CHAPTER 1

An Introduction to Solar Electricity

Like many other people throughout the world, I have been dreaming of a future powered by renewable energy for many years. Fortunately, that dream is becoming a reality. Today, solar and wind energy have become major contributors to global energy production. In the United States alone, solar, wind (mostly large-scale wind), biomass, and geothermal now produce about 7% of the nation's electricity. When you add hydroelectricity to the mix, renewable energy now supplies over 13% of America's electricity. That's a recent change, occurring within the last few years. Although we have a ways to go, that's pretty amazing.

What is even more amazing is that some states now generate about 25% of their electricity from renewables. Kansas and Iowa, for example, both do, mostly with wind power. Colorado generates 18% of its electricity from renewables, but its goal is 30% by 2020. California is aiming for 33% by 2020. While impressive, get this: Germany now produces over 60% of its electricity from renewables.

Although there are many reasons why renewables have gone wild in recent years, one of them has been cost. For years, renewable energy advocates have dreamed of a day when we could say that renewables cost the same or less than conventional energy resources. At least for solar electricity, those days are here. Solar electric systems, even without subsidies, often produce electricity at or below the cost of power from utilities. They have reached price parity, and the future is looking quite bright.

This book focuses on an important element of the renewable energy dream: solar electricity. Solar electric systems are also known as *photovoltaic systems* or *PV systems*, for short. In this book, I will focus primarily on residential-scale PV systems, that is, systems suitable for homes and small businesses. These systems generally fall in the range of 1,000 watts for very small, energy-efficient cabins or cottages to 5,000 to 15,000 watts for typical suburban homes. All-electric homes could require even larger systems, on the order of 25,000 watts. What does all this mean?

Understanding Rated Power

One of the most frequent questions solar installers are asked is "What size system do I need?" It's probably the question that's burning in your mind right now.

The answer is almost always the same: it depends. More specifically, it depends on how much electricity you and your family use. Once an installer knows how much electricity you consume, he or she can size a system.

The size of a solar electric system is given in its *rated power*, also known as *rated capacity*. Rated power of a system is the output of the modules (PV panels) times the number of modules. If your system contains twenty 250-watt modules, its rated capacity is 5,000 watts. Because *kilo* means 1,000, a 5,000-watt system is also called a 5-kilowatt, or 5-kW system. But what does it mean when I say a module's rated power is 250 watts?

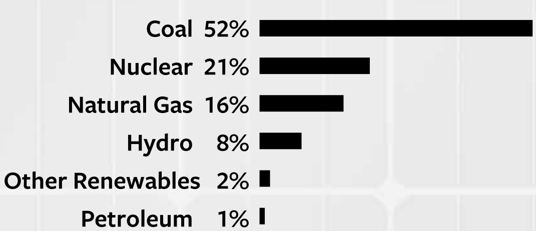
Rated power is the instantaneous output of a solar module measured in watts under standard test conditions (STC). Watts is a measure of power. Another way of thinking about it is as the rate of the flow of energy. The higher the wattage, the greater the flow.

Watts is also the measurement used to rate technologies that produce electricity, such as a solar module or a power plant. For example, most solar modules installed these days are rated at 250 to 300 watts. Power plants are rated in millions of watts, or megawatts: a typical coal-fired power plant produces 500 to 1,000 megawatts of power.

Most readers are probably more familiar with the terms watt and wattage when they are used to rate power consumption of a device, such as a light bulb or a hair dryer. You may have a 12-watt compact fluorescent light bulb, for instance, or an 1,800-watt hair dryer. Your microwave may be 1,200 watts. In such cases, wattage indicates power consumption. The higher the wattage, the greater the consumption.

Where Does Your Electricity Come From?

Did you ever wonder where your electricity comes from? According to the US Energy Information Administration (EIA), in 2014, electricity sold by utilities came from the following sources:



As in many cases, national averages can be deceiving. Your utility may rely almost entirely on coal, nuclear, or hydropower. In the Midwest, for instance, it is not uncommon for 75% of one's electrical energy to come from coal. In the Pacific Northwest, the vast majority of the electricity comes from hydropower. You may be able to find out where your electricity comes from by calling your local utility and talking with their public information specialists.

As just noted, the rated output of a PV module is determined under standard test conditions—a set of conditions that all manufacturers use to rate their modules. To test a module, workers set it up in a room that is maintained at 77°F (25°C). A light is flashed on the module at an intensity of 1,000 watts per square meter. That is equivalent to full sun on a cloudless day in most parts of the United States. The light is arranged so light rays strike the module at a 90° angle, that is, perpendicularly. (Light rays striking the module perpendicular to its surface result in the greatest absorption of the light.)

Rating modules under standard test conditions is useful for comparing one manufacturer's module to another's. A 285-watt module from company A should perform the same as a 285-watt module from company B.

