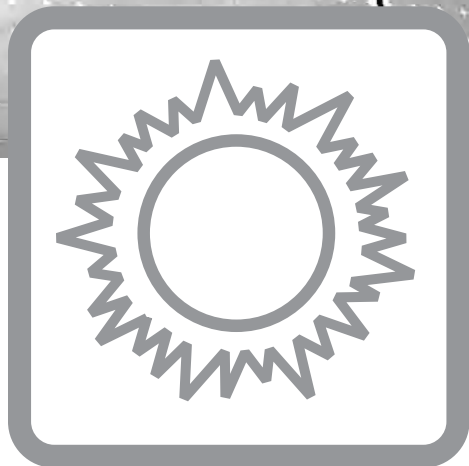
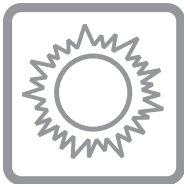


Photovoltaics

Student Guide



National Energy Education Development Project



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 in one second than people have used since the beginning of time! 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 hydrogen atoms to come apart and their **nuclei** (the central cores of the atoms) to **fuse** or combine. Four hydrogen nuclei fuse to become one helium atom; but the helium atom contains less mass than the four hydrogen atoms that fused. Some matter is converted to energy during nuclear fusion. The converted matter is emitted into space in the form of radiant energy.

Scientists theorize that the time for the energy in the sun's core to make its way to the solar surface varies from 10,000 years to 170,000 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 186,000 miles per second (3.0×10^8 meters per second), the speed of light. Heat energy is not transmitted from the sun because space between the sun and Earth is mostly a vacuum. Rather, radiant energy transforms into **thermal** (heat) **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. Every day enough energy strikes the United States to supply the nation's energy needs for one and a half years!

Where does all this energy go? About 15 percent of the sun's energy that hits the Earth is reflected back into space. Another 30 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.

Solar energy is considered a renewable energy source. Renewable sources of energy are resources that are continually renewed 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.

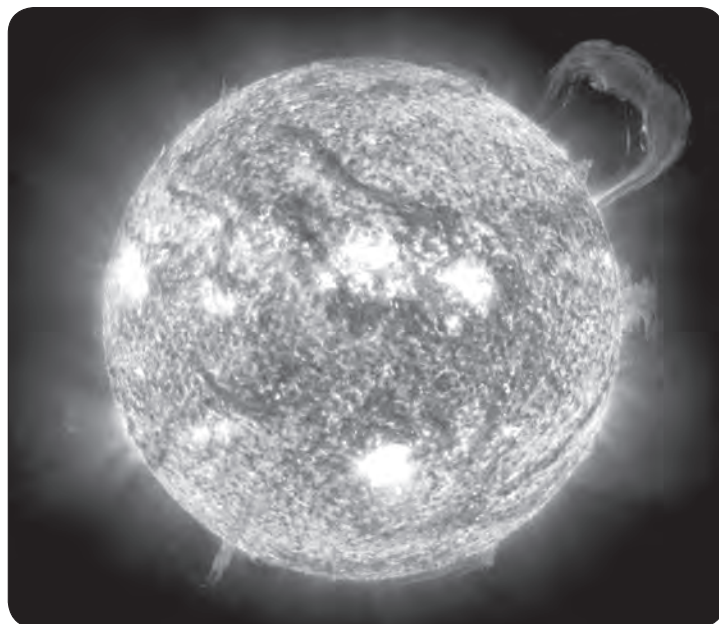
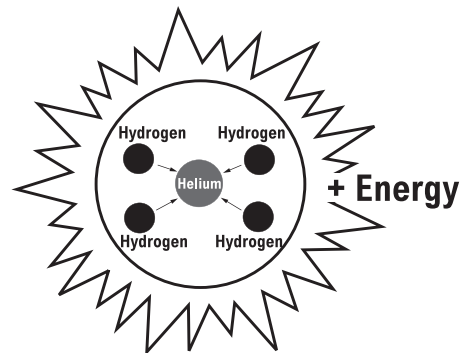


Image courtesy of NASA

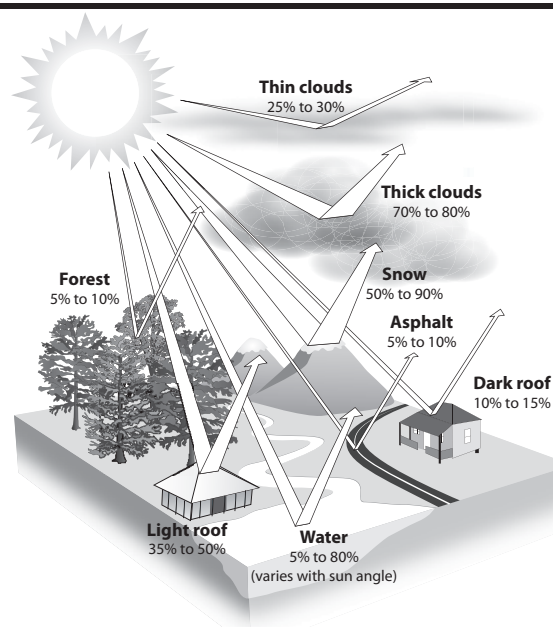
This image of our sun was captured by NASA's Solar Dynamics Observatory—a space telescope designed to study the sun.

FUSION

During a process called **FUSION**, four hydrogen atoms combine to form one helium atom, with a transformation of matter. This matter is emitted as radiant energy.



SOLAR ENERGY REFLECTED ON THE EARTH'S SURFACE



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.

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.

JOHN ERICSSON'S SOLAR ENGINE

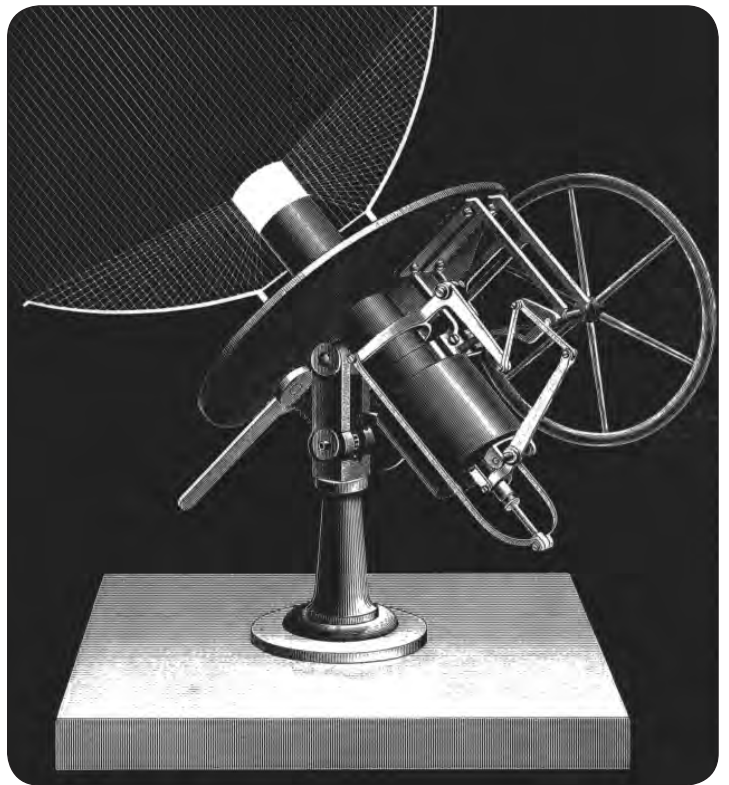
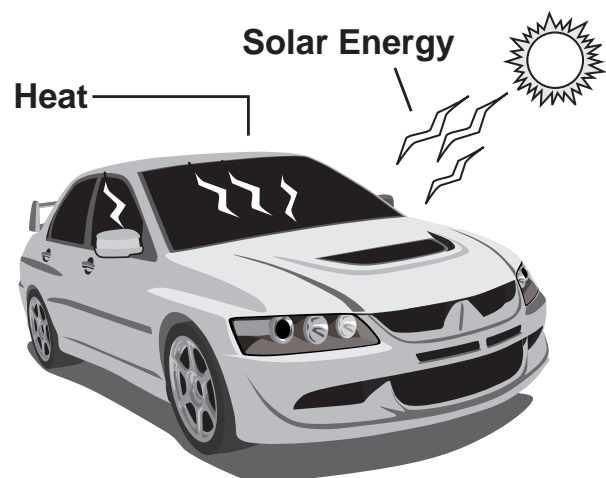


