar cell material's property of opposing the flow of an electric current, which results in heating the material.

Therefore, in designing grid contacts, we must balance shading effects against electrical resistance losses. The usual approach is to design grids with many thin, conductive fingers spreading to every part of the cell's surface. The fingers of the grid must be thick enough to conduct well (with low resistance), but thin enough not to block much of the incoming light. This kind of grid keeps resistance losses low while shading only about 3% to 5% of the cell's surface.

Grids can be expensive to make and can affect the cell's reliability. To make top-surface grids, we can either deposit metallic vapors on a cell through a mask or paint them on via a screen-printing method. Photolithography is the preferred method for the highest quality, but has the greatest cost. This process involves transferring an image via photography, as in modern printing.

An alternative to metallic grid contacts is a transparent conducting oxide (TCO) layer such as tin oxide (SnO2). The advantage of TCOs is that they are nearly invisible to incoming light, and they form a good bridge from the semiconductor material to the external electrical circuit.

TCOs are very useful in manufacturing processes involving a glass superstrate, which is the covering on the sun-facing side of a PV module. Some thin-film PV cells, such as amorphous silicon and cadmium telluride, use superstrates. In this process, the TCO is generally deposited as a thin film on the glass superstrate before the semiconducting layers are deposited. The semiconducting layers are then followed by a metallic contact that will actually be the bottom of the cell. As you can see, the cell is actually constructed "upside down," from the top to the bottom.

But the construction technique isn't the only thing that determines whether a metallic grid or TCO is best for a certain cell design. The sheet resistance of the semiconductor is also an important consideration. In crystalline silicon, for example, the semiconductor carries electrons well enough to reach a finger of the metallic grid. Because the metal conducts electricity better than a TCO, shading losses are less than losses associated with using a TCO. Amorphous silicon, on the other hand, conducts very poorly in the horizontal direction. Therefore, it benefits from having a TCO over its entire surface.

Antireflective Coating

Silicon is a shiny gray material and can act as a mirror, reflecting more than 30% of the light that shines on it. To improve the conversion efficiency of a solar cell, we want to minimize the amount of light reflected so that the semiconductor material can capture as much light as possible to use in freeing electrons.

Two techniques are commonly used to reduce reflection. The first technique is to coat the top surface with a thin layer of silicon monoxide (SiO). A single layer reduces surface reflection to about 10%, and a second layer can lower the reflection to less than 4%.

A second technique is to texture the top surface. Chemical etching creates a pattern of cones and pyramids, which capture light rays that might otherwise to deflected away from the cell. Reflected light is redirected down into the cell, where it has another chance to be absorbed.

Solar Cell Materials

Solar cells can be made from a wide range of semiconductor materials. In the following sections, we will discuss:

- Silicon (Si)—including single-crystalline Si, multicrystalline Si, and amorphous Si
- Polycrystalline thin films—including copper indium diselenide (CIS), cadmium telluride (CdTe), and thin-film silicon
- Single-crystalline thin films—including high-efficiency material such as gallium arsenide (GaAs)

First, though, we provide an overview of aspects that relate to all materials. This discussion serves as a basis for the more detailed section on individual materials. The aspects we will cover are crystallinity, absorption, bandgap, and complexity of manufacturing.

Crystallinity

The crystallinity of a material indicates how perfectly ordered the atoms are in the crystal structure. Silicon, as well as other solar cell semiconductor materials, can come in various forms: single-crystalline, multicrystalline, polycrystalline, or amorphous. In a single-crystal material, the atoms making up the framework of the crystal are repeated in a very regular, orderly manner from layer to layer. In contrast, in a material composed of numerous smaller crystals, the orderly arrangement is disrupted moving from one crystal to another. One classification scheme for silicon uses approximate crystal size and also includes the methods typically used to grow or deposit such material.