Installers can use this rating to determine the size of a system required to meet your needs. As noted above, most residential solar electric systems fall within the range of 5,000 to 15,000 watts, or 5 to 15 kW. It is important to note, however, that a 5-kW PV system won't produce 5,000 watts of electricity all the time the Sun's shining on it. This rating is based on standard test conditions, which are rarely duplicated in the real world. So, this rating system leaves a bit to be desired.

When mounted outdoors, PV modules typically operate at higher temperatures than those subjected to standard test conditions. That's because infrared radiation in sunlight striking PV modules causes them to heat up. To achieve a cell temperature of 77°F (25°C) under full sun, like that measured in the laboratory, the air temperature must be quite low—about 23°F to 32°F (0°C to –5°C), not a typical temperature for PV modules in most locations most of the year. This is important to know because higher temperatures decrease the output of a solar module. That's the reason why it is so important to mount a solar system so that the modules stay as cool as possible. It also explains why solar modules on a ground-mounted rack typically perform better than roof-mounted systems. Roofs are hotter.

To better simulate real-world conditions, the solar industry has developed an alternative rating system. They call it *PTC*, which stands for *PV-USA Test Conditions* (which stands for *PV for Utility-Scale Applications Test Conditions*).

PTC were developed at the PV-USA test site in Davis, California, and more closely approximate real-life operating conditions. In this rating system, the ambient temperature is held at 68°F (20°C). The modules face the Sun and output is measured when the Sun's irradiance reaches 1,000 watts per square meter. The conditions take into account higher module temperatures and the cooling effect of wind. Wind speed in the test is 2.24 miles per hour (or 1 meter per second) 10 meters above the surface of the ground. (That is, wind speed is monitored at 10 meters, or

33 feet.) Although the cell temperature varies with different modules, it is typically about 113°F (45°C) under PTC. Because power output (in watts) decreases with rising temperature, PTC ratings are roughly 10% lower than STC ratings.

When shopping for PV modules, I used to suggest that readers ignore the nameplate rating the manufacturers derived under STC and look up the PTC ratings. Some manufacturers publish these data on their spec sheets; others don't. As a rule, though, it's not that important. Solar installers will estimate the output of an array taking into account local conditions. If you must, you can find PTC ratings on the California Energy Commission's website: consumerenergycenter.org.

An Overview of Solar Systems

As their name implies, solar electric systems convert sunlight energy into electricity. This conversion takes place in the solar modules, more commonly referred to as *solar panels*. (The term *modules* is the correct one; that's what they are called in the National Electric Code, but few people use this term.)

A solar module consists of numerous *solar cells*. Most solar modules contain 60 solar cells, although manufacturers are also producing larger modules that contain 72 cells each. Solar cells are made from one of the most abundant chemical

FIGURE 1.1. These solar modules being installed by several students at The Evergreen Institute consist of numerous square solar cells. Each solar cell has a voltage of around 0.6 volts. The cells are wired in series to produce higher voltage, which helps move the electrons from cell to cell. Modules are also wired in series to increase voltage. Credit: Dan Chiras.

substances on Earth, silicon dioxide. (Silicon dioxide makes up 26% of the Earth's crust.) Silicon dioxide is found in quartz and from a type of sand that contains quartz particles. Silicon is extracted from silicon dioxide.

Solar cells are wired in series inside a module (see sidebar). The modules are encased in glass (in the front) and usually plastic (in the back). The plastic and glass layers protect the solar cells from the elements, especially moisture. Most modules these days have aluminum frames. Because the anodized (silver) aluminum frames are striking, many manufacturers produce modules with black aluminum frames. The aluminum rails and mounting hardware used to attach them to the roof are also black, so the array blends in well, and homeowners associations and neighbors are happy. Some manufacturers are now producing frameless modules to make them even more aesthetically appealing. One manufacturer's modules passed an unprecedented Class 4 hail testing (that is, they withstood 2-inch hail striking it at 75 mph), making them the most impact-resistant module in the industry. Frameless modules have been designed to make installation quick, easy, and less expensive.

Understanding Electricity: Series Wiring

Although few people know what series wiring is, we use it all the time. Every time you put batteries in a flashlight, for instance, you place the positive end of one battery against the negative end of the next one. Series wiring increases the voltage. Voltage is a force that moves electrons (it is considered an *electromotive* force). The higher the voltage, the more force. When placing two 1.5-volt batteries in series in a flashlight, you increase the voltage to 3. Place four 1.5-volt batteries in series and the voltage is 6.

In solar modules, each solar cell has a positive and a negative lead (wire). To wire in series, the positive lead of one module is soldered to the negative of the next, and so on and so on. Most solar cells in use today are square and measure 5 × 5 inches (125 × 125 mm) or 6 × 6 inches (156 × 156 mm) and have a voltage of about 0.6 volts. When manufactures wire (actually, solder) 60 solar cells together in series in a module, the voltage increases to 36. Wiring several solar modules together in series, in turn, increases the voltage of an array. Ten 36-volt modules wired in series results in an array voltage of around 360.

