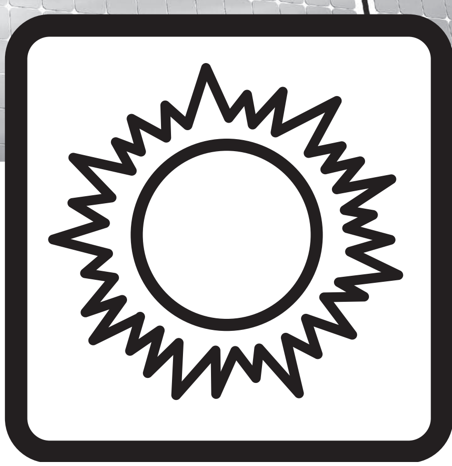
Exploring Photovoltaics
Student Guide

2013-2014



NEED
National Energy Education Development Project

SECONDARY

Solar Energy

What is Solar Energy?

Solar energy is **radiant energy** from the sun. It is vital to us because it provides the world—directly or indirectly—with almost all of its energy. In addition to providing the energy that sustains the world, solar energy is stored in fossil fuels and biomass, and is responsible for powering the water cycle and producing wind.

Every day the sun radiates, or sends out, an enormous amount of energy. The sun radiates more energy each day than the world uses in one year. Solar energy comes from within the sun itself. Like other stars, the sun is a big ball of gases—mostly hydrogen and helium. The hydrogen atoms in the sun's core combine to form helium and radiant energy in a process called **nuclear fusion**.

During nuclear fusion, the sun's extremely high pressure and temperature cause nuclei to separate from their electrons. At this extremely energized state, the nuclei are able to fuse, or combine. Hydrogen nuclei fuse to become one helium atom of a higher atomic number and greater mass, and one neutron remains free. This new helium atom, however, contains less mass than the combined masses of the hydrogen isotopes that fused. This **transmutation** of matter results in some mass being lost. The lost matter is emitted into space as radiant energy. The process of fusion occurs most commonly with lighter elements like hydrogen, but can also occur with heavier nuclei, until iron (Fe) is formed. Because iron is the lowest energy nucleus, it will neither fuse with other elements, nor can it be fissioned (split) into smaller nuclei.

Scientists theorize that the time for the energy in the sun's core to make its way to the solar surface takes about 150,000 years. The nuclear fusion process in the sun's core produces, among other things, **gamma rays**. These gamma rays are constantly absorbed and re-emitted as they move through the sun, essentially bouncing in random directions. By the time this "random walk" takes them to the sun's surface they have been transformed into visible light. This light escapes from the **photosphere**, the visible surface of the sun, and arrives at Earth about eight minutes later. The solar energy travels to the Earth at a speed of 3.0×10^8 meters per second (186,000 miles per second), the speed of light. Heat energy is not transmitted from the sun because the space between the sun and Earth is mostly a vacuum. Rather, radiant energy transforms into **thermal energy** when it strikes the molecules in the atmosphere or on the surface of the Earth.

Only a small portion of the energy radiated by the sun into space strikes the Earth—one part in two billion. Yet, this amount of energy is enormous. It was mentioned before that the sun provides more energy in a day than the world uses in a year. The sun also provides more energy in an hour than the United States uses in a year!

Where does all this energy go? About 30 percent of the sun's energy that hits the Earth is reflected back into space. Another 25 percent powers the water cycle; it evaporates water that is then drawn into the atmosphere, turns into clouds, condenses, and falls back to Earth as precipitation. Plants, the land, and the oceans also absorb a portion of solar energy. The rest is reflected and could be used to supply our energy needs.

THE SUN

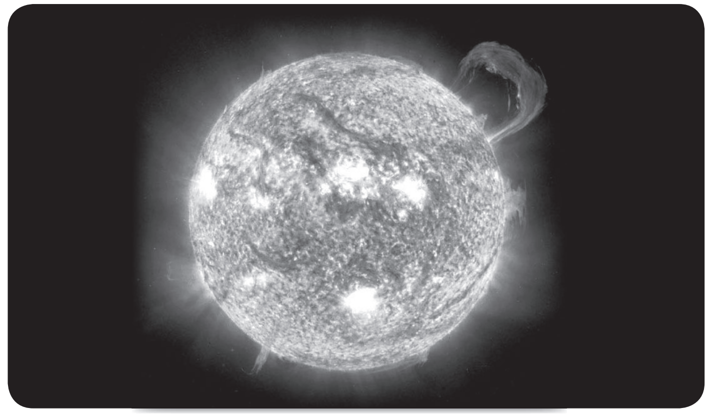
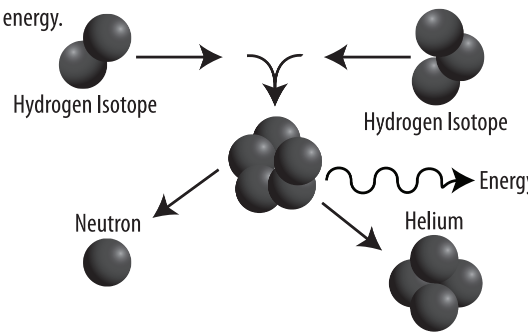


Image courtesy of NASA

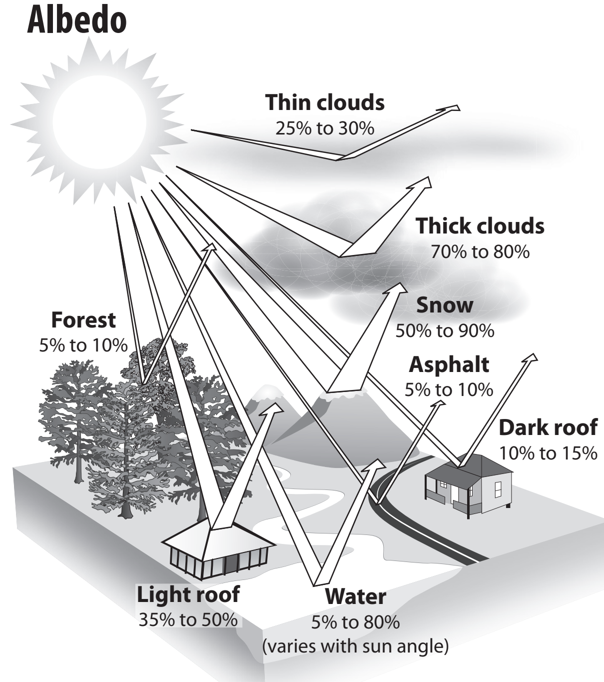
This image of our sun was captured by NASA's Solar Dynamics Observatory—a space telescope designed to study the sun.

Fusion

The process of fusion most commonly involves hydrogen isotopes combining to form a helium atom with a transformation of matter. This matter is emitted as radiant energy.



Albedo



Average reflectivity of solar radiation for various surfaces.

Solar energy is considered a **renewable** energy source. Renewable sources of energy are resources that are continually replenished by nature, and hence will never run out. Solar power is considered renewable because the nuclear fusion reactions that power the sun are expected to keep generating sunlight for many billions of years.

History of Solar Energy

People have harnessed solar energy for centuries. As early as the 7th century B.C., people used simple magnifying glasses to concentrate the light of the sun into beams so hot they could cause wood to catch fire.

In the 1860s in France, a scientist named Auguste Mouchout used heat from a solar collector to make steam to drive a steam engine. Around the same time in the United States, John Ericsson developed the first realistic application of solar energy using a solar reflector to drive an engine in a steam boiler. With coal becoming widely used, neither of these inventions became part of the mainstream.

Early in the 1900s, scientists and engineers began seriously researching ways to use solar energy. The solar water heater gained popularity during this time in Florida, California, and the Southwest. The industry was in full swing just before World War II. This growth lasted until the mid-1950s, when low-cost, natural gas became the primary fuel for heating homes and water, and solar heating lost popularity.