Image courtesy of www.stirlingengines.org

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.

A CAR AS A SOLAR COLLECTOR



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 and wrist watches we use 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. The effect was first studied in solids, such as selenium, by Heinrich Hertz in the 1870s. Soon selenium PV cells were converting light to electricity at one to two 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 7 to 17 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 minor concern.

SOLAR TRAFFIC SIGNAL

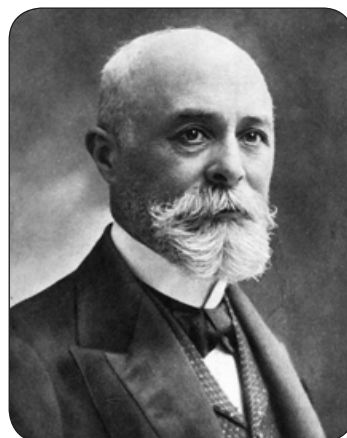


A solar cell provides power to this traffic signal. Attached to the support pole are two boxes: one that stores batteries for operation while it’s dark, and one that houses a control panel.

ALESSANDRO VOLTA



EDMOND BECQUEREL



SOLAR PANELS ON THE INTERNATIONAL SPACE STATION

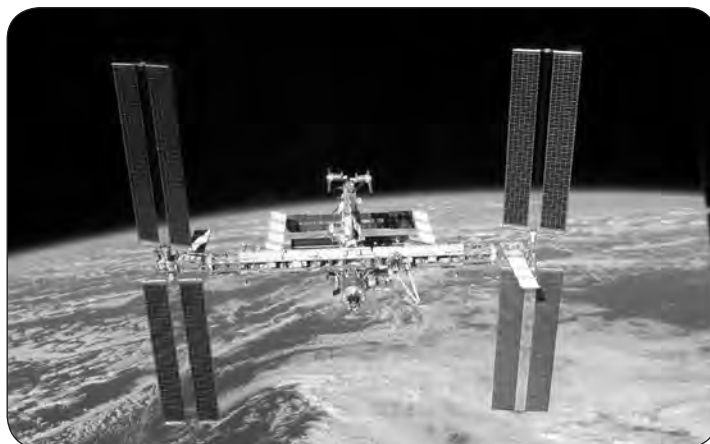
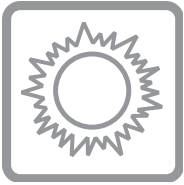


Image courtesy of NASA

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.

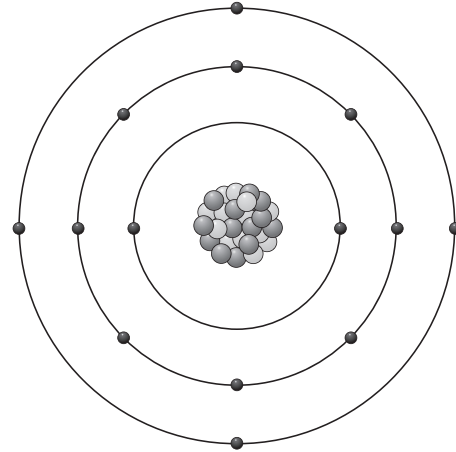
Photovoltaic Cells

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.

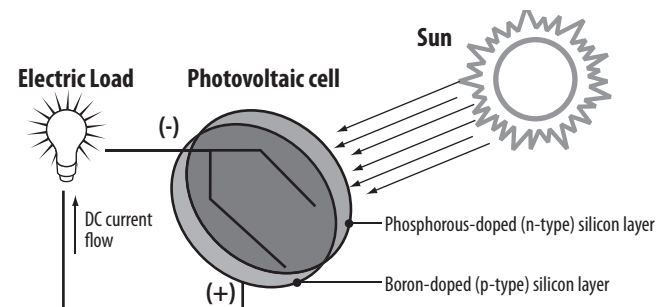
The most important parts of a PV cell are the **semi-conductor** layers, where the electric current is created. There are a number of different materials suitable for making these semi-conducting layers, and each has benefits and drawbacks. Unfortunately, there is no one ideal material for all types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

SILICON ATOM



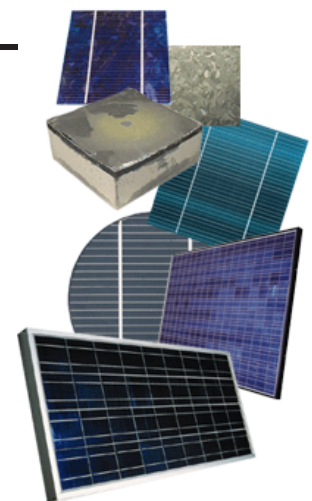
Silicon is used as a semiconductor because it has four valence electrons and does not want to lose or gain electrons. Therefore, the electrons flow across it from the boron side to the phosphorus side without the silicon interfering with the movement.

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**. 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.

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.

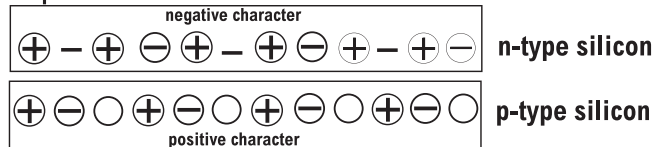
▪ Step 3

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.