A group of modules wired in series is known as a *series string*. Most residential solar arrays consist of series strings of 10 to 12 modules. String sizes in commercial PV array are larger.

Two or more modules are typically mounted on a rack and wired together. Together, the rack and solar modules are referred to as an *array*. Ground-mounted arrays are typically anchored to the earth by a steel-reinforced concrete foundation. Together, the rack, modules, and foundation are referred to as an *array*.

Solar modules produce direct current (DC) electricity. That's one of two types of electricity in use today. It consists of a flow of tiny subatomic particles called *electrons*. They flow through conductors, usually copper wires. In direct current electricity, electrons flow in one direction, as illustrated in Figure 1.2. In this case, electrons flow out of the battery through the light bulb, where they give off their energy, creating light and heat. The de-energized electrons then flow back into the battery.

Electricity generated by a PV array flows via wires to yet another component of the system, the *inverter*. This remarkable device converts DC electricity produced by solar cells into alternating current (AC) electricity. AC is the type of electricity used in homes and businesses throughout most of the world.

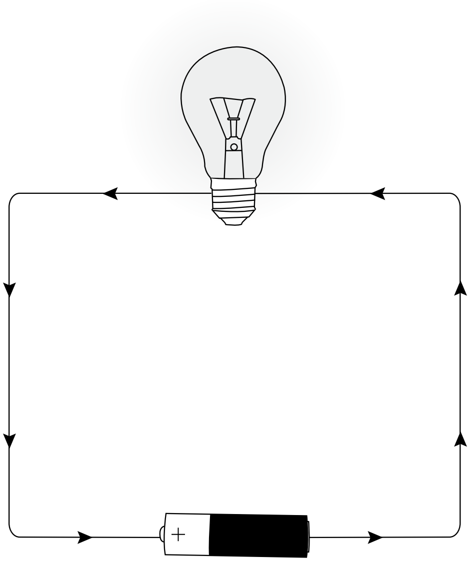


FIGURE 1.2. Solar electric systems produce direct current (DC) electricity just like batteries. As shown here, in DC circuits the electrons flow in one direction. The energy the electrons carry is used to power loads like light bulbs, heaters, and electronics. Credit: Forrest Chiras.

Applications

Once a curiosity, solar electric systems are becoming commonplace throughout the world. While many solar electric systems are being installed to provide electricity to homes, they are also being installed

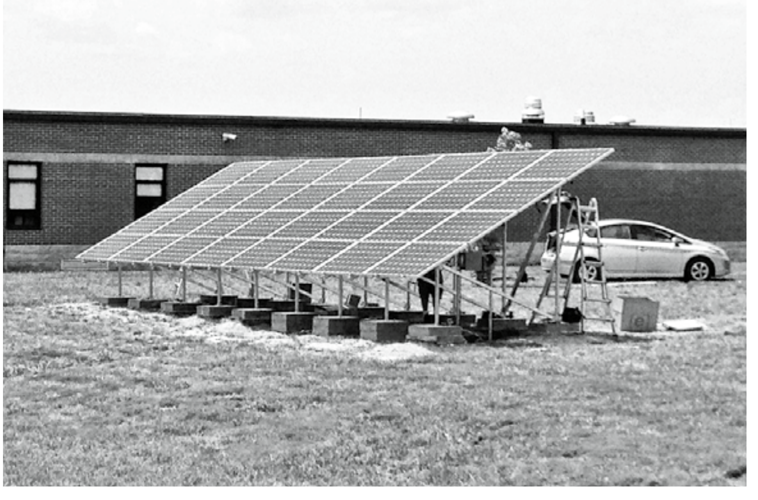


FIGURE 1.3. This solar array was installed at the Owensville Middle School in Owensville, Missouri, by the author and his business partner, Tom Bruns, and numerous hard-working students. The array is small for a school of this size, which uses almost 1,000 kilowatt-hours per day; the array only provides about 12 days' worth of electricity to the school. The array is also used for science and math education. Credit: Dan Chiras.

on schools, small businesses, office buildings, and even skyscrapers, like 4 Times Square in New York City, home of NASDAQ. Figure 1.3 shows a photo of a solar array my company installed at Owensville Middle School in Owensville, Missouri, with the help of several eager middle-schoolers. Many large corporations such as Microsoft, Toyota, and Google have also installed large solar electric systems. More and more electric utilities are installing large PV arrays to supplement conventional sources.

Even colleges are getting in on the act. Colorado College, where I once taught courses on renewable energy, installed a large solar system on one of its dormitories. And over the years, several airports have installed large solar arrays to help meet their needs. At Sacramento's airport, for instance, PVs were built to create parking structures that shade vehicles during the day while also generating electricity. Denver International Airport installed a 2,000 kilowatt solar electric system in 2008, and it has greatly expanded its system since then.