The public and world governments remained largely indifferent to the possibilities of solar energy until the energy crises of the 1970s. Research efforts in the U.S. and around the world since that time have resulted in tremendous improvements in solar technologies for heating water and buildings and making electricity.

JOHN ERICSSON'S SOLAR ENGINE

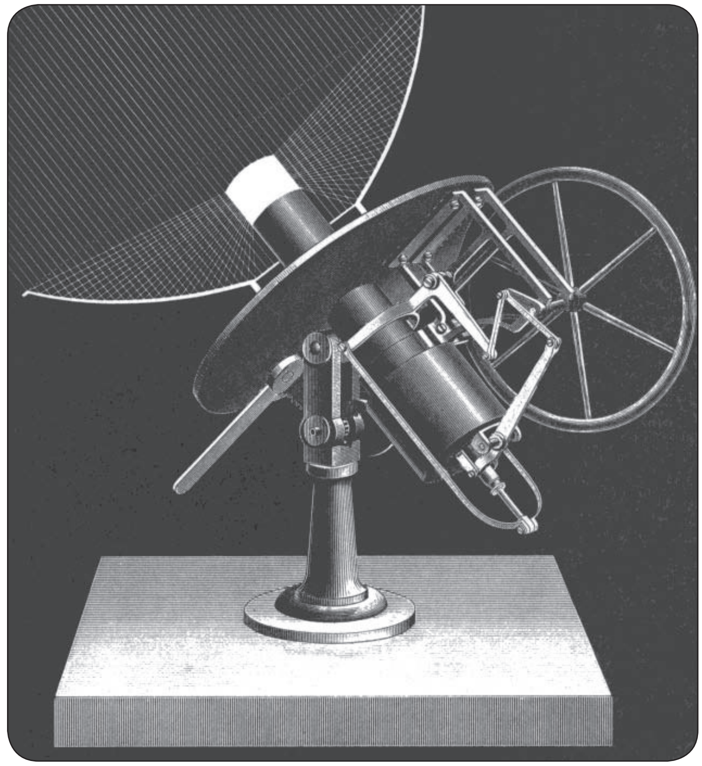


Image courtesy of www.stirlingengines.org

John Ericsson's Sun Motor. Built in New York in 1872. Ericsson had intended Californian agriculturists to take up his sun-motor for irrigation purposes, but in the end nothing came of the project.

Solar Collectors

Heating with solar energy is relatively easy—just look at a car parked in the sun with its windows closed. Getting the right amount of heat in a desired location, however, requires more thought and careful design. Capturing sunlight and putting it to work effectively is difficult because the solar energy that reaches the Earth is spread out over a large area. The sun does not deliver that much energy to any one place at any one time.

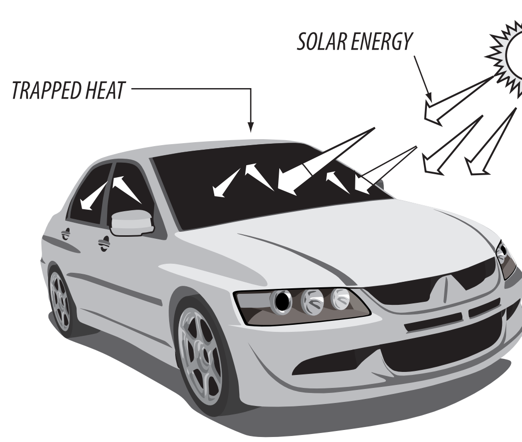
How much solar energy a place receives depends on several conditions. These include the time of day, the season of the year, the latitude of the area, the topography, and the clearness or cloudiness of the sky.

A **solar collector** is one way to collect heat from the sun. A closed car on a sunny day is like a solar collector. As the sunlight passes through the car's glass windows, it is absorbed by the seat covers, walls, and floor of the car. The light that is absorbed changes into heat. The car's glass windows let light in, but do not let all the heat out. This is also how greenhouses are designed to stay warm year-round. A greenhouse or solar collector:

- allows sunlight in through the glass;
- absorbs the sunlight and changes it into heat; and
- traps most of the heat inside.

Solar Collector

On a sunny day, a closed car becomes a solar collector. Light energy passes through the window glass, is absorbed by the car's interior, and converted into heat energy. The heat energy becomes trapped inside.



Photovoltaic Systems

Photovoltaic (or PV) **systems** convert light directly into electricity. The term *photo* comes from the Greek *phos*, which means "light." The term *volt* is a measure of electricity named for Alessandro Volta (1745-1827), a pioneer in the development of electricity. Photovoltaics literally means light–electricity.

Commonly known as solar cells, PV cells are already an important part of our lives. The simplest PV systems power many of the small calculators, wrist watches, and outdoor lights we see every day. Larger PV systems provide electricity for pumping water, powering communications equipment, and even lighting homes and running appliances.

In certain applications, such as motorist aid call boxes on highways and pumping water for livestock, PV power is the cheapest form of electricity. Some electric utility companies are building PV systems into their power supply networks.

History of Photovoltaics

French physicist Edmond Becquerel first described the photovoltaic effect in 1839, but it remained a curiosity of science for the next half century. At the age of 19, Becquerel found that certain materials would produce small amounts of electric current when exposed to light. In the 1870s, William Adams and Richard Day showed that light could produce an electric current in selenium. Charles Fritts then invented the first PV cell using selenium and gold leaf in 1883, which converted light to electricity at about one percent **efficiency**.

The **conversion efficiency** of a PV cell is the proportion of radiant energy the cell converts into electrical energy, relative to the amount of radiant energy that is available and striking the PV cell. This is very important when discussing PV devices, because improving this efficiency is vital to making PV energy competitive with more traditional sources of energy, such as fossil fuels.

During the second half of the 20th century, PV science was refined and the process more fully developed. Major steps toward commercializing photovoltaics were taken in the 1940s and 1950s, when the **Czochralski process** was developed for producing highly pure crystalline silicon.

In 1954, scientists at Bell Laboratories depended on the Czochralski process to develop the first crystalline silicon photovoltaic cell, which had a conversion efficiency of four percent.

As a result of technological advances, the cost of PV cells has decreased significantly over the past 25 years, as the efficiency has increased. Today's commercially available PV devices convert 18 to 24 percent of the radiant energy that strikes them into electricity.

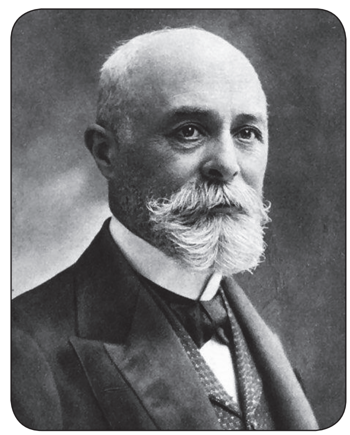
In the laboratory, combining exotic materials with specialized cell designs has produced PV cells with conversion efficiencies as high as 43 percent. The current expense of these technologies typically restricts their use to aerospace and industrial applications, where the unit cost of a solar array that powers, for example, a satellite is a

SOLAR TRAFFIC SIGNAL

Solar cells provide power to this traffic signal. Attached to the support pole are two boxes: one that stores batteries for operation while it's dark, and one that houses a control panel.

ALESSANDRO VOLTA

EDMOND BECQUEREL



SOLAR PANELS ON THE INTERNATIONAL SPACE STATION

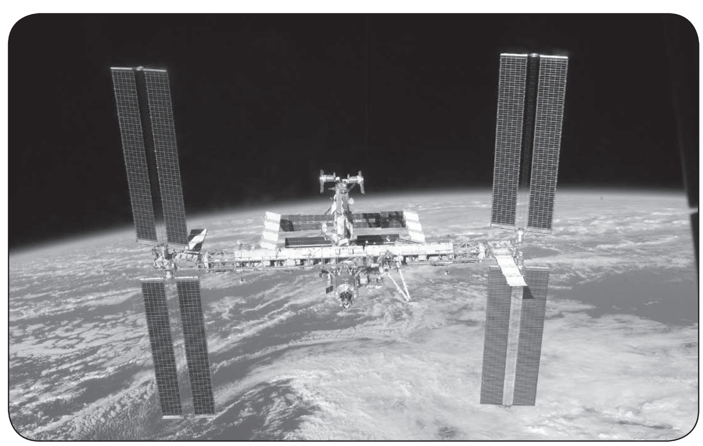


Image courtesy of NASA

High efficiency photovoltaic cells power the International Space Station.