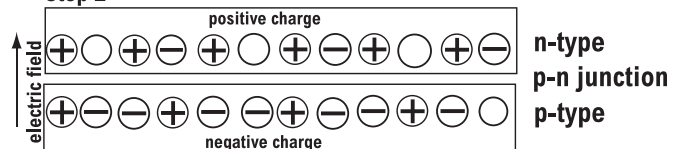
PHOTOVOLTAIC CELL

○	A location that can accept an electron
—	Free electron
⊕	Proton
⊖	Tightly-held electron

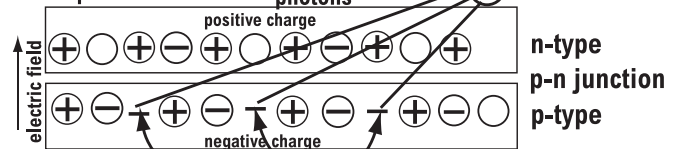
Step 1



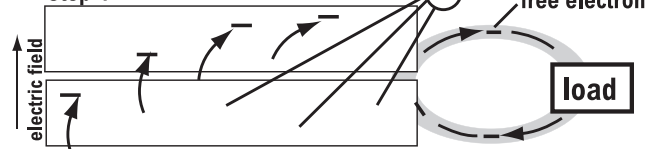
Step 2



Step 3



Step 4



▪ 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 semi-conductor 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 one 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.

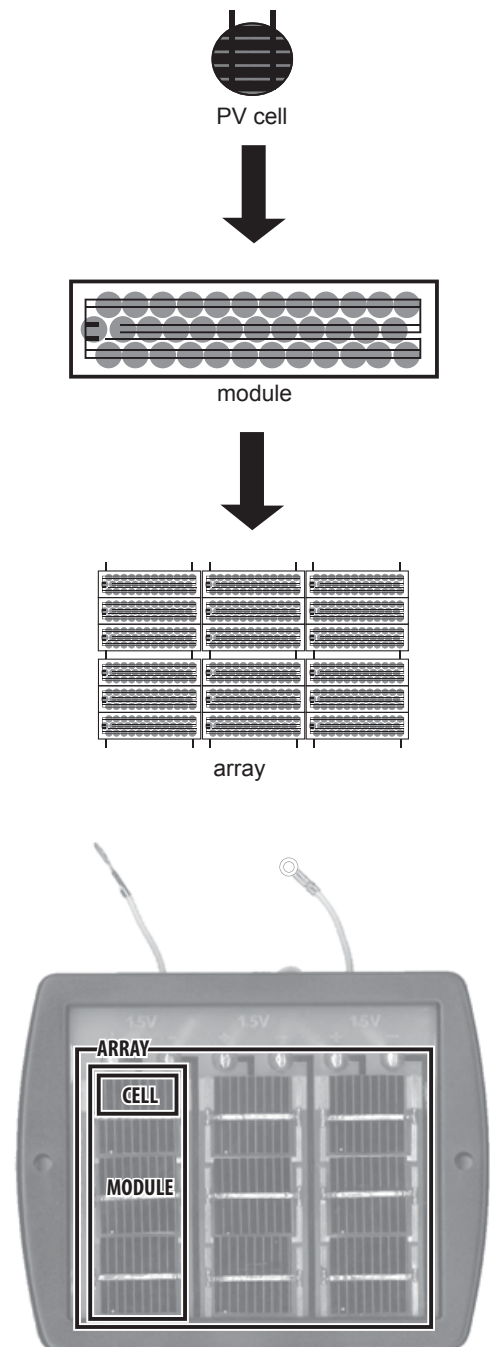
■ Battery System

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

PHOTOVOLTAIC ARRAYS ARE MADE UP OF INDIVIDUAL CELLS



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.

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

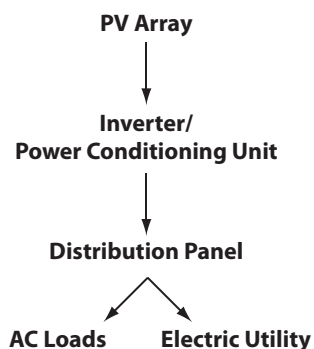


Image courtesy of PG&E

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

STAND-ALONE SYSTEMS

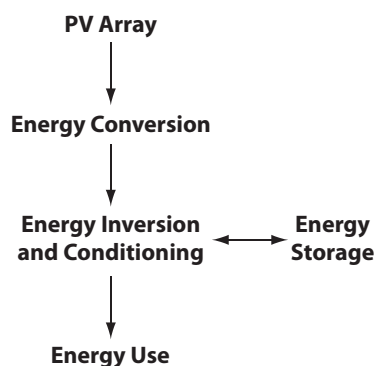


Image courtesy of NASA

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 not able 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 from one to a fraction 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. Another example would be a concentrating solar plant that uses parabolic mirrors to focus the sun's energy on a high efficiency PV array that produces a large amount of electricity to contribute to the grid. Systems at this scale can produce enough electricity to operate hundreds to thousands of homes based on size. The solar insolation values and slope of the site are significant concerns when siting such a plant. (add more detail for last sentence)

Relative Scale of Photovoltaic Systems



RESIDENTIAL



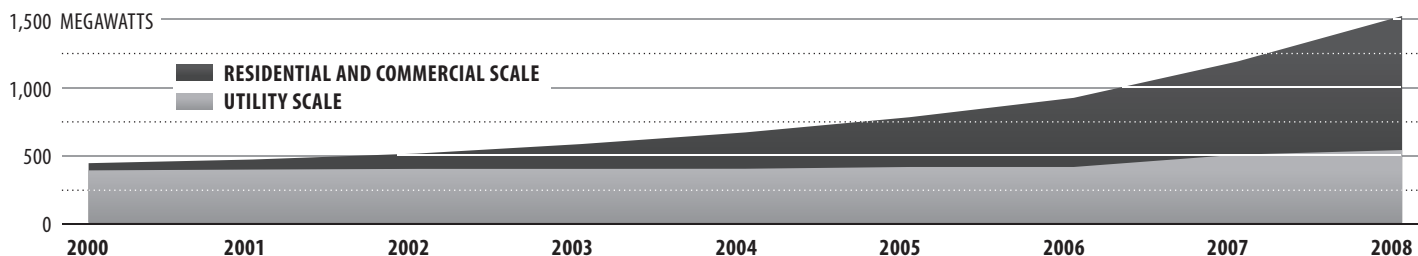
COMMERCIAL



UTILITY



Growth of Solar Electricity Production Since 2000



Source: U.S. Energy Information Agency

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.

▪ String / Ribbon Silicon

These use the same materials as typical crystalline silicon. It is drawn out of molten silicon rather than being sawed from an ingot, thereby making it less expensive to produce. In some cases, this manufacturing method can produce PV cells that have a higher conversion efficiency than that of cast silicon.

▪ Amorphous Silicon / Thin-Film Technologies

This new class of materials allows the production on 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 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).

▪ GaAs: Gallium Arsenide

Used in high-efficiency applications—space craft and concentrating solar power—very expensive

▪ CdTe: Cadmium Telluride

This thin-film technology has a great deal of potential, however, there are concerns about the chemicals necessary for its production.

▪ CIS: Copper Indium Diselenide

Provides efficiencies up to 17 percent but manufacturing processes are material specific.

▪ CIGS: Copper Indium Gallium Diselenide

These materials are generally applied to PV cells to increase the energy absorption of the 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.

▪ Multi-junction 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. These devices are currently in the research phase, but the concept has been proved.



The Schapfen Mill Tower is a flour mill in Germany. The southern facade is faced with 1,300 CIS 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 several practical limitations to PV systems:

- PV systems are not well suited for energy-intensive uses such as heating;
- 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.