On a smaller scale, ranchers often install solar electric systems to power electric fences to contain cattle and other livestock. Many have installed small solar systems to pump water for their stock, saving huge amounts of money on installation. We power our farm and my educational center, The Evergreen Institute, on solar electricity. I installed a solar pond aerator to lengthen the lifespan of our pond and keep it open during the winter (Figure 1.4).

Solar electricity has proven extremely useful on boats. Sailboats, for example, are often equipped with small PV systems—usually a few hundred watts—to power lights, fans, radio communications, GPS systems, and small refrigerators. Many recreational vehicles (RVs) are equipped with small PV systems that are used to power microwaves, TVs,

FIGURE 1.4. (*above*) Aerating my half-acre farm pond reduces bottom sludge and helps create a healthier environment for the fish. (*below*) To prevent the pond from icing over completely in the winter (so our ducks can swim), I designed and installed a solar pond aerator in conjunction with a St. Louis company, Outdoor Water Solutions. They are currently selling a design like this online. Credit: Dan Chiras.

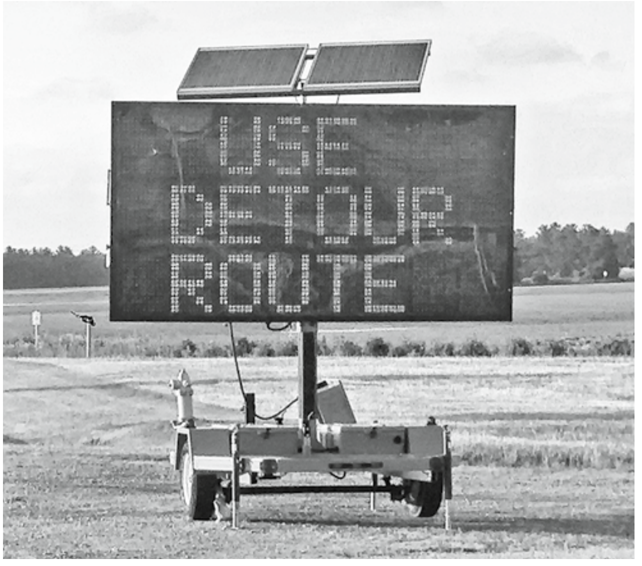


FIGURE 1.5. This electronic road sign is powered by a small solar array. Credit: Dan Chiras.

FIGURE 1.6. These bikes in downtown Denver, Colorado, can be rented by the hour. The payment system (*left*) is powered by solar electricity. Credit: Dan Chiras.

and satellite receivers. The electricity these systems produce reduces the run time for gas-powered generators that can disturb fellow "campers."

Many bus stops, parking lots, and roadways are now illuminated by superefficient lights powered by solar electricity, as are portable information signs used at highway construction sites (Figure 1.5). As electric cars become more and more popular, many homeowners have set up solar arrays to charge their vehicles. (Others, like me, just use the solar supplied by the arrays that power our homes or businesses.)

Numerous police departments now haul solar-powered radar units to neighborhoods to discourage speeding. These units display a car's speed and warn drivers if they're exceeding the speed limit.

The trash compactors at the Kennedy Space Center are powered by solar electricity. In downtown Colorado Springs, sidewalk parking meter pay stations are powered by solar. In Denver, credit card payment centers for city bikes that people can rent for the day are powered by solar (Figure 1.6). At the convention center in Topeka, Kansas, you can rent a bike, if you need some temporary transportation. Each bike is equipped with a small solar pay station.

Backpackers and river runners can take small solar chargers or larger lightweight fold-up solar modules with them on their ventures into the wild to power electronics. Military personnel have access to similar products, and there are numerous portable devices available for charging cell phones and tablets in our daily lives. Some are even sewn into backpacks, sports bags, or briefcases. There are also a number of cart- and trailer-mounted PV systems for emergency power after disasters. (To learn more, read Jeff Yago's article in *Home Power*, Issue 168.)

Solar electric systems are well suited for remote sites where it is often cost prohibitive to run power lines, such as cottages, cabins, and superefficient off-grid homes. In France, the government paid to install solar electric systems and wind turbines on farms at the base of the Pyrenees Mountains, rather than running electric lines to these distant operations.

Solar electricity is also used to power remote monitoring stations that collect data on rainfall, temperature, and seismic activity. PVs allow scientists to transmit data back to their labs from remote sites, like the tropical rain forests of South

Understanding Electricity: Power vs. Energy

If you are going to install a PV system on your home or become a professional installer, it is important to understand two very important terms: power and energy. In the electrical world, power is a measure of the flow of energy, in our case electrical energy. Power is measured in watts or kilowatts. (Remember: 1,000 watts is 1 kilowatt.) Power is an instantaneous measure. That is, it is like the speed of a car. If you glance down at your speedometer, and it reads 60 miles per hour (96 kph) you have just determined the rate or speed at which your car is traveling at that instant. A deer may dart across the road, causing you to step on the brakes, and the rate of speed will decrease. Shaken by the near miss, you might drive at 50 miles per hour (80 kph) for a while.