Type of Silicon	Abbreviation	Crystal Size Range	Deposition Method
Single-crystal silicon	**sc-Si**	**>10cm**	**Czochralski, float zone**
Multicrystalline silicon	mc-Si	1mm-10cm	Cast, sheet, ribbon
Polycrystalline silicon	pc-Si	1mm-1mm	Chemical-vapor deposition
Microcrystalline silicon	mc-Si	<1mm	Plasma deposition

Absorbtion

The absorption coefficient of a material indicates how far light having a specific wavelength (or energy) can penetrate the material before being absorbed. A small absorption coefficient means that light is not readily absorbed by the material. Again, the absorption coefficient of a solar cell depends on two factors: the material making up the cell, and the wavelength or energy of the light being absorbed. Solar cell material has an abrupt edge in its absorption coefficient. The reason is that light whose energy is below the material's bandgap cannot free an electron. And so, it isn't absorbed.

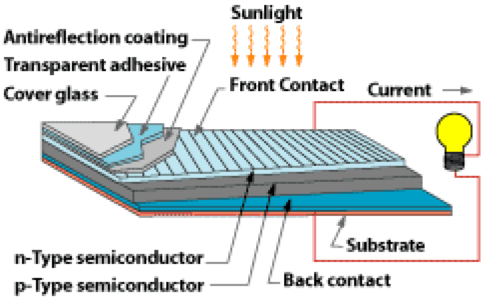
Bandgap

The bandgap of a semiconductor material is an amount of energy. Specifically, it's the minimum energy needed to move an electron from its bound state within an atom to a free state. This free state is where the electron can be involved in conduction. The lower energy level of a semiconductor is called the "valence band." And the higher energy level where an electron is free to roam is called the "conduction band." The bandgap (often symbolized by E^g) is the energy difference between the conduction band and valence band.

Complexity of Manufacturing

The most important parts of a solar cell are the semiconductor layers, because this is where electrons are freed and the electric current is created—it's the active layer "where the action is," so to speak. Several different semiconductor materials are used to make the layers in different types of solar cells, and each material has its benefits and drawbacks.

The cost and complexity of manufacturing may vary across these materials and device structures based on many factors, including deposition in a vacuum environment, amount and type of material utilized, number of steps involved, need to move cells into different deposition chambers or processing processes, and others.



A typical solar cell consists of a glass or plastic cover or other encapsulant, an antireflective layer, a front contact to allow electrons to enter a circuit, a back contact to allow them to complete the circuit, and the semiconductor layers where the electrons begin and complete their journey.

Solar Cell Structures

The actual structural design of a photovoltaic device depends on the limitations of the material used in the PV cell. We will look briefly at four basic device designs commonly used with the materials we have discussed.

- Homojunction
- Heterojunction
- p-i-n/n-i-p
- Multijunction

Homojunction Device

Crystalline silicon is the primary example of this kind of cell. A single material—crystalline silicon—is altered so that one side is p-type, dominated by positive holes, and the other side is n-type, dominated by negative electrons. The p/n junction is located so that the maximum amount of light is absorbed near it. The free electrons and holes generated by light deep in the silicon diffuse to the p/n junction, then separate to produce a current if the silicon is of sufficient high quality.

In this homojunction design, we may vary several aspects of the cell to increase conversion efficiency:

- Depth of the p/n junction below the cell's surface
- Amount and distribution of dopant atoms on either side of the p/n junction
- Crystallinity and purity of the silicon

Some homojunctions cells have also been designed with the positive and negative electrical contacts on the back of the cell. This geometry eliminates the shadowing caused by the electrical grid on top of the cell. A disadvantage is that the charge carriers, which are mostly generated near the top surface of the cell, must travel farther—all the way to the back of the cell—to reach an electrical contact. To be able to do this, the silicon must be of very high quality, without crystal defects that cause electrons and holes to recombine.