Image courtesy of BP Solar

In August 2002, BP Solar installed a new photovoltaic facility 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; electrical current is the number of electrons flowing past a fixed point.

Electrical 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.

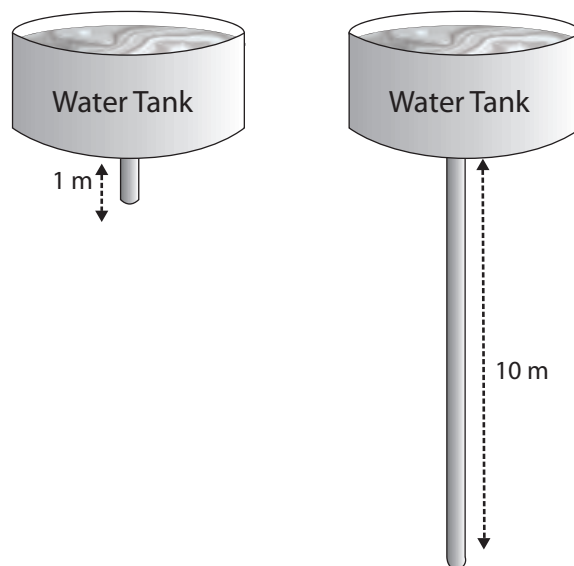
Resistance

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.

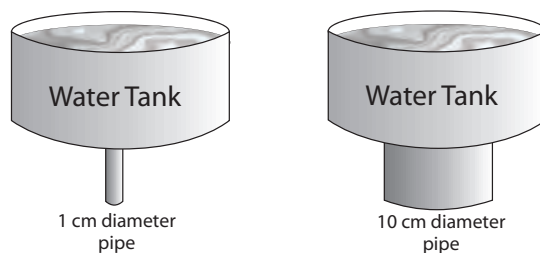
In electrical terms, the resistance of a conducting wire depends on the properties of the metal used to make the wire and the wire's diameter. Copper, aluminum, and silver—metals used in conducting wires—have different resistance.

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.

VOLTAGE



CURRENT



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:

$$\text{voltage} = \text{current} \times \text{resistance}$$
$$V = I \times R \quad \text{or} \quad V = A \times \Omega$$

Electrical Power

Power (P) is a measure of the rate of doing work or the rate at which energy is converted. Electrical 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.

Electrical 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. Electrical power is measured in **watts (W)**. The formula is:

$$\text{power} = \text{voltage} \times \text{current}$$
$$P = V \times I \quad \text{or} \quad W = V \times A$$

Electrical Energy

Electrical energy introduces the concept of time to electrical 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 electrical 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)**.

$$\text{energy} = \text{power} \times \text{time}$$
$$E = P \times t \quad \text{or} \quad E = W \times h = Wh$$

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.

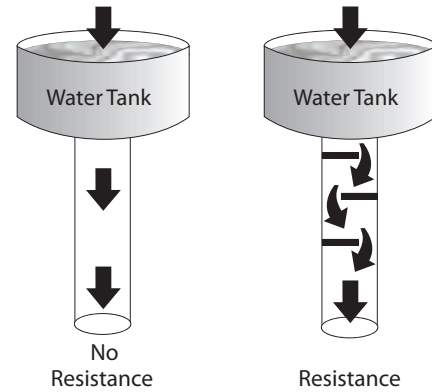
If a car travels at 40 miles per hour for 1 hour, it would travel 40 miles.

$$\text{distance} = 40 \text{ mph} \times 1 \text{ hour} = 40 \text{ miles}$$

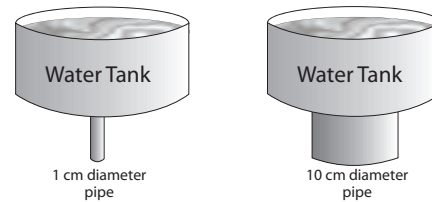
If a car travels at 40 miles per hour for 3 hours, it would travel 120 miles.

$$\text{distance} = 40 \text{ mph} \times 3 \text{ hours} = 120 \text{ miles}$$

RESISTANCE



ELECTRICAL POWER



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 electrical 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:

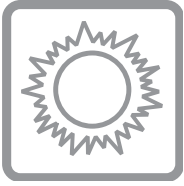
$$\text{energy} = \text{power} \times \text{time} (E = P \times t)$$
$$\text{energy} = 100 \text{ W} \times 5 \text{ hour} = 500 \text{ Wh}$$

One watt-hour is a very small amount of electrical energy. Usually, we measure electrical 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 \$0.11.

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:

$$500 \text{ Wh} / 1,000 = 0.5 \text{ kWh}$$
$$0.5 \text{ kWh} \times \$0.11/\text{kWh} = \$0.055$$

Therefore, it would cost about five and a half 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.

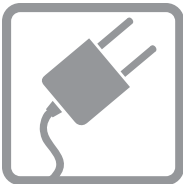
voltage:

current:

resistance:

power:

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

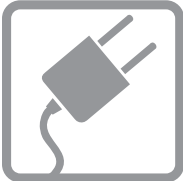


Calculation of Power

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

$$\text{power} = \text{voltage} \times \text{current}$$

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

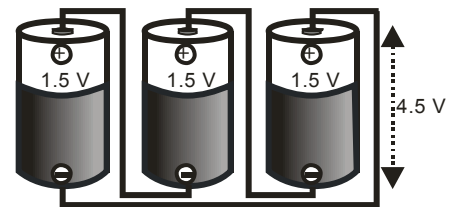


Series Circuits

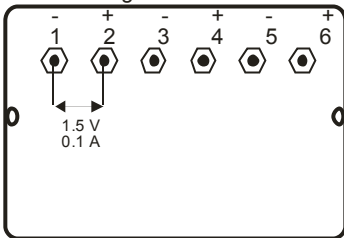
In series circuits, the current remains constant while the voltage changes. To calculate total voltage, add the individual voltages together:

$$I_{\text{total}} = I_1 = I_2 = I_3$$

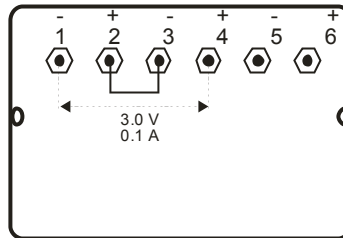
$$V_{\text{total}} = V_1 + V_2 + V_3$$



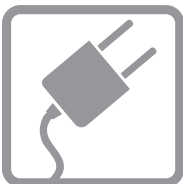
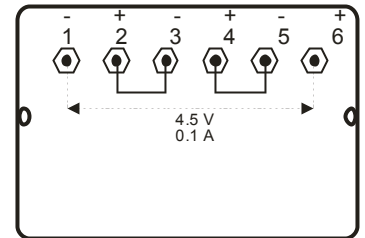
Single PV Module