Also noted in the previous sidebar, engineers and scientists rate electrical loads (devices that consume electricity) such as light bulbs and electric motors in watts or kilowatts. For example, a light bulb might be rated at 12 watts. An electric motor might be rated at 1,000 watts. An element in an electric water heater might be rated at 4,500 watts.

Scientists and engineers also use watts to rate electric-generating technologies, such as solar electric systems. A small PV system for an energy-efficient home, for instance, might be rated at 5,000 watts. A larger, less-efficient home might require a 15,000-watts or 15-kW system.

Energy, in contrast, is power consumption or production over time. Put another way, it is a quantity. Something you can measure. For the mathematically inclined, it is the product of rate × time. For example, suppose a CFL light bulb consumes 12 watts for one hour. The amount of electricity consumed is expressed in watt-hours. To determine watt-hours, multiply watts by time in hours. In this example, a 12-watt light bulb that operates for 1 hour consumes 12 watt-hours of electricity. If it operates for 10 hours, it uses 120 watt-hours of energy or 0.12 kilowatt-hours (kWh) of energy.

Both watt-hours and kilowatt-hours are measures of energy use. Utilities charge us for the energy we consume—the amount of power we consume—each month. Your utility probably charges somewhere between 8 and 30 cents per kWh of electricity you use.

While we consume energy in our homes, PV systems produce energy. A solar electric system producing electricity at a rate of 1,000 watts for a period of one hour produces 1,000 watt-hours or 1 kWh (kilowatt-hours) of energy. If it produces 1,000 watts for four hours, it has produced 4 kWh. If it produces 500 watts for two more hours, the daily total is 5 kWh.

America. Stream flow monitors on many rivers and streams throughout the world rely on solar-powered transmitters to beam data to solar-powered satellites. In the United States, this data is then beamed back to Earth to the US Geological Survey, where it is processed and disseminated.

Solar electric modules often power lights on buoys, vital for nighttime navigation on large rivers like the Saint Lawrence Seaway. Railroad signals and aircraft warning beacons are also often solar-powered.

PV modules are used to boost radio, television, and telephone signals. Signals from these sources are often transmitted over long distances. For successful transmission, however, they must be periodically amplified at relay towers. The towers are often situated in inaccessible locations, far from power lines. Because they are reliable and require little, if any, maintenance, PV systems are ideal for such applications. They make it possible for us to communicate across long distances. Next time you make a long-distance telephone call from a phone on a landline, rest assured solar energy is making it possible.

While PV systems are becoming very popular in more developed countries, they're also widely used in the developing world. They are, for instance, being installed in remote villages in less developed countries to power lights and computers and the refrigerators and freezers used to store vaccines and other medicine. They're also used to power water pumps.

The ultimate in remote and mobile applications, however, has to be the satellite. Virtually all military and telecommunications satellites are powered by solar electricity, as is the International Space Station.

World Solar Energy Resources

Solar electricity is rapidly growing in popularity, which is fortunate because global supplies of fossil-fuel resources like coal, natural gas, and oil are on the decline. As they decline, and as concern over global climate change increases, solar electric systems along with small and large wind systems and other forms of renewable energy farms will become a major source of electricity throughout the world. It's inevitable. But is there enough solar energy to meet our needs?

Although solar energy is unevenly distributed over the Earth's surface, significant resources are found on every continent. "Solar energy's potential is off the chart," write energy experts Ken Zweibel, James Mason, and Vasilis Fthenakis in a December 2007 article, "A Solar Grand Plan," published in *Scientific American*. Less than one billionth of the Sun's energy strikes the Earth, but, as they point out, the solar energy striking the Earth in a 40-minute period is equal to all the energy human society consumes in a year. That is, 40 minutes of solar energy is equivalent to all the coal, oil, natural gas, oil shale, tars sands, hydropower, and wood we consume in an entire year. What is more, we'd only need to capture about 0.01% of the solar energy striking the Earth to meet *all* of our energy demands. Solar electric systems mounted on our homes and businesses or in giant commercial solar arrays could tap into the Sun's generous supply of energy, providing us with an abundance of electricity.

Could solar electric provide 100% of the United States' or the world's electrical energy needs?