Photovoltaic Technology

Photovoltaic Effect

The **photovoltaic effect** is the basic physical process through which a PV cell converts sunlight directly into electricity. PV technology works any time the sun is shining, but more electricity is produced when the light is more intense and when it is striking the PV modules directly—when the rays of sunlight are perpendicular to the PV modules.

Unlike solar systems for heating water, PV technology does not produce heat to make electricity. Instead, PV cells generate electricity directly from the electrons freed by the interaction of radiant energy with the semiconductor materials in the PV cells.

Sunlight is composed of **photons**, or bundles of radiant energy. When photons strike a PV cell, they may be reflected, absorbed, or transmitted through the cell.

Only the absorbed photons generate electricity. When the photons are absorbed, the energy of the photons is transferred to electrons in the atoms of the solar cell, which is actually a **semiconductor**.

With their new-found energy, the electrons are able to escape from their normal positions associated with their atoms to become part of the current in an electrical circuit. By leaving their positions, the electrons cause holes to form in the atomic structure of the cell into which other electrons can move.

Special electrical properties of the PV cell—a built-in electric field—provide the voltage needed to drive the current through a circuit and power an external load, such as a light bulb.

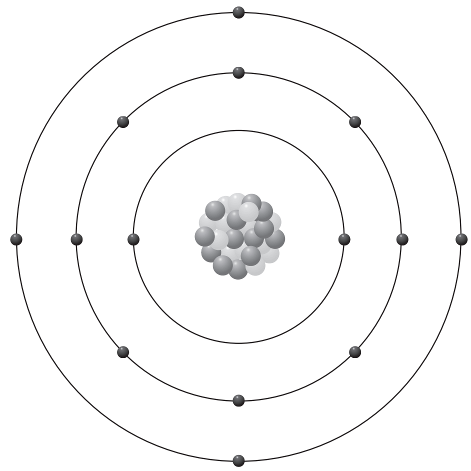
Photovoltaic Cells

The basic building block of PV technology is the **photovoltaic cell**. Different materials are used to produce PV cells, but silicon—the main ingredient in sand—is the most common basic material. Silicon, a common semiconductor material, is relatively cheap because it is widely available and used in other things, such as televisions, radios, and computers. PV cells, however, require very pure silicon, which can be expensive to produce.

The amount of electricity a PV cell produces depends on its size, its conversion efficiency, and the intensity of the light source. Efficiency is a measure of the amount of electricity produced from the sunlight a cell receives. A typical PV cell produces 0.5 volts of electricity. It takes just a few PV cells to produce enough electricity to power a small watch or solar calculator.

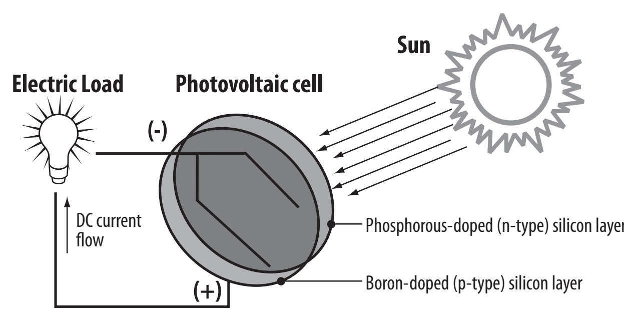
The most important parts of a PV cell are the semiconductor layers, where the electric current is created. There are a number of different materials suitable for making these semi-conducting layers, and each has benefits and drawbacks. Unfortunately, there is no one ideal material for all types of cells and applications.

Silicon Atom



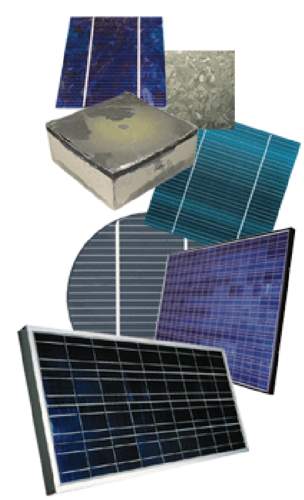
Silicon is used as a semiconductor because it has four valence electrons and does not want to lose or gain electrons. Therefore, the electrons flow across it from the boron side to the phosphorus side without the silicon interfering with the movement.

Sunlight to Electricity



Types of PV Cells

PV cells come in many shapes and sizes. The most common shapes are circles, rectangles, and squares. The size and the shape of a PV cell, and the number of PV cells required for one PV module, depend on the material of which the PV cell is made.



How a Traditional PV Cell is Made

Let's look more closely at how a PV cell is made and how it produces electricity.

Step 1

A slab (or wafer) of pure silicon is used to make a PV cell. The top of the slab is very thinly diffused with an "n" dopant, such as phosphorous. On the base of the slab, a small amount of a "p" **dopant**, typically boron, is diffused. The boron side of the slab is 1,000 times thicker than the phosphorous side. Dopants are similar in atomic structure to the primary material. The phosphorous has one more electron in its outer shell than silicon, and the boron has one less. These dopants help create the electric field that motivates the energetic electrons out of the cell created when light strikes the PV cell.

The phosphorous gives the wafer of silicon an excess of free electrons; it has a negative character. This is called the **n-type silicon** (n = negative). The n-type silicon is not charged—it has an equal number of protons and electrons—but some of the electrons are not held tightly to the atoms. They are free to move to different locations within the layer. This silicon has a negative character, but not a negative charge.

The boron gives the base of the silicon wafer a positive character, which will cause electrons to flow toward it. The base of the silicon is called **p-type silicon** (p = positive). The p-type silicon has an equal number of protons and electrons; it has a positive character, but not a positive charge.

Step 2

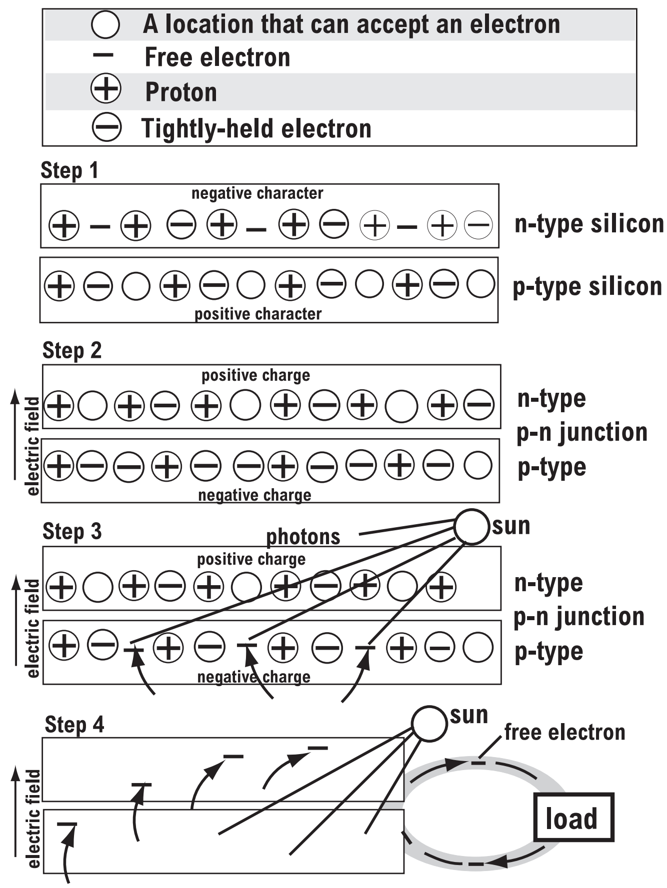
Where the n-type silicon and p-type silicon meet, free electrons from the n-layer flow into the p-layer for a split second, then form a barrier to prevent more electrons from moving between the two sides. This point of contact and barrier is called the p-n junction.