Series - 2 PV Modules



Series - 3 PV Modules

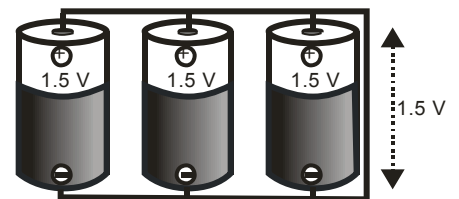


Parallel Circuits

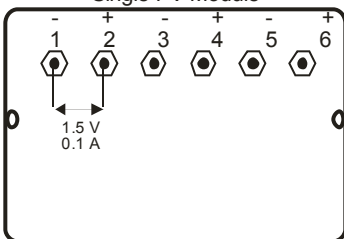
In parallel circuits, the voltage remains constant while the current changes. To calculate total current, add the individual currents together:

$$I_{\text{total}} = I_1 + I_2 + I_3$$

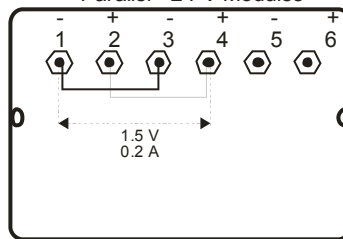
$$V_{\text{total}} = V_1 = V_2 = V_3$$



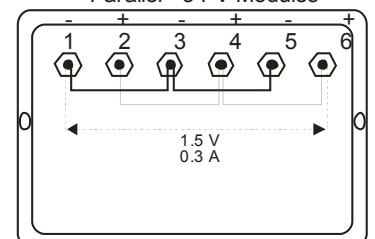
Single PV Module

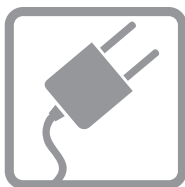


Parallel - 2 PV Modules



Parallel - 3 PV Modules





Basic Measurement Values in Electronics

SYMBOL	VALUE	METER	UNIT
E	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 x 1/1000000000 or .000000001

(p)ico x 1/1000000000000 or .000000000001

▪ Bigger

(K)ilo x 1,000

(M)ega x 1,000,000

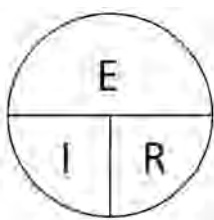
(G)iga x 1,000,000,000

Formulas for Measuring Electricity

$$E = I \times R$$

$$I = E/R$$

$$R = E/I$$



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.

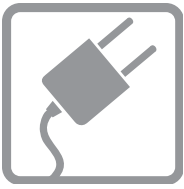
▪ Series Resistance (Resistance is additive)

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

▪ Parallel Resistance (Resistance is reciprocal)

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

Note: ALWAYS convert the values you are working with to the "BASE unit." For example - don't plug kilo-ohms ($K\Omega$) into the equation – convert the value to Ω first.



Digital Multimeter



Directions

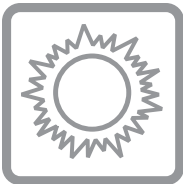
DC Voltage

1. Connect RED lead to VΩmA socket 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

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.



Solar 1

QUESTION

How do similar PV modules in an array vary in electrical output? Think about which varies more, current or voltage?

HYPOTHESIS

MATERIALS

- Bright light source
- Connecting cables
- Alligator clips
- Electrical load (motor, fan, light, or buzzer)
- PV array
- Multimeter

PROCEDURE

1. Test each PV module in the array by connecting the electrical load to each cell.
2. With the multimeter, measure the current and voltage of each PV module in the array under identical external conditions.
3. Record the data below and compare.

OBSERVATIONS

DATA

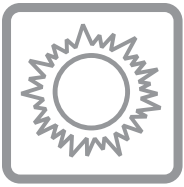
	CURRENT	VOLTAGE	WATTS
LEFT PV MODULE			
CENTER PV MODULE			
RIGHT PV MODULE			

CONCLUSION

REFLECTIONS

Were the output voltages of the PV modules close to one another?

Were the output currents of the PV modules similar?



Solar 2

QUESTION

How does a PV array wired in series affect the electrical output? Think about what will happen to current and voltage output.

HYPOTHESIS

MATERIALS

- PV array
- Electrical load
- Multimeters
- Alligator connectors or jumper wires

PROCEDURE

1. Attach the multimeter to the PV array wired in series with an electrical load. See in diagram to the right.
2. Measure the current and voltage. Record the data in the chart.
3. Calculate the wattage (current x voltage) of each trial and record the data in the chart.

DATA

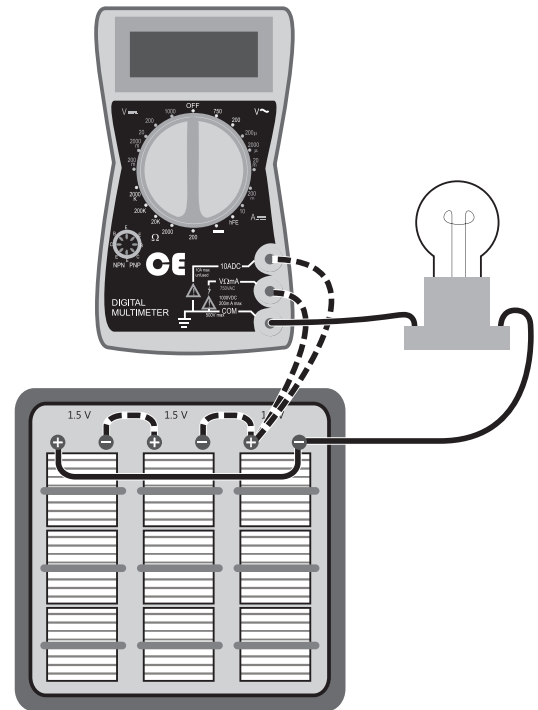
TRIALS	CURRENT	VOLTAGE	WATTS
PARALLEL			

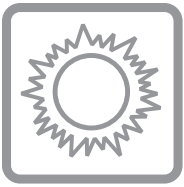
CONCLUSION

REFLECTIONS

How did the current produced in a series circuit compare to the current of an individual PV module?

How did the voltage produced in a series circuit compare to the voltage of an individual PV module?





Solar 3

QUESTION

How does light intensity affect the electrical output of a PV array wired in series?

HYPOTHESIS

MATERIALS

- Multimeter
- PV array
- Bright light source
- Dim light source
- Electrical load

PROCEDURE

1. Attach the multimeter to the PV array wired in series with an electrical load.
2. Place the PV array under the bright light source.
3. Measure the current and voltage produced by the PV array.
4. Record results in chart below.
5. Place the PV array under the dim light source.
6. Measure the current and voltage produced by the PV array.
7. Record results in chart below.
8. Calculate the wattage (current x voltage) of each trial. Record results in chart below.

NOTE

When comparing light output of different sources (e.g. bulbs), lumens should be used to compare light intensity rather than watts, which compare power consumption.

OBSERVATIONS

DATA

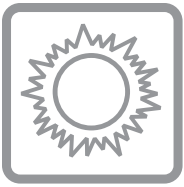
	CURRENT	VOLTAGE	WATTS
BRIGHT LIGHT			
DIM LIGHT			

CONCLUSION

REFLECTIONS

What differences did you observe in the variables of the two light intensities?

How does light intensity affect the output of the PV array?



Solar 4

QUESTION

How does the angle of a PV array wired in series to a light source affect the electrical output?