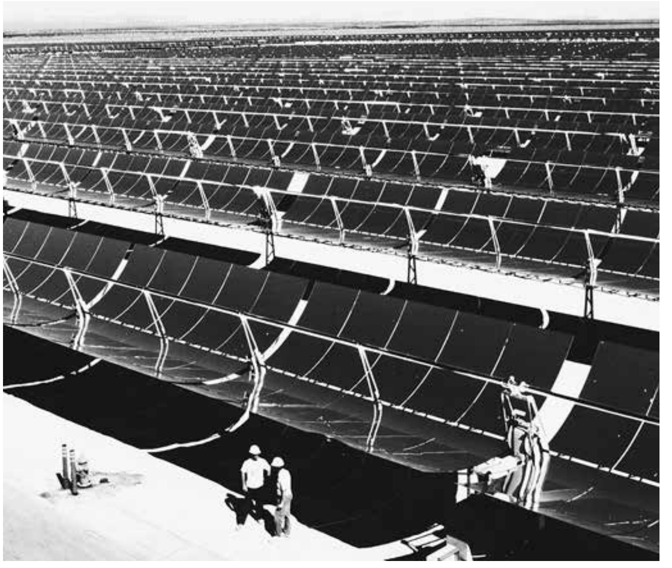
Yes, it could.

Will it?

Probably not.

In fact, no one is planning on a 100% solar future. Rather, most renewable energy experts envision a system that consists of a mix of renewable energy technologies such as solar hot water, solar electricity, passive solar, wind, hydro, geothermal, and biomass. These renewable energy resources, combined with radical improvements in energy efficiency, will become the mainstay of the world's energy production.

In a sustainable global energy system, PV systems could play a significant role. They could produce enormous amounts of electricity for homes, businesses, farms, ranches, schools, and factories. Another solar technology, large-scale solar thermal electric systems, could supplement PV systems and play a role in meeting our needs. Solar thermal electric systems concentrate sunlight energy to generate heat that's used to boil water. Steam generated from this process is used to spin a turbine connected to generator that makes electricity (Figure 1.7). Some of the newest solar thermal electric systems even store hot water so electricity can be generated on cloudy days or in the evening.



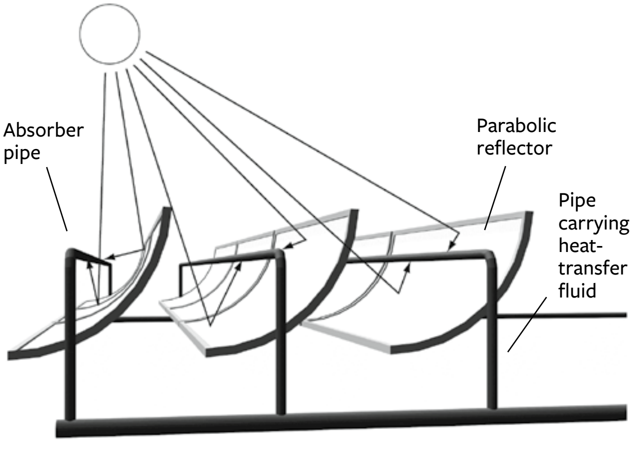


FIGURE 1.7. (*top*) Solar thermal electric systems like the one shown here reflect sunlight off of highly polished parabolic reflectors onto pipes (*bottom*) that contain heat-transfer fluid that absorbs energy from the intense, focused light. The heat is transferred via a heat exchanger to a large, well-insulated tank where it boils, producing steam. Steam turns a turbine that generates electricity much the same as in a conventional power plant. Although solar thermal electric systems can produce electricity at rates competitive with conventional power plants, they require a lot more maintenance than traditional solar electric systems. Photo Credit: Sandia National Laboratory. Art Credit: Anil Rao.

It is likely that large-scale wind farms will provide more electricity to power our future than PVs. (The world currently produces three times as much electricity from wind as it does from solar). Geothermal and biomass resources could contribute as well. *Biomass* is plant matter that can either be burned directly to produce heat or to generate steam that's used to power a turbine that generates make electricity. Biomass can also be converted to liquid or gaseous fuels that can be burned to produce electricity or heat (or power vehicles). Hydropower currently contributes a significant amount of electricity throughout the world, and it will continue to add to the energy mix in our future.

What will happen to conventional fuels such as oil, natural gas, coal, and nuclear energy? Although their role will diminish over time, these fuels will very likely contribute to the energy mix for many years to come. In the future, however, they will very likely take a back seat to solar, wind, and other renewables. They could eventually become pinch hitters to renewable energy.

Despite what many ill-informed critics say, renewable energy is splendidly abundant. What is more, the technologies needed to efficiently capture and convert solar energy to useful forms of energy like heat, light, and electricity are available now and, for the most part, quite affordable. Costs have plummeted in recent years. Take solar electricity, for example: the cost of solar electric modules has fallen from over $75 per watt in 1977 to $0.72 in 2015 (Figure 1.8).