When both sides of the silicon slab are doped, there is a negative charge in the p-type section of the junction and a positive charge in the n-type section of the junction due to movement of the electrons and "holes" at the junction of the two types of materials. This imbalance in electrical charge at the p-n junction produces an electric field between the p-type and n-type.

Step 3

If the PV cell is placed in the sun, photons of light strike the electrons in the p-n junction and energize them, knocking them free of their atoms. These electrons are attracted to the positive charge in the n-type silicon and repelled by the negative charge in the p-type silicon. Most photon-electron collisions actually occur in the silicon base.

Photovoltaic Cell



Step 4

A conducting wire connects the p-type silicon to an external load such as a light or battery, and then back to the n-type silicon, forming a complete circuit. As the free electrons are pushed into the n-type silicon, they repel each other because they are of like charge. The wire provides a path for the electrons to move away from each other. This flow of electrons is an electric current that can power a load, such as a calculator or other device, as it travels through the circuit from the n-type to the p-type.

In addition to the semi-conducting materials, solar cells consist of a top metallic grid or other electrical contact to collect electrons from the semiconductor and transfer them to the external load, and a back contact layer to complete the electrical circuit.

PV Modules and Arrays

For more power, PV cells are connected together to form larger units called **modules**. Photovoltaic cells are connected in series and/or parallel circuits to produce higher voltages, currents, and power levels. A PV module is the smallest PV component sold commercially, and can range in power output from about 10 watts to 300 watts.

A typical PV module consists of PV cells sandwiched between a clear front sheet, usually glass, and a backing sheet, usually glass or a type of tough plastic. This protects them from breakage and from the weather. An aluminum frame can be fitted around the PV module to enable easy affixing to a support structure. Photovoltaic **arrays** include two or more PV modules assembled as a pre-wired, field-installable unit. A PV array is the complete power-generating unit, consisting of any number of modules and panels.

PV System Components

Although a PV module produces power when exposed to sunlight, a number of other components are required to properly conduct, control, convert, distribute, and store the energy produced by the array. Depending on the type of system, these components may include:

▪ Power Inverter

PV modules, because of their electrical properties, produce direct current rather than alternating current. **Direct current (DC)** is electric current that flows in a single direction. Many simple devices, such as those that run on batteries, use direct current. **Alternating current (AC)**, in contrast, is electric current that reverses its direction of flow at regular intervals (120 times per second). This is the type of electricity provided by utilities, and the type required to run most modern appliances and electronic devices.

In the simplest systems, DC current produced by PV modules is used directly. In applications where AC current is necessary, an **inverter** can be added to the system to convert DC to AC current.

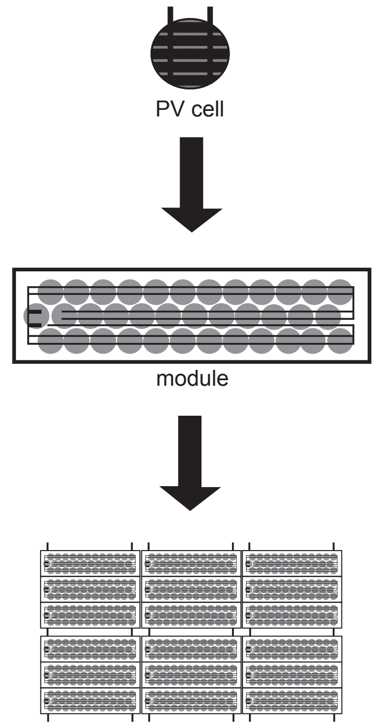
▪ Battery System

PV systems cannot store electricity, so batteries are often added. A PV system with a battery is configured by connecting the PV array to an inverter. The inverter is connected to a battery bank and to any load. During daylight hours, the PV array charges the battery bank. The battery bank supplies power to the load whenever it is needed. A device called a **charge controller** keeps the battery properly charged and prolongs its life by protecting it from being overcharged or completely discharged.

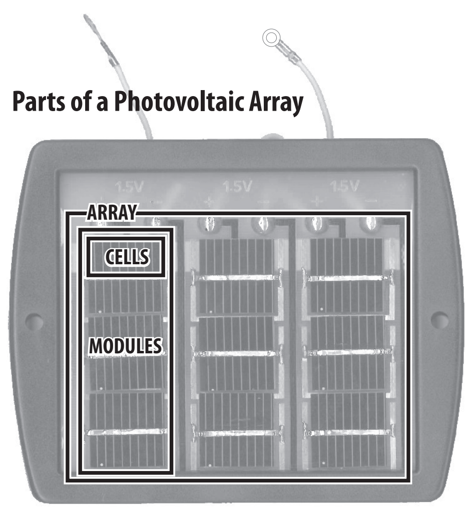
PV systems with batteries can be designed to power DC or AC equipment. Systems operating only DC equipment do not need an inverter, only a charge controller.

It is useful to remember that any time conversions are made in a system, there are associated losses. For example, when an inverter is used there is a small loss of power that can be described by the inverter's conversion efficiency. Likewise, when batteries are used to store power, not only is there additional expense to purchase the batteries and associated equipment, but due to the internal resistance of the batteries there is a small loss of power as the charge is drawn out of the batteries.

Photovoltaic Arrays Are Made of Individual Cells



Parts of a Photovoltaic Array



PV Systems

Two types of PV systems are grid-connected systems and stand-alone systems. The main difference between these systems is that one is connected to the utility **grid** and the other is not.

▪ Grid-Connected Systems

Grid-connected systems are designed to operate in parallel with, and interconnected with, the national electric utility grid. What is the grid? It is the network of cables through which electricity is transported from power stations to homes, schools, and other places. A grid-connected system is linked to this network of power lines.

The primary component of a grid-connected system is the inverter, or power conditioning unit (PCU). The inverter converts the DC power produced by the PV system into AC power, consistent with the voltage and power quality requirements of the utility grid. This means that it can deliver the electricity it produces into the electricity network and draw it down when needed; therefore, no battery or other storage is needed.

▪ Stand-Alone Systems

As its name suggests, this type of PV system is a separate electricity supply system. A stand-alone system is designed to operate independent of the national electric utility grid, and to supply electricity to a single system. Usually a stand-alone system includes one or more batteries to store the electricity.

Historically, PV systems were used only as stand–alone systems in remote areas where there was no other electricity supply. Today, stand-alone systems are used for water pumping, highway lighting, weather stations, remote homes, and other uses away from power lines.

Grid-Connected Systems

PV Array
↓
Inverter/ Power Conditioning Unit
↓
Distribution Panel
↙ ↘
AC Loads **Electric Utility**

Image courtesy of PG&E

PG&E's Vaca-Dixon Solar Station in California is a 2-MW grid-connected system.

Stand-Alone Systems

Energy Source
↓
Energy Conversion
↓
Energy Inversion and Conditioning ↔ **Energy Storage**
↓
Energy Use ← **Energy Distribution** ↔ **Grid**

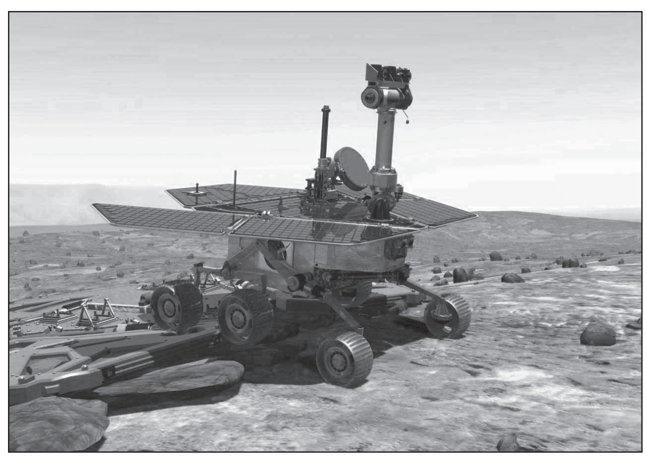


Image courtesy of NASA

The Mars Rovers, Spirit and Opportunity, are powered by stand-alone systems because they operate far away from Earth.

