Solar PV Fundamentals

How sunlight becomes electricity, and the parts of a PV system

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How solar energy works

The sun emits heat and light in the form of solar radiation, also known as electromagnetic radiation. Solar technologies capture this radiation and turn it into useful forms of energy. There are two main types of solar energy technologies: photovoltaics (PV) and concentrating solar-thermal power (CSP).

You are likely most familiar with PV, which is used in solar panels. When the sun shines onto a solar panel, energy from the sunlight is absorbed by the PV cells in the panel. This energy creates electrical charges that move in response to an internal electrical field in the cell, causing electricity to flow.

CSP systems use mirrors to reflect and concentrate sunlight onto receivers that collect solar energy and convert it to heat, which can then be used to produce electricity or stored for later use. CSP is used primarily in very large power plants. This course is about PV.

Solar cells that are strung together make a module, and when modules are connected, they make a solar system, or installation. A typical residential rooftop solar system has about 30 modules.

The solar resource

Solar radiation, often called the solar resource or just sunlight, is a general term for the electromagnetic radiation emitted by the sun. Every location on Earth receives sunlight at least part of the year. The amount of solar radiation that reaches any one spot on the Earth's surface varies according to:

- geographic location
- time of day
- season
- local landscape
- local weather

Because the Earth is round, the sun strikes the surface at different angles, ranging from 0 degrees (just above the horizon) to 90 degrees (directly overhead). When the sun's rays are vertical, the Earth's surface gets the most energy possible. More slanted rays travel through the atmosphere longer, making them more scattered and diffuse.

The 23.5 degree tilt in the Earth's axis of rotation is a significant factor in determining the amount of sunlight striking the Earth at a particular location. Tilting results in longer days in the northern hemisphere from the spring equinox to the fall equinox, and longer days in the southern hemisphere during the other six months.

Countries in the middle latitudes, such as the United States, receive more solar energy in the summer, not only because days are longer, but also because the sun is almost directly overhead. The sun's rays are far more slanted during the shorter days of the winter months. For example, Denver, Colorado, near

40 degrees latitude, receives nearly three times more solar energy in June than in December.

The rotation of the Earth is also responsible for hourly variations in sunlight. In the early morning and late afternoon, the sun is low in the sky. Its rays travel further through the atmosphere than at noon, when the sun is at its highest point. For this reason, the greatest amount of solar energy reaches the Earth around solar noon.

Types of solar radiation

As sunlight passes through the atmosphere, some of it is absorbed, scattered and reflected by air molecules, water vapor, clouds, dust and pollutants. This is called diffuse solar radiation. Sunlight that reaches the Earth's surface without being diffused is called direct beam solar radiation. Atmospheric conditions can reduce direct beam radiation by 10% on clear, dry days and by 100% during thick, cloudy days. The sum of the diffuse and direct solar radiation is called global solar radiation.

Measuring solar radiation

Scientists measure the amount of sunlight falling on specific locations at different times of the year, then estimate the amount falling on regions at the same latitude with similar climates. Measurements of solar energy are typically expressed as total radiation on a surface area. Radiation data for PV systems are often given in kilowatt-hours per square meter (kWh per square meter). Direct estimates of solar power may also be given in watts per square meter.

The solar cell

A photovoltaic (PV) cell, also called a solar cell, contains a semiconductor material that can absorb sunlight and convert it to electricity. The "semi" means that it can conduct electricity better than an insulator but not as well as a good conductor like a metal. Not all semiconductors can convert light to electricity, a property known as the photovoltaic effect.

When the semiconductor is exposed to sunlight, it absorbs the light's energy and transfers it to negatively charged particles in the material called electrons. This extra energy allows the electrons to flow through the material as an electrical current. The current is extracted through conductive metal contacts, the grid-like lines on a solar cell, and then travels to an inverter. The inverter converts the direct current (DC) to alternating current (AC), which flows into the building's electrical system and the grid. As long as sunlight reaches the module and the circuit is connected, electricity will continue to be generated.

The amount of electricity produced from PV cells depends on the characteristics of the light, such as its intensity and wavelength, and on the performance of the cell.

Silicon cells

Silicon is by far the most common semiconductor material used in solar cells. It is the second most abundant material on Earth, after oxygen, and the most common semiconductor used in computer chips. Crystalline silicon cells are made of silicon atoms connected to one another to form a crystal lattice. This lattice provides an organized structure that makes conversion of light into electricity more efficient.

To make a silicon solar cell, blocks of crystalline silicon are cut into very thin wafers. The wafer is processed on both sides to separate the electrical charges and form a diode, a device that allows current to flow in only one direction. The diode is sandwiched between metal contacts to let the electrical current easily flow out of the cell.

Most solar panels on the market use either monocrystalline or polycrystalline silicon. Monocrystalline silicon wafers are made of one crystal structure, and polycrystalline silicon is made of many different crystals. Monocrystalline panels are more efficient because the electrons move more freely, but polycrystalline cells are less expensive to manufacture.