HYPOTHESIS

MATERIALS

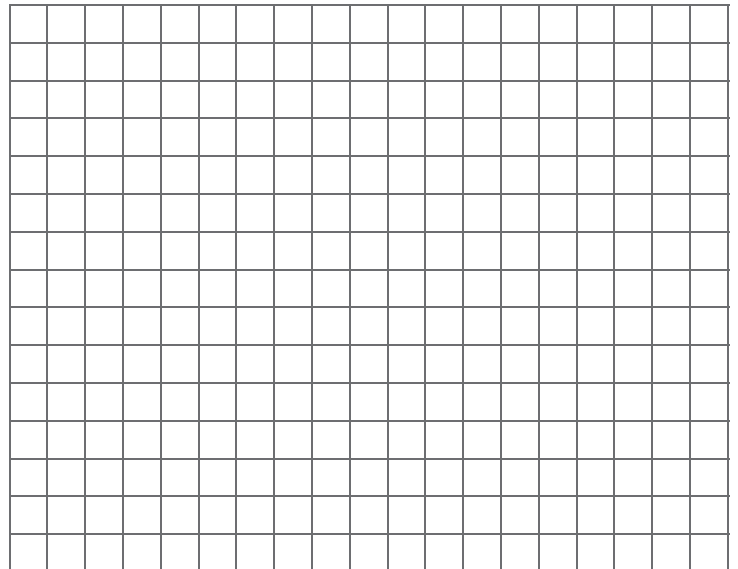
- PV array
- Bright light source
- Electrical load
- Multimeter
- Protractor

PROCEDURE

1. Attach the multimeter to the PV array wired in series with an electrical load.
2. Measure current and voltage when the PV module is 90° to the light. Record data in the chart.
3. Using the protractor, measure current and voltage when the PV module is 75° to the light. Record data in the chart.
4. Using the protractor, measure current and voltage when the PV module is 60°, 45°, 30°, and 15° to the light. Record data in the chart.
5. Calculate the wattage (current x voltage) of each trial. Record data in the chart.
6. Graph your experimental results wattage (y) vs. degrees (x).

DATA

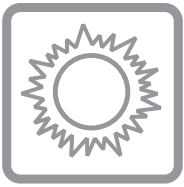
DEGREES	CURRENT	VOLTAGE	WATTS
90°			
75°			
60°			
45°			
30°			
15°			



CONCLUSION

REFLECTIONS

From the graph of your data, what is the relationship between the angle of a PV array to wattage produced?



Solar 5

QUESTION

How does the distance from a light source affect the electrical output of a PV array wired in series?

HYPOTHESIS

MATERIALS

- PV array
- Bright light source
- Electrical load
- Multimeter
- Tape measure or meter stick

PROCEDURE

1. Attach the multimeter to the PV array wired in series with an electrical load.
2. Place the PV array at increasing distances from light source according to the data chart below.
3. At each distance, measure current and voltage, and record data in chart.
4. Calculate wattage (current x voltage).
5. Graph your experimental results, wattage (y) vs. distance (x) from light source.

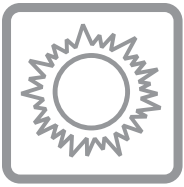
DATA

DISTANCE (CM)	CURRENT	VOLTAGE	WATTS
10 CM			
20 CM			
25 CM			
50 CM			
75 CM			
100 CM			

** CONCLUSION

REFLECTIONS

From the graph of your data, what is the relationship of wattage to distance from the light source?



Solar 6

QUESTION

How does covering different parts of the PV array wired in series affect its electrical output?

HYPOTHESIS

MATERIALS

- Bright light source
- Electrical load
- PV array
- Multimeter
- 3x5" Piece of cardboard

PROCEDURE

1. Attach the multimeter to the PV array wired in series with an electrical load.
2. Measure current and voltage and record in the data chart as trial 1.
3. Using the cardboard, cover half the PV array horizontally as in diagram 1. Measure and record the current and voltage as trial 2.
4. Using the cardboard, cover half of the complete cells vertically as in diagram 2.
5. Measure and record the current and voltage in the data chart as trial 3.
6. Calculate the wattage (current x voltage) of each trial. Record data in the chart.



Diagram 1

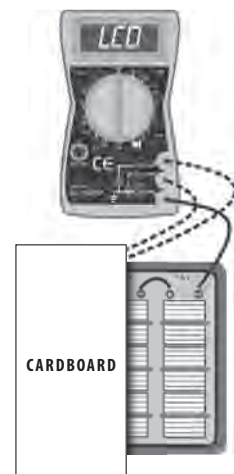


Diagram 2

DATA

HORIZONTAL CARDBOARD

TRIALS	CURRENT	VOLTAGE	WATTS
1			
2			
3			

VERTICAL CARDBOARD

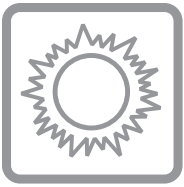
TRIALS	CURRENT	VOLTAGE	WATTS
1			
2			
3			

CONCLUSION

REFLECTIONS

What did you observe about the differences in your data?

What function does the silver strip perform in the PV array?



Solar 7

QUESTION

How does concentrating the light from a light source affect the electrical output of a PV array wired in series?

HYPOTHESIS

MATERIALS

- PV array
- Electrical load
- Bright light
- Multimeter
- Fresnel lens
- Metric ruler

PROCEDURE

1. Attach the multimeter to the PV array wired in series with an electrical load.
2. Measure the current and voltage and record data in chart.
3. Lay the Fresnel lens over the PV array.
4. Measure the current and voltage. Record data in chart.
5. Conduct additional trials with the lens, changing the distance from the lens to the PV array.
6. Measure the current and voltage. Record data in the chart.
7. Calculate the wattage (current x voltage) of each trial. Record data in the chart.

DATA

TRIALS	CURRENT	VOLTAGE	WATTS
NO LENS			
LENS (0 cm)			
LENS ____ cm			
LENS ____ cm			
LENS ____ cm			

CONCLUSION

REFLECTIONS

From your observations, what is the affect of concentrating the light on a PV array?



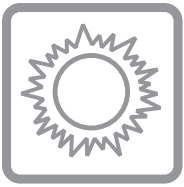
How does surface temperature affect the electrical output of a PV array wired in series?

- PV array
- Electrical load
- Multimeter
- Ice water
- Bright sunny day
- Stopwatch

1. Attach the multimeter to the PV array wired in series with an electrical load.
2. Place the array in the sun for 10 minutes.
3. After the 10 minutes record, data in chart.
4. With conductors at the top of the array, angle the PV array at 45° , carefully pour ice water across the surface of the PV array.
Caution: DO NOT LET WATER TOUCH LEADS.
5. Measure change in voltage every 15 seconds as the surface of the PV module cools. Record data in the chart.
6. Graph data with voltage (y) vs. time (x).

TIME (SEC)	VOLTAGE
0	
15	
30	
45	
60	

How does cooling down the surface of the PV array affect the voltage produced? Why do you think this is?



Solar 9

QUESTION

How does a PV array wired in parallel affect the electrical output? Think about what will happen to current and voltage output.

HYPOTHESIS

MATERIALS

- PV array
- Electrical load
- Multimeters
- Alligator connectors or jumper wires

PROCEDURE

1. Attach the multimeter to the PV array wired in parallel with an electrical load. See in diagram to the right.
2. Measure the current and voltage. Record the data in the chart.
3. Calculate the wattage (current x voltage).