Scale of PV Systems

There are three general scales at which photovoltaic systems are generally installed. They are:

▪ Residential

A residential system is designed to offset power usage at an individual residence. While usually unable to provide all power used by the homeowners, the system could help to offset the home's electricity usage. This type of system might produce enough electricity to power part, or all, of one home's electricity needs.

▪ Commercial

A commercial system is designed to offset power usage at a business or industrial site. These systems are much larger than residential systems that can produce more power due to the often expansive roof-top space available for their installation. An example would be a grocery store that contracts with a company to place a solar array on their flat roof while simultaneously contracting to buy power from the installer at a fixed rate for many years. This type of system might produce enough electricity to operate all or part of the business or industrial site.

▪ Utility

Utility systems are employed by energy companies to produce base-load or peak-load power for sale to consumers. Large areas of land are typically required for their installation. An example would be a large PV array that is employed to produce power at peak usage times in the summer months when air conditioning accounts for a large part of the electrical usage. The array produces the most power when the sun is at its peak and causing consumers to turn down their thermostats—requiring the extra electricity produced by the array.

▪ Other Solar Technologies

Like solar cells, solar thermal systems use solar energy to make electricity. **Concentrated solar power** (CSP) technologies focus heat in one area to produce the high temperatures required to make electricity. Since the solar radiation that reaches the Earth is so spread out and diluted, it must be concentrated to produce the high temperatures required to generate electricity. There are several types of technologies that use mirrors or other reflecting surfaces to concentrate the sun's energy up to 2,000 times its normal intensity.

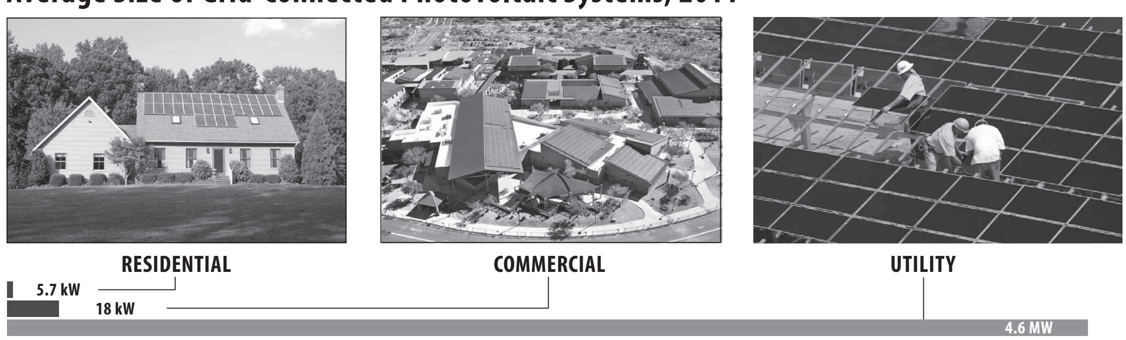
Parabolic troughs use long reflecting troughs that focus the sunlight onto a pipe located at the focal line. A fluid circulating inside the pipe collects the energy and transfers it to a heat exchanger, which produces steam to drive a turbine. The world's largest parabolic trough power plant is located in the Mojave Desert in California. This plant has a total generating capacity of 354 megawatts, one-third the size of a large nuclear power plant.

Solar power towers use a large field of rotating mirrors to track the sun and focus the sunlight onto a thermal receiver on top of a tall tower. The fluid in the receiver collects the heat and either uses it to generate electricity or stores it for later use.

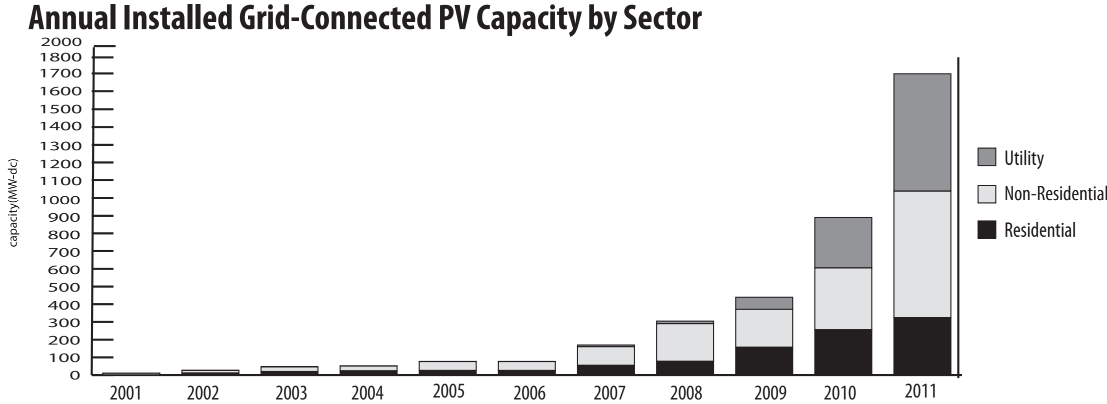
Dish/engine systems are like satellite dishes that concentrate sunlight rather than signals, with a heat engine located at the focal point to generate electricity. These generators are small mobile units that can be operated individually or in clusters, in urban and remote locations.

Concentrated solar power technologies require a continuous supply of strong sunlight, like that found in hot, dry regions such as deserts. Developing countries with increasing electricity demand will probably be the first to use CSP technologies on a large scale.

Average Size of Grid-Connected Photovoltaic Systems, 2011



Annual Installed Grid-Connected PV Capacity by Sector



Data: Interstate Renewable Energy Council

Emerging PV Technologies

Today there are many new PV technologies either on the market, in the pipeline, or in the research phase. These technologies will have a direct effect on how much of our energy we derive from solar power in the future. Look for technologies that will make things less expensive or serve multiple purposes as they are applied to new designs.

▪ Ribbon Silicon

Thin crystalline silicon sheets are drawn out of molten silicon rather than being sawed from an **ingot**. This method is less expensive and less wasteful to produce silicon. However, the finished product is usually a lower quality material. In some cases, they will have cells of a higher conversion efficiency.

▪ Amorphous Silicon / Thin-Film Technologies

This new class of materials allows the production of PV cells that are smaller and more flexible than the delicate silicon wafer technology that has dominated PV cell production in the past. These materials are not crystalline, but **amorphous**, in structure. This type of PV cell can actually be applied to a variety of materials to make any number of materials that you might use for another purpose—such as glazing for a window, or shingles for a roof. Imagine windows that produce electricity! Materials used for dual purposes (building material and PV cell) are called Building Integrated Photovoltaics (BIPV).

▪ CdTe: Cadmium Telluride

This thin-film technology has higher solar spectrum absorption and lower costs to manufacture, however, there are concerns about the toxicity and scarcity of chemicals necessary for its production.

▪ CIGS: Copper Indium Gallium Diselenide

The gallium is added to these thin-film cells to increase the energy absorption of the cells, which increases efficiency.

▪ Earth Abundant Materials

Manufacturing PV cells from abundant, low cost resources is a research priority. One of the promising technologies is sulfoselenide or CZTS. The drawback to CZTS is a lower efficiency than other PV cells.

Thin-film materials are much cheaper to produce. They are very versatile in how they can be applied to many structural materials. They are also less efficient than current silicon crystal PV cells. However, what they lack in efficiency may be overcome by their flexibility of application and low cost.

▪ Multijunction Technologies

This category actually combines multiple layers of materials that are designed to absorb different wavelengths of solar energy—improving the efficiency of the cell by combining the output of the various layers. Multijunction cells are a high-cost PV technology, but can reach efficiencies of over 43 percent.