While nuclear and fossil fuels are on the decline, the Sun will enjoy a long future. The Sun, say scientists, will continue to shine for at least five billion more years. To be truthful, however, scientists estimate that the Sun's output will increase by about 10% in one billion years, making planet Earth too hot to sustain life. So, we don't

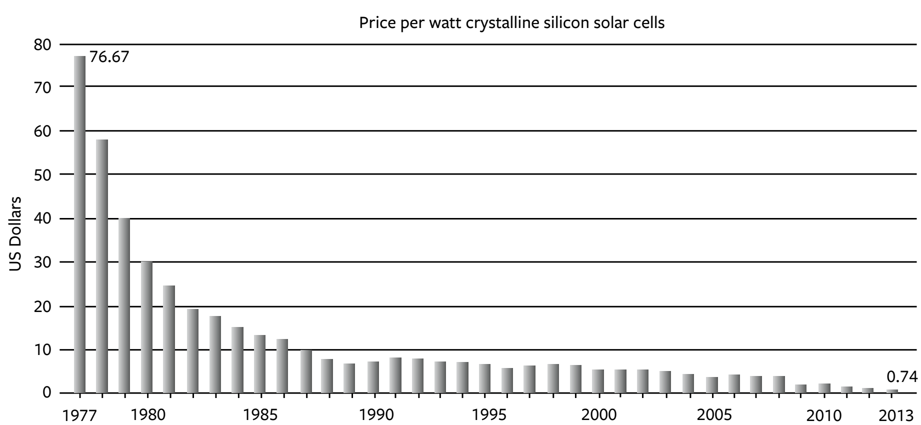


FIGURE 1.8. This graph shows the remarkable decline in the cost of solar electricity since 1977. The decline is the result of mass production directly or indirectly subsidized by government programs in China, the United States, and elsewhere. Credit: Bloomberg New Energy Finance, economist.com. Credit: Forrest Chiras.

have five billion years of sunshine, we have less than a billion years before we'll have to check out. But that's a lot more than the 30 to 50 years of oil we have left.

What the Critics Say

Proponents of a solar-powered future view solar energy as an ideal fuel source. It's clean. It's free. It's abundant. And it will be available for a long, long time. Its use could ease many of the world's most pressing problems, such as global climate change, species extinction, and desertification.

Like all fuels, solar energy is not perfect. Critics like to point out that, unlike conventional resources such as coal, the Sun is not available 24 hours a day. Some people don't like the looks of solar electric systems. And, for years, solar electric systems have been pretty pricey, too. Let's take a look at these arguments and respond to the criticisms.

Availability and Variability

Although the Sun shines 24 hours a day and beams down on the Earth at all times, half the planet is always blanketed in darkness. This poses a problem for humankind, especially those of us in the more developed countries, as we consume electricity 24 hours a day, 365 days a year.

Another problem is the daily variability of solar energy. That is, even during daylight hours, clouds can block the sun, sometimes for days on end. At night, PVs produce no energy at all. If solar electric systems are unable to generate electricity 24 hours a day like coal-fired and natural-gas-fired power plants, how can we use them to meet our 24-hour-per-day demand for electricity?

Some homeowners who live off grid (that is, not connected to the electrical grid) solve the problem by using batteries to store the electricity needed to meet nighttime use and the demand on cloudy days. (Remember, however, even on a cloudy day, a solar system will often produce 10% to 20% of its rated output.) I lived off grid for 14 years, and had electricity 24 hours a day, 365 days a year—all supplied by my PV system. I rarely ran out. And when I did, I fired up my backup generator.

One thing all off-gridders learn is that batteries don't store a lot of electricity. In order to live this way, you need to be frugal. It is doubtful that batteries could serve as a backup for modern society. We use—and waste—way too much electricity. We'd need gargantuan, costly battery banks to store energy for nighttime use. Although many strides have been made to store solar electricity, the scale at which we'd have to store it suggest we need an alternative. What is that?

The answer is *coupling*.

Put another way, solar's less-than-24-hour-per-day availability can also be offset by coupling solar electric systems with other renewable energy sources, for example, wind-electric systems, or hydroelectric systems. Wind systems, for instance, generate electricity day and night—so long as the winds blow. In some areas, winds are fairly constant throughout the year. Wind farms in these areas could make up for solar's nighttime absence. Hydroelectric systems tap the energy of flowing water in streams or rivers. These systems range in size from tiny to massive. Microhydro and macrohydro and everything in between can also be used to generate electricity to supplement solar systems, compensating for the Sun's "shortcomings," if you want to call it that.

Solar and wind are especially good partners, as I have found out at my home and educational center in Missouri. Figure 1.9 shows data on the solar and wind resources at my place. As illustrated, the Sun shines quite a lot in the spring, summer, and early fall, but less so during the winter. During winter, however, the winds blow more often and more forcefully. My wind turbine easily makes up for the reduced output of my PV systems during the less-sunny periods of the year, ensuring a reliable, year-round supply of electricity. The same coupling of solar and wind could provide a reliable source of electricity to much of the world.