DATA

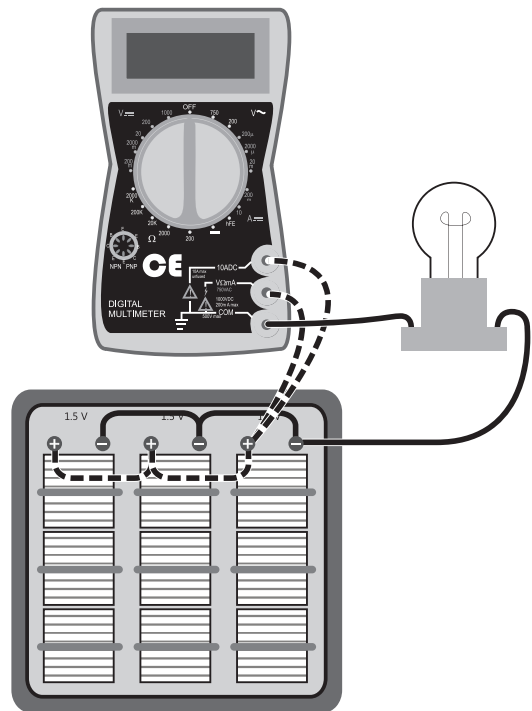
TRIALS	CURRENT	VOLTAGE	WATTS
PARALLEL			

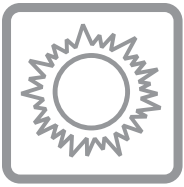
CONCLUSION

REFLECTIONS

In previous investigations the array was wired in series. How has the current changed in parallel connections?

In previous investigations the array was wired in series. How has the voltage changed in parallel connections?





Extension 1

QUESTION

How do changes in supply current and voltage affect operation of electrical device loads?

HYPOTHESIS

MATERIALS

- PV array
- 2 fan motors
- 2 Multimeters
- Bright light source

PROCEDURE

1. Assemble 2 PV modules in series with 2 fan motors and multimeter.
2. Measure current and voltage. Record the data below.
3. Assemble 3 PV modules in series with 2 fan motors and multimeter.
4. Measure current and voltage. Record the data below.
5. Assemble 2 PV modules in parallel with 2 fan motors and multimeter.
6. Measure current and voltage. Record the data below.
7. Assemble 3 PV modules in parallel with 2 fan motors and multimeter.
8. Measure current and voltage. Record the data below.
9. Calculate the power (current x voltage). Record the data below.
10. Record any observations in the chart below.

DATA

CIRCUIT TYPE	# MODULES	CURRENT (AMPS)	VOLTAGE (VOLTS)	POWER (WATTS)	OBSERVATIONS
SERIES	2				
SERIES	3				
PARALLEL	2				
PARALLEL	3				

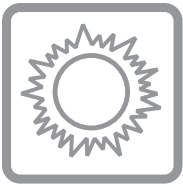
CONCLUSION

REFLECTIONS

How did the current change when the PV module was connected in series?

What was observed when two modules were used? When three modules were used?

What was the difference in fan performance between series and parallel circuits?



Extension 2

QUESTION

How do changes in different circuit configurations affect the operation of multiple loads in the circuit?

HYPOTHESIS

MATERIALS

- 2 PV arrays
- 3 DC motors with fans
- 2 Multimeters
- Bright light source

PROCEDURE

1. Connect three PV modules in series and three PV modules in parallel.
2. Measure the changes in current and voltage of two fans and then three fans connected in series to each of the PV module configurations. Record the data below.
3. Measure the changes in current and voltage to two fans and then three fans connected in parallel to each of the PV module configurations. Record the data below.
4. Calculate the power (current x voltage). Record the data below.
5. Record any observations in the chart below.

DATA

CIRCUIT TYPE PV ARRAY	NUMBER OF FANS	CIRCUIT TYPE FANS	CURRENT (AMPS)	VOLTAGE (VOLTS)	POWER (WATTS)	OBSERVATIONS
SERIES	2	SERIES				
SERIES	3	SERIES				
SERIES	2	PARALLEL				
SERIES	3	PARALLEL				
PARALLEL	2	SERIES				
PARALLEL	3	SERIES				
PARALLEL	2	PARALLEL				
PARALLEL	3	PARALLEL				

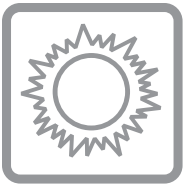
CONCLUSION

REFLECTIONS

What was observed when two fans were used? When three fans were used?

Give examples of loads in parallel and series circuits that you have at home?

What might happen if too many loads are drawing power in your classroom?



Extension 3

QUESTION

What effects on current and voltage will using different light sources have?

HYPOTHESIS

MATERIALS

- 1 PV array
- Electrical load
- 1 Multimeter
- Various light sources

PROCEDURE

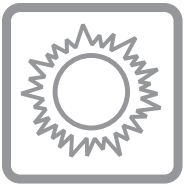
Design a procedure to compare the output of the PV array using natural sunlight and a variety of artificial light sources (e.g., incandescent, CFL, halogen, LED).

DATA

CONCLUSION

REFLECTIONS

How would you do this activity differently to improve the electrical output of your circuit?



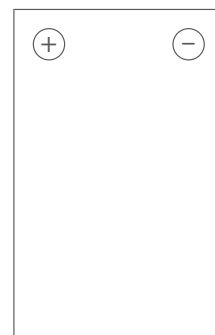
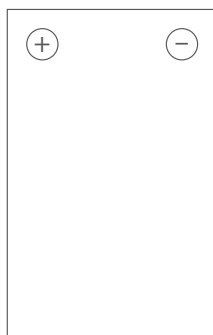
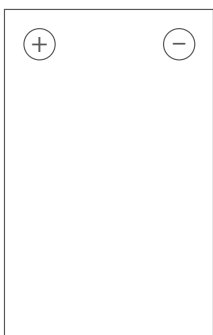
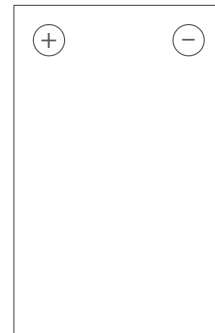
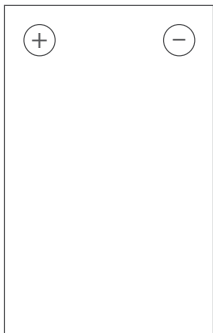
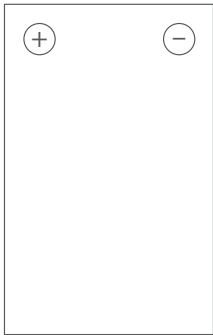
Extension 4

QUESTION

Below are twelve 12 volt photovoltaic modules rated at 80 watts each.

Design an array to deliver 48 volts to the inverter by using a combination of series and parallel circuits.

Use dashed lines to represent the black (-) wires and solid lines to represent the red (+) wires.

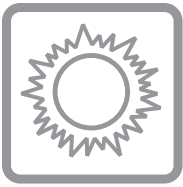


REFLECTIONS

Write an algebraic equation representing the 48 volt circuit you created.