Heterojunction Device

An example of this type of device structure is a CIS cell, where the junction is formed by contacting two different semiconductors—CdS and $CuInSe_2$. This structure is often chosen for producing cells made of thin-film materials that absorb light much better than silicon. The top and bottom layers in a heterojunction device have different roles. The top layer, or "window" layer, is a material with a high bandgap selected for its transparency to light. The window allows almost all incident light to reach the bottom layer, which is a material with low bandgap that readily absorbs light. This light then generates electrons and holes very near the junction, which helps to effectively separate the electrons and holes before they can recombine.

Heterojunction devices have an inherent advantage over homojunction devices, which require materials that can be doped both p- and n-type. Many PV materials can be doped either p-type or n-type, but not both. Again, because heterojunctions don't have this constraint, many promising PV materials can be investigated to produce optimal cells.

Also, a high-bandgap window layer reduces the cell's series resistance. The window material can be made highly conductive, and the thickness can be increased without reducing the transmittance of light. As a result, light-generated electrons can easily flow laterally in the window layer to reach an electrical contact.

p-i-n and n-i-p Devices

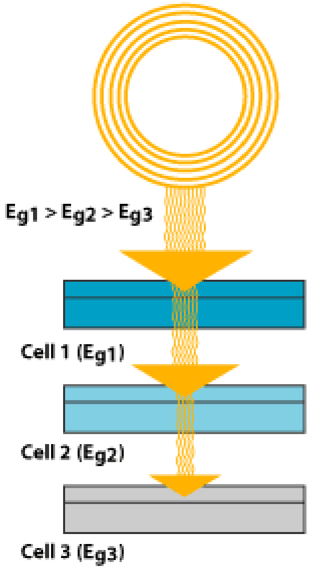
Typically, amorphous silicon thin-film cells use a p-i-n structure, whereas CdTe cells use an n-i-p structure. The basic scenario is as follows: A three-layer sandwich is created, with a middle intrinsic (i-type or undoped) layer between an n-type layer and a p-type layer. This geometry sets up an electric field between the p- and n-type regions that stretches across the middle intrinsic resistive region. Light generates free electrons and holes in the intrinsic region, which are then separated by the electric field.

In the p-i-n amorphous silicon (a-Si) cell, the top layer is p-type a-Si, the middle layer is intrinsic silicon, and the bottom layer is n-type a-Si. Amorphous silicon has many atomic-level electrical defects when it is highly conductive. So very little current would flow if an a-Si cell had to depend on diffusion. However, in a p-i-n cell, current flows because the free electrons and holes are generated *within* the influence of an electric field, rather than having to move toward the field.

In a CdTe cell, the device structure is similar to the a-Si cell, except the order of layers is flipped upside down. Specifically, in a typical CdTe cell, the top layer is p-type cadmium sulfide (CdS), the middle layer is intrinsic CdTe, and the bottom layer is n-type zinc telluride (ZnTe).

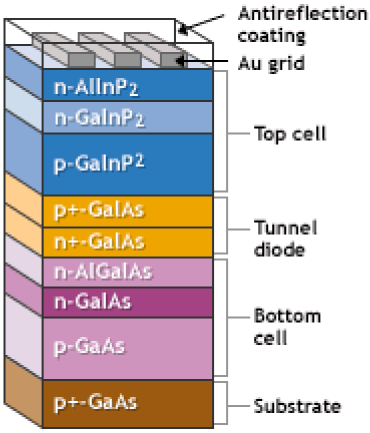
Multi-Junction Devices

This structure, also called a cascade or tandem cell, can achieve a higher total conversion efficiency by capturing a larger portion of the solar spectrum. In the typical multijunction cell, individual cells with different bandgaps are stacked on top of one another. The individual cells are stacked in such a way that sunlight falls first on the material having the largest bandgap. Photons not absorbed in the first cell are transmitted to the second cell, which then absorbs the higher-energy portion of the remaining solar radiation while remaining transparent to the lower-energy photons. These selective absorption processes continue through to the final cell, which has the smallest bandgap.