▪ Dye Sensitized Solar Cells

While not yet in production, this organic-inorganic hybrid technology shows promise to be a very low cost technology. Using a small-molecule dye that absorbs photons, an acceping material such as zinc ozide, and an electrolyte, this technology is easy to manufacture from abundant materials. Research continues to improve durability.

THIN-FILM TECHNOLOGY

The Schapfen Mill Tower is a flour mill in Germany. The southern facade is faced with 1,300 thin-film solar modules.

Benefits and Limitations

▪ Benefits

Solar electric systems offer many advantages:

- they are safe, clean, and quiet to operate;
- they are highly reliable;
- they require virtually no maintenance;
- they are cost-effective in remote areas and for some residential and commercial applications;
- they are flexible and can be expanded to meet increasing electrical needs;
- they can provide independence from the grid or backup during outages; and
- the fuel is renewable and free.

▪ Limitations

There are also some practical limitations to PV systems:

- PV systems are not well suited for energy-intensive uses such as heating; and
- grid-connected systems are rarely economical, primarily because the current cost of the PV technology is much higher than the cost of conventional electricity in the United States.

MUNICH INTERNATIONAL AIRPORT

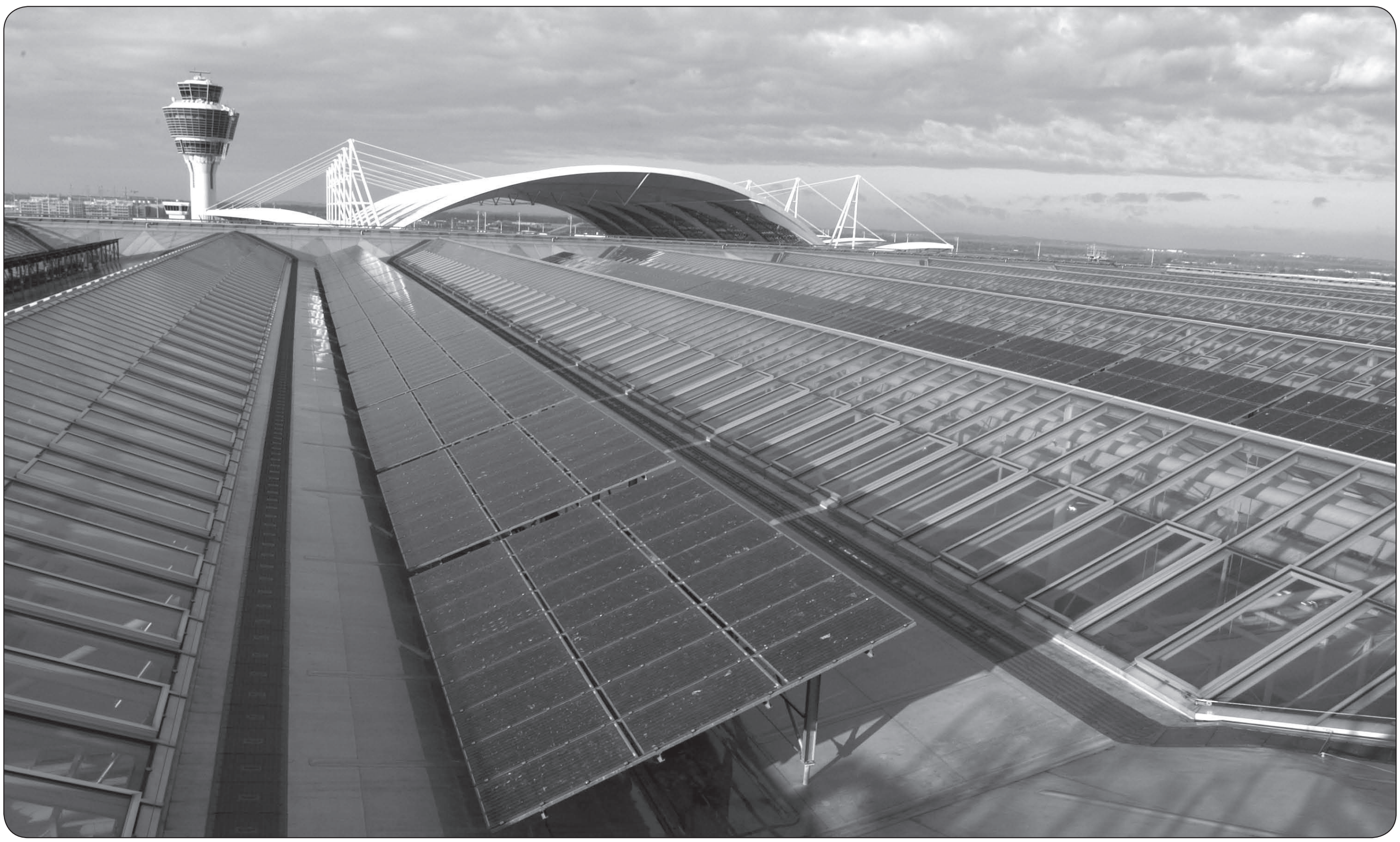


Image courtesy of BP Solar

In August 2002, BP Solar installed a new photovoltaic facility on the roof of the new Terminal 2 at the Munich International Airport. It is one of the largest solar facilities of its kind and produces an average of approximately 500,000 kWh a year—representing the electricity needs of about 200 households. High production of energy is guaranteed even in winter through the use of the latest polycrystalline silicon cells and the optimal alignment of the solar modules at a 20° angle facing south.

Measuring Electricity

Electricity makes our lives easier, but it can seem like a mysterious force. Measuring electricity is confusing because we cannot see it. We are familiar with terms such as watt, volt, and amp, but we do not have a clear understanding of these terms. We buy a 60-watt light bulb, a tool that requires 120 volts, or an appliance that uses 8.8 amps, but we do not think about what those units mean.

Using the flow of water as an analogy can make electricity easier to understand. The flow of electrons in a circuit is similar to water flowing through a hose. If you could look into a hose at a given point, you would see a certain amount of water passing that point each second. The amount of water depends on how much pressure is being applied—how hard the water is being pushed. It also depends on the diameter of the hose. The harder the pressure and the larger the diameter of the hose, the more water passes each second. The flow of electrons through a wire depends on the electrical pressure pushing the electrons and on the cross-sectional area of the wire.

Voltage

The pressure that pushes electrons in a circuit is called voltage. Using the water analogy, if a tank of water were suspended one meter above the ground with a one-centimeter pipe coming out of the bottom, the water pressure would be similar to the force of a shower. If the same water tank were suspended 10 meters above the ground, the force of the water would be much greater, possibly enough to hurt you.

Voltage (V) is a measure of the pressure applied to electrons to make them move. It is a measure of the strength of the current in a circuit and is measured in **volts (V)**. Just as the 10-meter tank applies greater pressure than the 1-meter tank, a 10-volt power supply (such as a battery) would apply greater pressure than a 1-volt power supply.

AA batteries are 1.5-volt; they apply a small amount of voltage for lighting small flashlight bulbs. A car usually has a 12-volt battery—it applies more voltage to push current through circuits to operate the radio or defroster. The standard voltage of wall outlets is 120 volts—a dangerous voltage. An electric clothes dryer is usually wired at 240 volts—a very dangerous voltage.

Current

The flow of electrons can be compared to the flow of water. The water current is the number of molecules of water flowing past a fixed point; electric current is the number of electrons flowing past a fixed point.

Electric current (I) is defined as electrons flowing between two points having a difference in voltage. Current is measured in **amperes** or **amps (A)**. One ampere is 6.25×10^{18} electrons per second passing through a circuit.