Is there more than one design that could have created the 48 volt circuit?





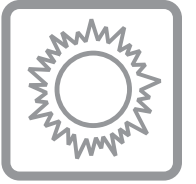
The Solar Choice

Can solar energy meet your electricity demands?

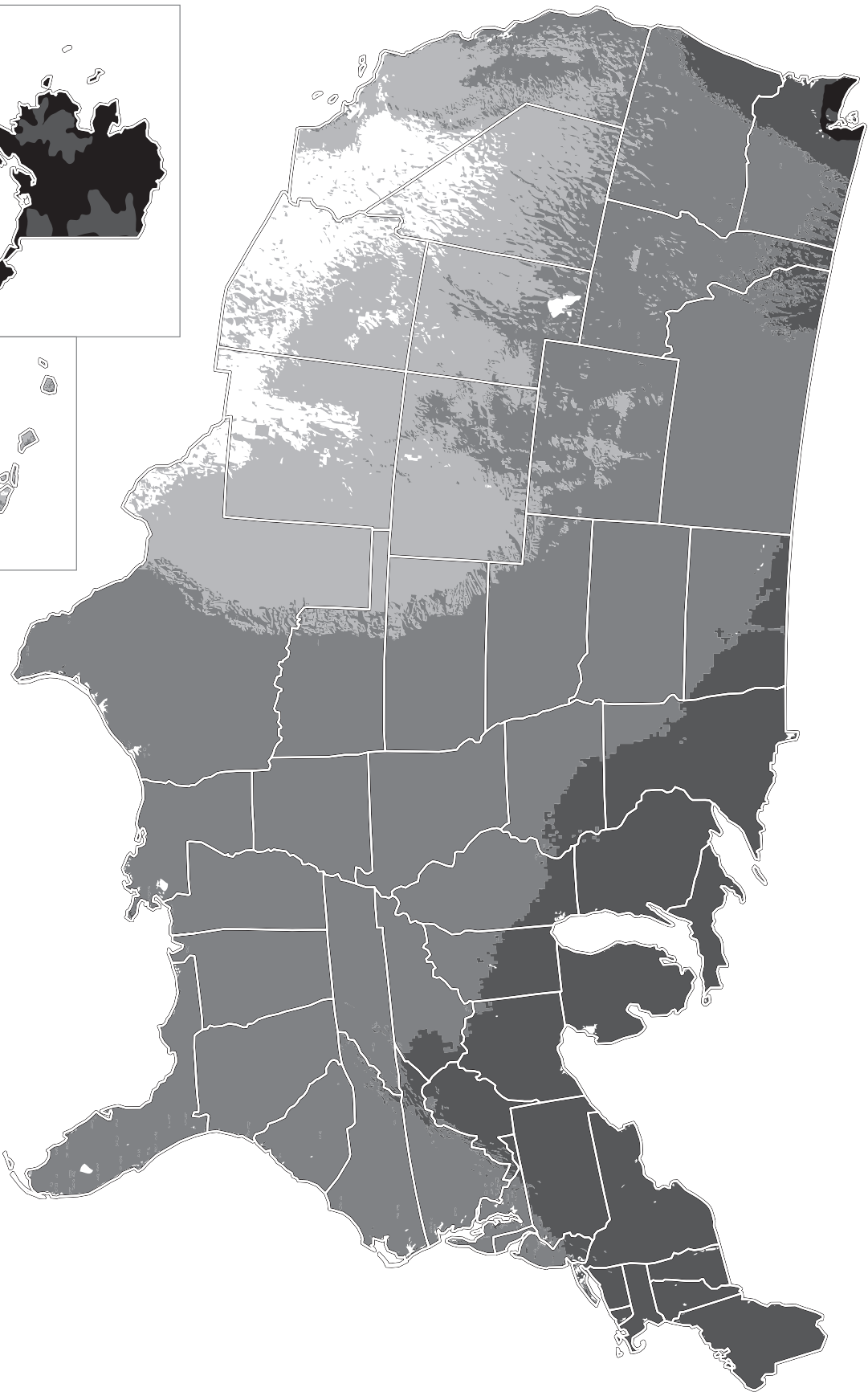
1. Look at your monthly power bill.
2. How much energy does your family consume each month (in kilowatt hours, kWh)? _____
3. What is your daily energy use? (monthly kWh/30 days) _____
4. "Peak sun hours" are the number of hours per day where solar insolation equals 1,000 watts/square meter. Use the U.S. Photovoltaic Solar Resource Map on the next page to determine how many peak sun hours your location receives each day. _____
5. Find out how many watts you use each day. (daily kWh/peak sun hours = watts)

6. How many 235 watt solar modules would you need to produce enough electricity for your home? _____
7. If each module costs \$700.00, how much would it cost for the number of solar modules you need? _____
8. Look at your monthly electric bill. About how much are you paying each month? _____
9. A payback period is the amount of time it takes for you to save money that you spent to install solar panels. What is the payback period for your PV system? _____
10. Do you think meeting your electricity needs completely with solar would be a good choice? Why or why not?
11. Are there measures you could take to reduce the amount of electricity you use? If so, what are they and why? If not, why not?
12. Given the cost of PV systems, why do you think some residential and commercial customers choose to use solar energy to generate electricity?



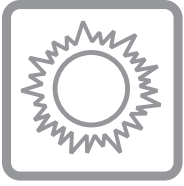


U.S. Solar Resource Map



Note: Alaska and Hawaii not shown to scale





Your Solar-Powered Cabin

Your crazy old Uncle Ed has just willed you a cabin that he has on a river near Page, AZ. The only problem is that the cabin has no electricity. Uncle Ed believes in hard work and he's specified one condition—if you are to take possession of this prime parcel, you must plan and install a PV system to support the following four specifications:

- a light for the kitchen (LED, 12 volts at 15 watts);
- a power supply for charging your laptop (12 volts at 90 watts);
- an electric pump for the well (12 volts at 100 watts intermittent); and
- a refrigerator (12 volts at 50 watts intermittent).

Before you can collect your inheritance, the lawyer will need to approve your plan. The lawyer will need to see:

- a description of the PV modules that you will use along with their ratings;
- a schematic diagram of your system design; and
- a spreadsheet detailing your budget and sources for parts.

Have fun!

Extension

When you finish your plan, design a battery system to store the electrical energy generated for use at night or during storms.



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Eaton	NASA Educator Resource Center–WV	U.S. Department of Energy–Hydrogen Program
EDF	National Association of State Energy Officials	U.S. Department of Energy–Wind Powering America
El Paso Foundation	National Association of State Universities and Land Grant Colleges	U.S. Department of Energy–Wind for Schools
E.M.G. Oil Properties	National Fuel	U.S. Department of the Interior–Bureau of Land Management
Encana	National Hydropower Association	U.S. Department of the Interior–Bureau of Ocean Energy Management, Regulation and Enforcement
Encana Cares Foundation	National Ocean Industries Association	U.S. Environmental Protection Agency
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Energy Solutions Foundation	New Mexico Landman's Association	Virginia Department of Mines, Minerals and Energy
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