A multijunction device is a stack of individual single-junction cells in descending order of bandgap (Eg). The top cell captures the high-energy photons and passes the rest of the photons on to be absorbed by lower-bandgap cells.

A multijunction cell can be made in two different ways. In the mechanical stack approach, two individual solar cells are made independently, one with a high bandgap and one with a lower bandgap. Then the two cells are mechanically stacked, one on top of the other. In the monolithic approach, one complete solar cell is made first, and then the layers for the second cell are grown or deposited directly on the first.



This multijunction device has a top cell of gallium indium phosphide, then a "tunnel junction" to allow the flow of electrons between the cells, and a bottom cell of gallium arsenide.

Much of today's research in multijunction cells focuses on gallium arsenide as one (or all) of the component cells. These cells have efficiencies of more than 35% under concentrated sunlight—which is high for PV devices. Other materials studied for multijunction devices are amorphous silicon and copper indium diselenide.

PV Systems

A photovoltaic cell, the most basic building block of a PV system.

This array supplies 6.5 kilowatts of electricity to the Canyonlands Needles Outpost, an all-purpose general store, restaurant, gas station, and campground that serves visitors to the national park near Moab, Utah.

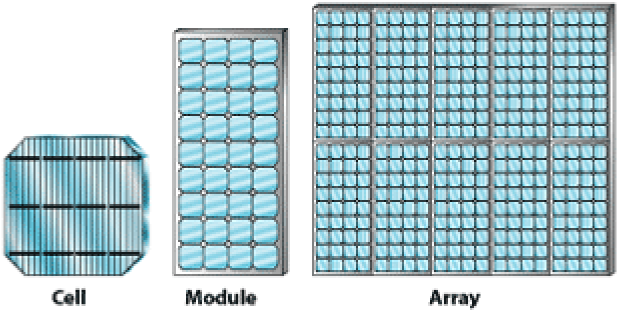
These two silicon modules are rated at about 50 watts each and generate power to illuminate an entry sign.

A photovoltaic (PV) or solar cell is the basic building block of a PV (or solar electric) system. An individual PV cell is usually quite small, typically producing about 1 or 2 watts of power. To boost the power output of PV cells, we connect them together to form larger units called modules. Modules, in turn, can be connected to form even larger units called arrays, which can be interconnected to produce more power, and so on. In this way, we can build PV systems able to meet almost any electric power need, whether small or large.

PV systems can be classified into two general categories: flat-plate systems or concentrator systems. We will talk about the differences between these two types of systems later on.

By themselves, modules or arrays do not represent an entire PV system. We also need structures to put them on that point them toward the sun, and components that take the direct-current electricity produced by modules and "condition" that electricity, usually by converting it to alternate-current electricity. We might also want to store some electricity, usually in batteries, for later use. All these items are referred to as the "balance of system" (BOS) components.

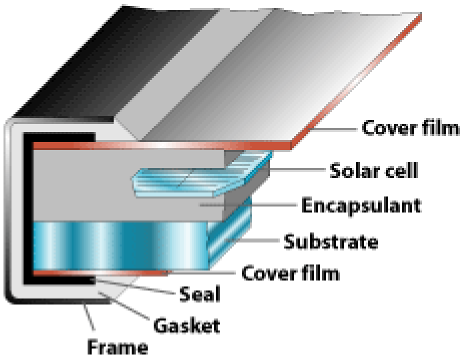
Combining modules with the BOS components creates an entire PV system. This system is usually everything we need to meet a particular energy demand, such as powering a water pump, or the appliances and lights in a home, or, if the PV system is large enough, all the electrical requirements of a whole community.



The basic photovoltaic or solar cell typically produces only a small amount of power. To produce more power, cells can be interconnected to form modules, which can in turn be connected into arrays to produce yet more power. Because of this modularity, PV systems can be designed to meet any electrical requirement, no matter how large or how small.