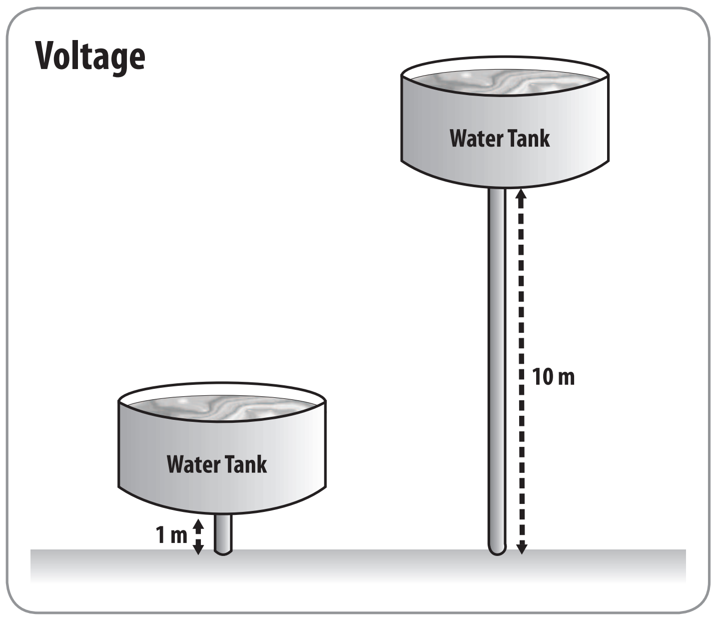
With water, as the diameter of the pipe increases, so does the amount of water that can flow through it. With electricity, conducting wires take the place of the pipe. As the cross-sectional area of the wire increases, so does the amount of electric current (number of electrons) that can flow through it.

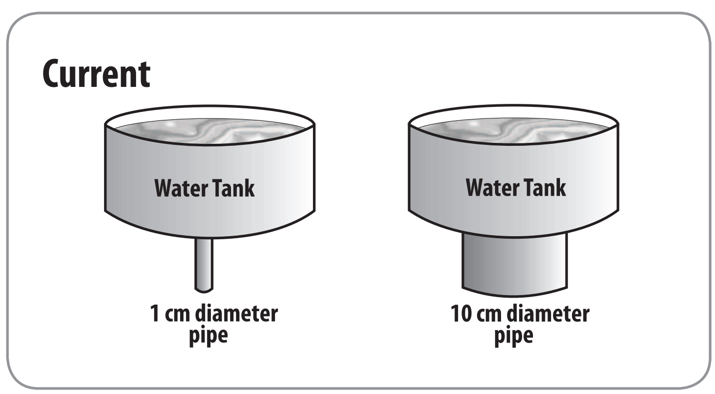
Resistance

Resistance (R) is a property that slows the flow of electrons. Using the water analogy, resistance is anything that slows water flow, such as a smaller pipe or fins on the inside of a pipe.

In electrical terms, the resistance of a conducting wire depends on the properties of the metal used to make the wire and the wire's diameter. Copper, aluminum, and silver—metals used in conducting wires—have different resistance.

Resistance is measured in units called **ohms (Ω)**. There are devices called resistors, with set resistances, that can be placed in circuits to reduce or control the current flow. Any device placed in a circuit to do work is called a load. The light bulb in a flashlight is a load. A television plugged into a wall outlet is also a load. Every load has resistance.





Ohm's Law

George Ohm, a German physicist, discovered that in many materials, especially metals, the current that flows through a material is proportional to the voltage. He found that if he doubled the voltage, the current also doubled. If he reduced the voltage by half, the current dropped by half. The resistance of the material remained the same.

This relationship is called **Ohm's Law** and can be described using a simple formula. If you know any two of the measurements, you can calculate the third using the following formula:

voltage = current x resistance
V = I x R or V = A x Ω

Electric Power

Power (P) is a measure of the rate of doing work or the rate at which energy is converted. Electric power is the rate at which electricity is produced or consumed. Using the water analogy, electric power is the combination of the water pressure (voltage) and the rate of flow (current) that results in the ability to do work.

A large pipe carries more water (current) than a small pipe. Water at a height of 10 meters has much greater force (voltage) than at a height of one meter. The power of water flowing through a 1-centimeter pipe from a height of one meter is much less than water through a 10-centimeter pipe from 10 meters.

Electric power is defined as the amount of electric current flowing due to an applied voltage. It is the amount of electricity required to start or operate a load for one second. Electric power is measured in **watts (W)**. The formula is:

power = voltage x current
P = V x I or W = V x A

Electrical Energy

Electrical energy introduces the concept of time to electric power. In the water analogy, it would be the amount of water falling through the pipe over a period of time, such as an hour. When we talk about using power over time, we are talking about using energy. Using our water example, we could look at how much work could be done by the water in the time that it takes for the tank to empty.

The electrical energy that an appliance or device consumes can be determined only if you know how long (time) it consumes electric power at a specific rate (power). To find the amount of energy consumed, you multiply the rate of energy consumption (measured in watts) by the amount of time (measured in hours) that it is being consumed. Electrical energy is measured in watt-hours (Wh).

energy = power x time
E = P x t or E = W x h = Wh

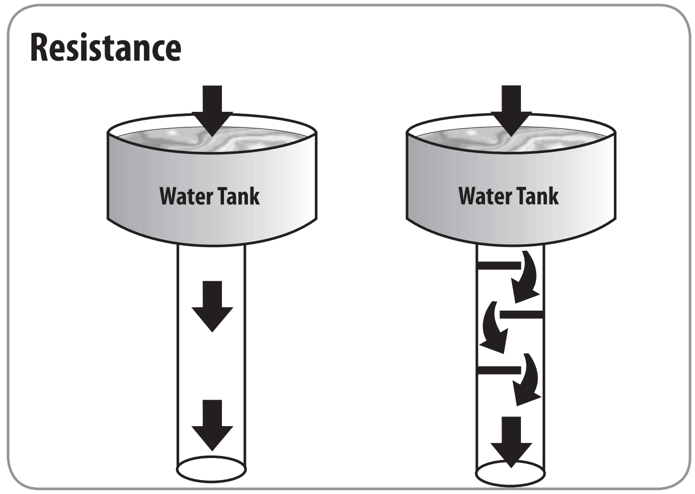
Another way to think about power and energy is with an analogy to traveling. If a person travels in a car at a rate of 40 miles per hour (mph), to find the total distance traveled, you would multiply the rate of travel by the amount of time you traveled at that rate.

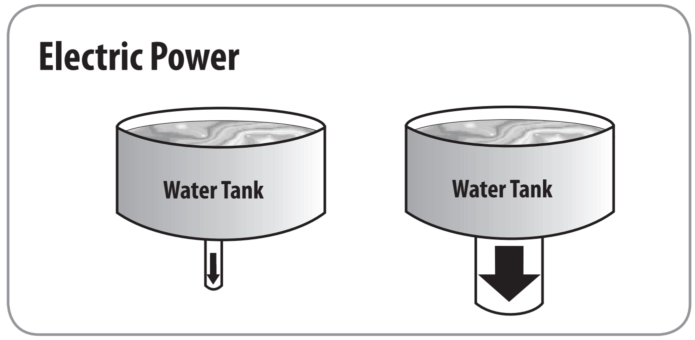
If a car travels at 40 miles per hour for 1 hour, it would travel 40 miles.

distance = 40 mph x 1 hour = 40 miles

If a car travels at 40 miles per hour for 3 hours, it would travel 120 miles.

distance = 40 mph x 3 hours = 120 miles





The distance traveled represents the work done by the car. When we look at power, we are talking about the rate that electrical energy is being produced or consumed. Energy is analogous to the distance traveled or the work done by the car.

A person would not say he took a 40-mile per hour trip because that is the rate. The person would say he took a 40-mile trip or a 120-mile trip. We would describe the trip in terms of distance traveled, not rate traveled. The distance represents the amount of work done.

The same applies with electric power. You would not say you used 100 watts of light energy to read your book, because a watt represents the rate you use energy, not the total energy used. The amount of energy used would be calculated by multiplying the rate by the amount of time you read.