Solar cells made from silicon currently provide a combination of high efficiency, low cost and long lifetime. Modules are expected to last for 25 years or more, still producing more than 80% of their original power after this time. The maximum theoretical efficiency of a silicon solar cell is about 32%; the best panels for commercial use reach roughly 18% to 22%.

Other cell technologies

- Thin-film cells are made by depositing one or more thin layers of PV material on a supporting material such as glass, plastic or metal. The two main types on the market are cadmium telluride (CdTe) and copper indium gallium diselenide (CIGS). CdTe is the second most common PV material after silicon and can be made at low cost, but its efficiency is not quite as high as silicon's. Both CdTe and CIGS need more protection than silicon to last outdoors.
- Perovskite cells are a type of thin-film cell made with layers of material that are printed, coated or vacuum-deposited onto a support layer. Their efficiencies in the lab have improved faster than any other PV material, but they must become stable enough to survive many years outdoors before they are widely used.
- Organic PV cells are made of carbon-rich compounds. They are currently about half as efficient as crystalline silicon and do not last as long, but they could be cheaper to make and can be applied to flexible materials.
- Multijunction cells stack different semiconductors, each absorbing a different part of the solar spectrum, so they use more of the sunlight. A cell with exactly two layers is called a tandem cell. The most efficient multijunction cells are costly and are mainly used in space.
- Concentration PV uses a mirror or lens to focus sunlight onto a small, very efficient cell.

Performance and efficiency

The conversion efficiency of a PV cell is the percentage of the solar energy shining on it that is converted into usable electricity. Not all of the sunlight that reaches a PV cell is converted into electricity; in fact, most of it is lost. Four factors matter most:

- Wavelength: sunlight contains a wide range of wavelengths and energies, from ultraviolet through visible light to infrared. Some light is reflected, some passes straight through, and some absorbed light only becomes heat. Only light with the right amount of energy frees electrons to produce current.
- Recombination: when a freed electron meets a "hole" (the absence of an electron, which acts like a positive charge), they can recombine and cancel out their contribution to the current. Impurities and defects in the material make this more likely.

- Temperature: solar cells generally work best at low temperatures. Higher temperatures cause a slight increase in current but a much larger decrease in voltage. Since much of the sunlight on a cell becomes heat, keeping modules cool improves both efficiency and lifetime. This is why installers leave space for air to flow behind modules.
- Reflection: untreated silicon reflects more than 30% of the light that strikes it. Anti-reflection coatings and textured surfaces reduce reflection, which is why high-efficiency cells look dark blue or black.

Electrical power is the product of current and voltage. If a load is connected across a cell or module, the current and voltage it produces adjust according to Ohm's law. Efficiency is measured by exposing a cell to a constant, standard level of light at a constant cell temperature, and measuring the current and voltage it produces for different loads. Outdoors, heat, dirt and shade all reduce a module's output below its rating.

The parts of a PV system

Solar photovoltaic modules are where the electricity is generated, but they are only one of the many parts of a complete PV system. For the electricity to be useful in a home or business, several other technologies must be in place.

Mounting structures

PV arrays must be mounted on a stable, durable structure that can support the array and withstand wind, rain, hail and corrosion over decades. These structures tilt the array at a fixed angle chosen for the local latitude, the orientation of the building and the energy needed. To get the highest yearly energy output, modules in the northern hemisphere point due south and are tilted at an angle equal to the local latitude. Rack mounting is the most common method because it is robust, versatile, and easy to build and install.

For arrays mounted on the ground, tracking mechanisms can move the modules to follow the sun across the sky, which produces more energy. One-axis trackers usually follow the sun from east to west. Two-axis trackers keep the modules pointed directly at the sun all day. Tracking costs more up front and needs more maintenance.

Modules can also be built into building materials such as roofing, windows or walls. These are called building-integrated PV (BIPV).

Inverters

Inverters convert the direct current (DC) produced by PV modules into alternating current (AC), which is used by most appliances and by the electric grid. A system has either one inverter that converts the electricity from all the modules, or microinverters attached to each module. A single inverter is generally less expensive and easier to cool and service. Microinverters let each module work independently, which helps when some modules may be shaded. Inverters are expected to be replaced at least once during the 25-year life of a PV array.

Advanced or "smart" inverters can communicate with the electric utility, which helps balance supply and demand and keep the grid stable.

Storage

Batteries store solar energy so it can be used at night or when clouds block the sun. They are used in homes and, increasingly, by utilities to store solar energy fed into the grid and return it to customers later.

Check yourself

1. What is the difference between a cell, a module and an array?
2. Why does a location receive more solar energy in June than in December?
3. What is the difference between direct beam, diffuse and global solar radiation?
4. In your own words, how does a PV cell turn sunlight into an electric current?
5. Give one advantage of monocrystalline silicon and one advantage of polycrystalline silicon.
6. Why does a hot module produce less power than a cool one?
7. At what tilt and direction should a fixed array in [your city] face for the most energy over a year?
8. Give one advantage of a single inverter and one advantage of microinverters.

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