Flat-Plate PV Systems

The most common array design uses flat-plate PV modules or panels. These panels can either be fixed in place or allowed to track the movement of the sun. They respond to sunlight that is either direct or diffuse. Even in clear skies, the diffuse component of sunlight accounts for between 10% and 20% of the total solar radiation on a horizontal surface. On partly sunny days, up to 50% of that radiation is diffuse. And on cloudy days, 100% of the radiation is diffuse.



One typical flat-plate module design uses a substrate of metal, glass, or plastic to provide structural support in the back; an encapsulant material to protect the cells; and a transparent cover of plastic or glass.

The simplest PV array consists of flat-plate PV panels in a fixed position. The advantages of fixed arrays are that they lack moving parts, there is virtually no need for extra equipment, and they are relatively lightweight. These features make them suitable for many locations, including most residential roofs. Because the panels are fixed in place, their orientation to the sun is usually at an angle that practically speaking is less than optimal. Therefore, less energy per unit area of array is collected compared with that from a tracking array. However, this drawback must be balanced against the higher cost of the tracking system.

Modules

This solar-powered water-pumping station is on the Martin Ketterling Ranch north of Heil, North Dakota. This system has two Solarjack 50-watt flat-plate panels and a Solarjack water pump and controller. Because the water tanks are relatively small, two Interstate marine batteries provide backup on cloudy days and at night. The system pumps about 4 gallons per minute, enough to water about 40 head of cattle.

Let's look at a typical crystalline silicon PV module. It consists of a transparent top surface, an encapsulant, a rear layer, and a frame around the outer edge. In most modules, the top surface is glass, the encapsulant is ethyl vinyl acetate (EVA), and the rear layer is Tedlar.

Front Surface Materials — The front surface of a PV module must have a high transmission in the wavelengths that can used by the solar cells in the PV module. For example, for silicon solar cells, the top surface must have high transmission of light having wavelengths in the 350 to 1200 nm range.

Also, the reflection from the front surface should be minimal. An antireflection coating to the top surface can greatly reduce the reflection of sunlight, and texturing of the surface can cause light that strikes the surface to stay within the cells. Unfortunately, these textured modules are not "self-cleaning," and the advantage of reduced reflection is usually outweighed by losses due to dust sticking to the surface.

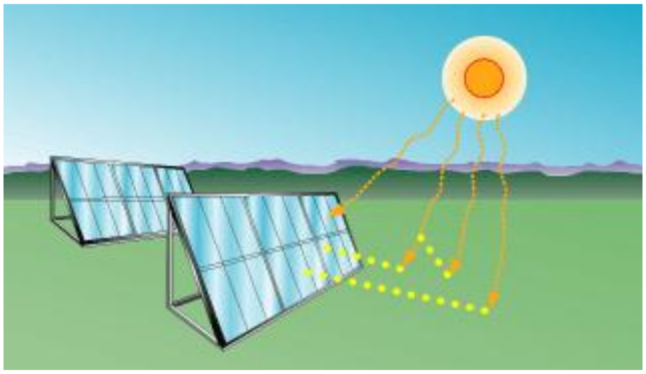
The top surface should also be impervious to water, be able to resist damage from hail impact, be stable under long-term exposure to ultraviolet radiation, and have low thermal resistivity. If water as liquid or a vapor is able to get inside a PV module, it will cause corrosion of metal contacts and interconnects, which will greatly shorten the lifetime of the PV module. Also, the front surface often provides rigidity for the module.

Of several choices for a top surface material, a common choice is tempered, low-iron glass, which is low cost, strong, stable, highly transparent, impervious to water and gases, and has good self-cleaning properties.