If you read for five hours with a 100-W light bulb, for example, you would use the formula as follows:

energy = power x time (E = P x t)
energy = 100 W x 5 hours = 500 Wh

One watt-hour is a very small amount of electrical energy. Usually, we measure electric power in larger units called **kilowatt-hours (kWh)** or 1,000 watt-hours (kilo = thousand). A kilowatt-hour is the unit that utilities use when billing most customers. The average cost of a kilowatt-hour of electricity for residential customers is about $0.12.

To calculate the cost of reading with a 100-W light bulb for five hours, you would change the watt-hours into kilowatt-hours, then multiply the kilowatt-hours used by the cost per kilowatt-hour, as shown below:

500 Wh / 1,000 = 0.5 kWh
0.5 kWh x $0.12/kWh = $0.06

Therefore, it would cost about six cents to read for five hours with a 100-W light bulb.

Review Questions

1. Identify and explain the nuclear reaction in the sun that produces radiant energy.

2. Define renewable energy. Explain why solar energy is considered renewable.

3. Explain why a car parked in the sun becomes hot inside.

4. Why is a solar cell called a PV cell? What does the word photovoltaic mean?

5. Explain the conversion efficiency of a PV cell. How efficient are PV cells today?

6. How do new thin-film technologies compare to conventional PV cells?

7. Explain briefly how a PV cell converts radiant energy into electricity.

8. Do PV modules produce AC or DC current? Which type of current do most appliances use? What device converts DC to AC current?

9. Define the following electrical measures and the unit of measurement for each.

   voltage:

   current:

   resistance:

   power:

10. What is the average cost of a kilowatt-hour of electricity for U.S. residential customers?

Calculation of Power

Power (P) is a measure of the rate of doing work or the rate at which energy is converted. **Electric power** is defined as the amount of electric current flowing due to an applied voltage. Electric power is measured in **watts (W)**. The formula is:

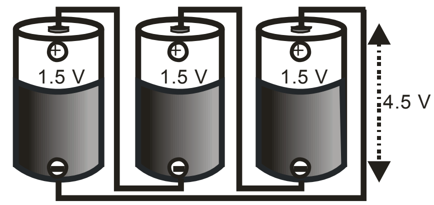
power = voltage x current

$$P = V \times I \qquad \text{or} \qquad W = V \times A$$

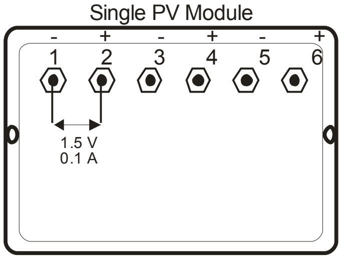
Series Circuits

In series circuits, the current remains constant while the voltage changes. To calculate total voltage, add the individual voltages together:

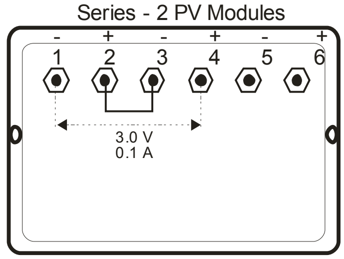
$$I_{total} = I_1 = I_2 = I_3$$
$$V_{total} = V_1 + V_2 + V_3$$



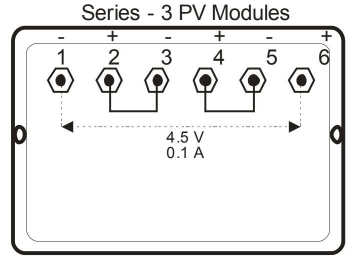
Single PV Module



Series - 2 PV Modules



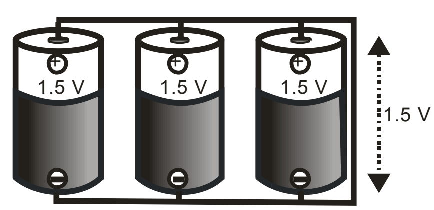
Series - 3 PV Modules



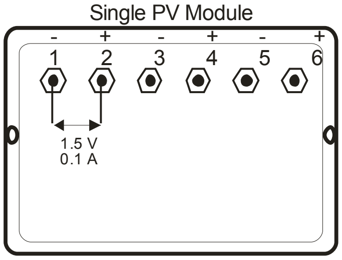
Parallel Circuits

In parallel circuits, the voltage remains constant while the current changes. To calculate total current, add the individual currents together:

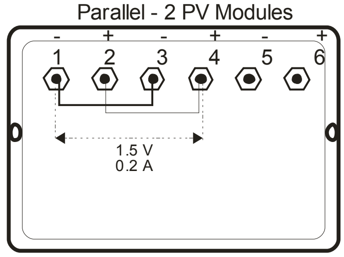
$$I_{total} = I_1 + I_2 + I_3$$
$$V_{total} = V_1 = V_2 = V_3$$



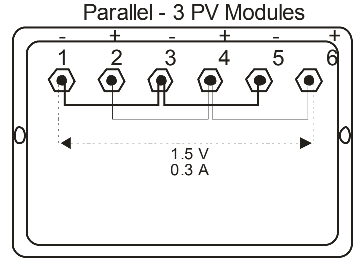
Single PV Module



Parallel - 2 PV Modules



Parallel - 3 PV Modules



Basic Measurement Values in Electronics

SYMBOL	VALUE	METER	UNIT
V	Voltage (the force)	Voltmeter	Volts (V)
I	Current (the flow)	Ammeter	Amps/Amperes (A)
R	Resistance (the anti-flow)	Ohmmeter	Ohms (Ω)

1 Ampere = 1 coulomb/second

1 Coulomb = 6.24×10^{18} electrons (about a triple axle dump truck full of sand where one grain of sand is one electron)

Prefixes for Units

- **Smaller**

  (m)illi x 1/1000 or .001

  (µ) micro x 1/1000000 or .000001

  (n)ano x1/100000000 or .000000001

  (p)ico x 1/1000000000000 l or .000000000001

- **Bigger**

  (K)ilo x 1,000

  (M)ega x 1,000,000

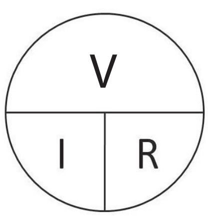
  (G)iga x 1,000,000,000

Formulas for Measuring Electricity

V = I x R

I = V/R

R = V/I



The formula pie works for any three variable equation. Put your finger on the variable you want to solve for and the operation you need is revealed.

- **Series Resistance (Resistance is additive)**

  $R_T = R_1 + R_2 + R_3 \ldots + R_n$

- **Parallel Resistance (Resistance is reciprocal)**

  $1/R_T = 1/R_1 + 1/R_2 + 1/R_3 \ldots + 1/R_n$

Note: ALWAYS convert the values you are working with to the “BASE unit.” For example—don’t plug kilo-ohms (KΩ) into the equation—convert the value to Ω first.

Digital Multimeter

Directions

DC Voltage (V⎓)

1. Connect RED lead to VΩmA connector and BLACK to COM.
2. Set SWITCH to highest setting on DC VOLTAGE scale (1000).
3. Connect leads to the device to be tested using the alligator clips provided.
4. Adjust SWITCH to lower settings until a satisfactory reading is obtained.
5. With the solar modules or array the 20 setting usually provides the best reading.

DC Current (A⎓)

1. Connect RED lead to VΩmA connector and BLACK to COM.
2. Set SWITCH to 10 ADC setting.
3. Connect leads to the device to be tested using the alligator clips provided.
   Note: The reading indicates DC AMPS; a reading of 0.25 amps equals 250 ma (milliamps).

YOUR MULTIMETER MIGHT BE SLIGHTLY DIFFERENT FROM THE ONE SHOWN. BEFORE USING THE MULTIMETER READ THE OPERATOR'S INSTRUCTION MANUAL INCLUDED IN THE BOX FOR SAFETY INFORMATION AND COMPLETE OPERATING INSTRUCTIONS.