Encapsulant — An encapsulant helps to hold together the top surface, PV cells, and rear surface of the PV module. The encapsulant must be stable at high temperatures and high levels of ultraviolet radiation. It must also be optically transparent and have a low thermal resistance. Ethyl vinyl acetate—or EVA—is the most commonly used encapsulant. Thin sheets of EVA are inserted between the solar cells and the top and rear surfaces. Heating this "sandwich" causes the EVA to polymerize, thus bonding the module into one piece.

Rear Surface — The material used as the rear surface of the PV module must have low thermal resistance and must prevent the ingress of water and gases. In many modules, the rear surface material is a thin polymer sheet, typically Tedlar.

Frame — A final structural component of the module is the frame, which is typically made of aluminum.



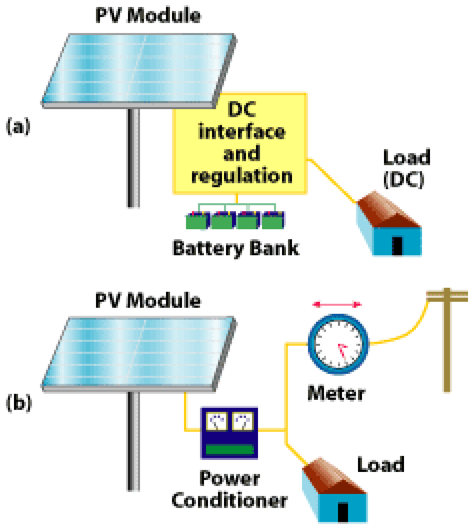
Flat-plate collectors, which typically contain a large number of solar cells mounted on a rigid, flat surface, can make use of both direct sunlight and the diffuse sunlight reflected from clouds, the ground, and nearby objects.

We add one final point. Because the amount of power produced by a single cell is relatively small, designers group solar cells together to form electrical modules that supply a more useful level of voltage, current, and power. Solar cells may be connected in series to produce higher voltages. This is accomplished by connecting the positive terminal of one cell to the negative terminal of the next cell. Cells may also be connected in parallel to produce more current. This is accomplished by connecting the positive terminal of the first cell to the positive terminal of the next cell, and the negative terminal of the first cell to the negative terminal of the second cell.

Balance of System

We can think of a complete photovoltaic (PV) energy system as composed of three subsystems.

- On the power-generation side, a subsystem of PV devices (cells, modules, arrays) converts sunlight to direct-current (DC) electricity.
- On the power-use side, the subsystem consists mainly of the load, which is the application of the PV electricity.
- Between these two, we need a third subsystem that enables the PV-generated electricity to be properly applied to the load. This third subsystem is often called the "balance of system," or BOS.

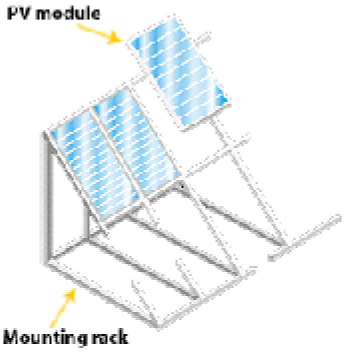


This simple illustration shows the elements needed to get the power created by a PV system to the load (in this example, a house). The stand-alone PV system (a) uses battery storage to provide dependable DC electricity day and night. Even for a home connected to the utility grid (b), PV can produce electricity (converted to AC by a power conditioner) during the day. The extra electricity can then be sold to the utility during the day, and the utility can in turn provide electricity at night or during poor weather.

The BOS typically consists of structures for mounting the PV arrays or modules and power-conditioning equipment that adjusts and converts the DC electricity to the proper form and magnitude required by an alternating-current (AC) load. The BOS can also include storage devices, such as batteries, so PV-generated electricity can be used during cloudy days or at night.

Mounting Structures

Photovoltaic arrays must be mounted on a stable, durable structure that can support the array and withstand wind, rain, hail, and other adverse conditions. Sometimes, this mounting structure is designed to track the sun. However, stationary structures are usually used with flat-plate systems. These structures tilt the PV array at a fixed angle determined by the latitude of the site, the requirements of the load, and the availability of sunlight. Among the choices for stationary mounting structures, rack mounting may be the most versatile. It can be constructed fairly easily and installed on the ground or on flat or slanted roofs.



A typical PV array mounting rack.

- Power Conditioners
- Electricity Storage
- Charge Controllers
- Tracking Structures

Power Conditioners

Power conditioners process the electricity produced by a PV system so it will meet the specific demands of the load. Although most equipment is standard, it is very important to select equipment that matches the characteristics of the load. Power conditioners may have these functions:

- Limit current and voltage to maximize power output
- Convert DC power to AC
- Match the converted AC electricity to a utility's electrical network
- Have safeguards that protect utility personnel and the network from harm during repairs

Specific requirements of power conditioners depend on the type of PV system they are used with and the applications of that system. For DC applications, power conditioning is often done with regulators, which control output at some constant level of voltage and current to maximize output. For AC loads, power conditioning must include an inverter that converts the direct current generated by the PV array into alternating current. Many simple devices—for example, ones that run on batteries—use DC electricity. However, AC electricity, which is what is generated by utilities, is needed to run most modern appliances and electronic devices.

Workers install a 1-kilowatt PV/battery system at Camp Leakey in Kalimantan Tengah, Borneo, Indonesia. Part of the Solar in the Jungle project, this system supplies remote power for the Orangutan Foundation International.

Electricity Storage

We need electricity at night and on cloudy days as well as on the sunny days that are so perfect for PV power generation. If tapping into the utility grid is not an option, a battery backup system is necessary for energy storage. However, batteries do lower the efficiency of a PV system, because only about 80% of the energy that goes into them can be reclaimed. They usually need to be replaced every 5 to 10 years. Also, they take up considerable floor space, pose a few possible safety problems, and require periodic maintenance. Still, they provide one way to store PV electricity for later use.

Like PV cells, batteries are direct-current devices that are directly compatible only with DC loads. However, batteries can also serve as a power conditioner for these loads by regulating power. This allows the PV array to operate closer to its optimum power output.

Charge Controllers

An inverter (left) and charge controller (right) are known as the power conditioning components of a PV system.

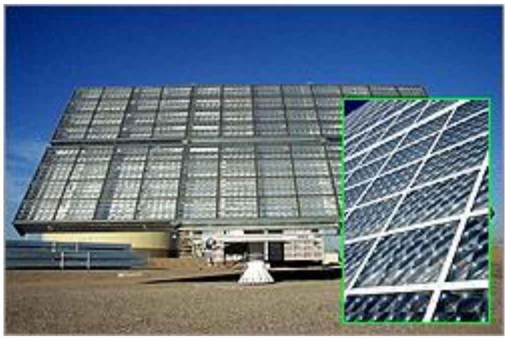
An inverter converts the direct current (DC) electricity generated by the PV array into alternating current (AC) and the charge controller protects the battery (the electricity storage device) from overcharging and also excessive discharge. Most batteries must be protected from overcharge and excessive discharge, which can cause electrolyte loss and even damage or ruin the battery plates. Most charge controllers also have a mechanism that prevents current from flowing from the battery back into the array at night.

Tracking Structures

There are two basic kinds of tracking structures: one-axis and two-axis. The one-axis trackers are typically designed to track the sun from east to west. They are used with flat-plate systems and sometimes with concentrator systems. The two-axis type is used primarily with PV concentrator systems. These units track the sun's daily course, but also, its seasonal course between the northern and southern hemispheres. Naturally, the more sophisticated systems are the more expensive ones, and they usually require more maintenance.

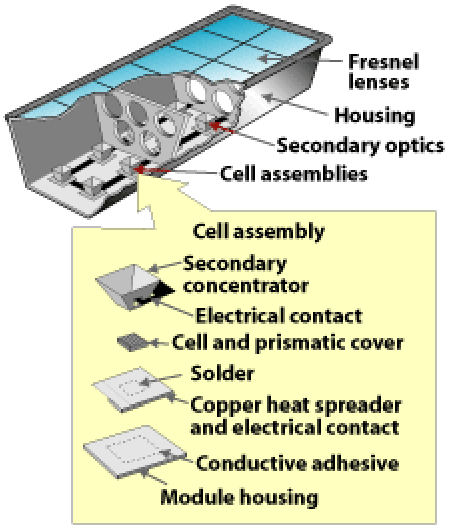
Concentrator PV Systems

The primary reason for using concentrators is to be able to use less solar cell material in a PV system. PV cells are the most expensive components of a PV system, on a per-area basis. A concentrator makes use of relatively inexpensive materials such as plastic lenses and metal housings to capture the solar energy shining on a fairly large area and focus that energy onto a smaller area, where the solar cell is. One measure of the effectiveness of this approach is the concentration ratio—in other words, how much concentration the cell is receiving.



The largest system being tested at Arizona Public Service Company's Solar Test and Research (STAR) Center is a high-performance concentrating solar power generator. Although they're not suitable for small projects, concentrator systems could be very effective in large-scale power generation. The STAR Center unit produces 20 kilowatts of electricity—enough to power about five homes. Systems like these may some day supply power to entire communities.

Several advantages of concentrator PV systems, as compared to flat-plate systems, can be enumerated. Concentrator systems increase the power output while reducing the size or number of cells needed. An additional advantage is that a solar cell's efficiency increases under concentrated light. How much that efficiency increases depends largely on the design of the solar cell and the material used to make it. Another advantage is that a concentrator can be made of small individual cells. This is an advantage because it is harder to produce large-area, high-efficiency solar cells than it is to produce small-area cells.



A typical basic concentrator unit consists of a lens to focus the light, cell assembly, housing element, secondary concentrator to reflect off-center light rays onto the cell, mechanism to dissipate excess heat produced by concentrated sunlight, and various contacts and adhesives. Notice that the module depicted uses 12 cell units in a 2x6 matrix. These basic units may be combined in any configuration to produce the desired module.

However, several challenges exist to using concentrators. For example, the required concentrating optics are significantly more expensive than the simple covers needed for flat-plate solar systems, and most concentrators must track the sun throughout the day and year to be effective. Thus, achieving higher concentration ratios means using not only expensive tracking mechanisms, but also, more precise controls than those of flat-plate systems with stationary structures.

Both reflectors and lenses have been used to concentrate light for PV systems. The most promising lens for PV applications is the Fresnel lens, which uses a miniature sawtooth design to focus incoming light. When the teeth run in straight rows, the lenses act as line-focusing concentrators. And when the teeth are arranged in concentric circles, light is focused at a central point. However, no lens can transmit 100% of the incident light. The best that lenses can transmit is only 90% to 95%, and in practice, most transmit less. Furthermore, concentrators cannot focus diffuse sunlight, which makes up about 20% of the solar radiation available on a clear day.

High concentration ratios also introduce a heat problem. When excess radiation is concentrated, so is the amount of heat produced. Cell efficiencies decrease as temperatures increase, and higher temperatures also threaten the long-term stability of solar cells. Therefore, the solar cells must be kept cool in a concentrator system.

One of the most important design considerations is to minimize electrical resistance where the external electrical contacts carry off the current generated by the cell. Wide fingers in the contacting electrical grid are ideal for low resistance, but they block too much light from reaching the cell because of their shadow. One solution to the problems of resistance and shadowing is prismatic covers. These special covers act like a prism and direct incoming light to parts of the cell's surface that are between the metal fingers of the electrical contact grid. Another solution is a the back-contact cell, which differs from conventional cells in that both the positive and negative electrical contacts are on the back. Placing all the electrical contacts on the back of the cell eliminates power losses from shadowing, but it also requires exceptionally good-quality silicon material.