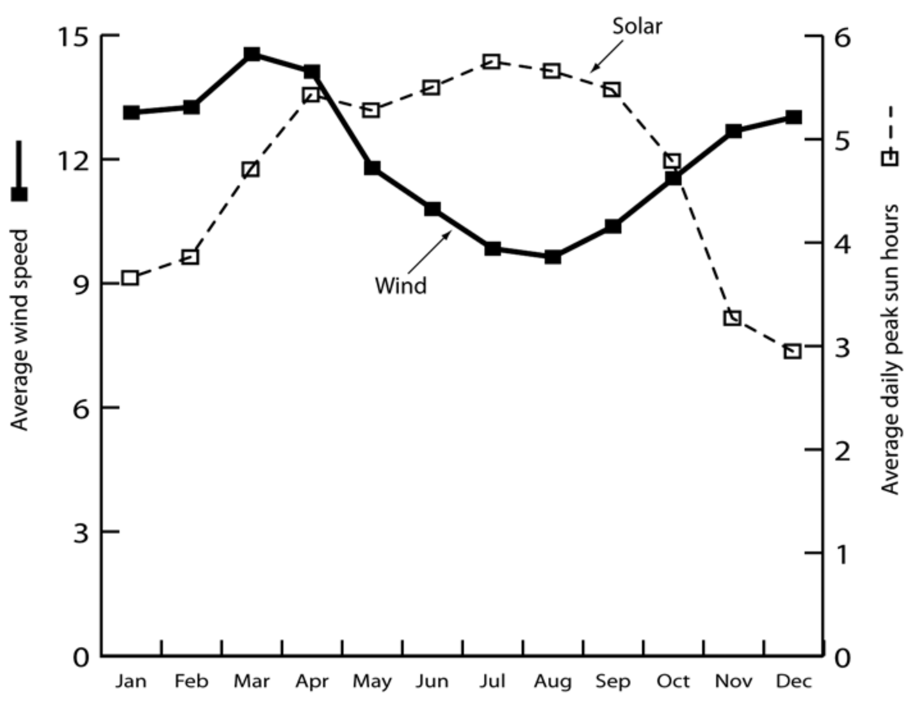


FIGURE 1.9. This graph of solar and wind energy resources at The Evergreen Institute illustrates how wind and solar energy complement each other. As shown here, sunlight is abundant in the late spring, summer, and early fall in our east-central Missouri location. Wind is most abundant in the late fall, winter, and early spring. This is a common scenario for many North American locations. Credit: Anil Rao.

Renewable energy coupling is much more efficient than all the fanciful schemes being proposed to store electricity from solar and wind systems. For example, some individuals have proposed using excess solar or wind electricity to power massive air compressors that pump compressed air into abandoned underground mines. When electricity is needed, the compressed air would be released through a turbine, not unlike those found in conventional power plants. The blades of the turbine would be attached to a shaft that is attached to a generator that produces electricity. While an interesting idea, this plan requires installation of massive solar and wind farms in mining country. Sites may not be suitable for massive renewable energy farms. Mines would also have to be pretty airtight to ensure efficient storage.

Solar electricity could also possibly be used to generate hydrogen gas from water. Hydrogen gas is created when electricity is run through water. This process, known as *electrolysis*, splits the water into its components, hydrogen and oxygen, both gases. Hydrogen can be stored in tanks and later burned to produce hot air or to heat water to produce steam. Hot air and steam can be used to spin a turbine attached to a generator. Hydrogen and oxygen can also be fed into fuel cells, devices that produce electricity.

While schemes such as these could work, they would be nowhere near as efficient as direct renewable energy coupling—that is, using the electrical output of solar and wind systems directly. That's because any time you convert one form of energy to another, energy is lost. Take the hydrogen storage idea as an example. In this system, electrical energy is required to generate hydrogen and oxygen gas from water. It also takes energy to compress these gases to store them. Hydrogen and oxygen then have to be combined in the fuel cell to create new electricity. This process, of course, is not 100% efficient, either.

Creating and storing energy in intermediate forms, like hydrogen, loses energy. It makes much more sense to use the electricity required to split water directly than to convert it into some other form and then convert it back to electricity. Each step in conversions such as these loses a lot the initial energy you started out with. Figure 1.10 shows an example, comparing the efficiency of generating electricity versus using electricity directly to power an electric car. As you can see, it is three to four times more efficient to use electricity directly than to convert it to a storage form, then convert it back. It's the laws of physics (notably the Second Law of Thermodynamics) at play.

As in residential systems, electricity for mass consumption can be supplied on cloudy days or at night by other renewable energy resources, such as wind, hydropower, or biomass (Figure 1.11). For example, commercial wind farms in Iowa and

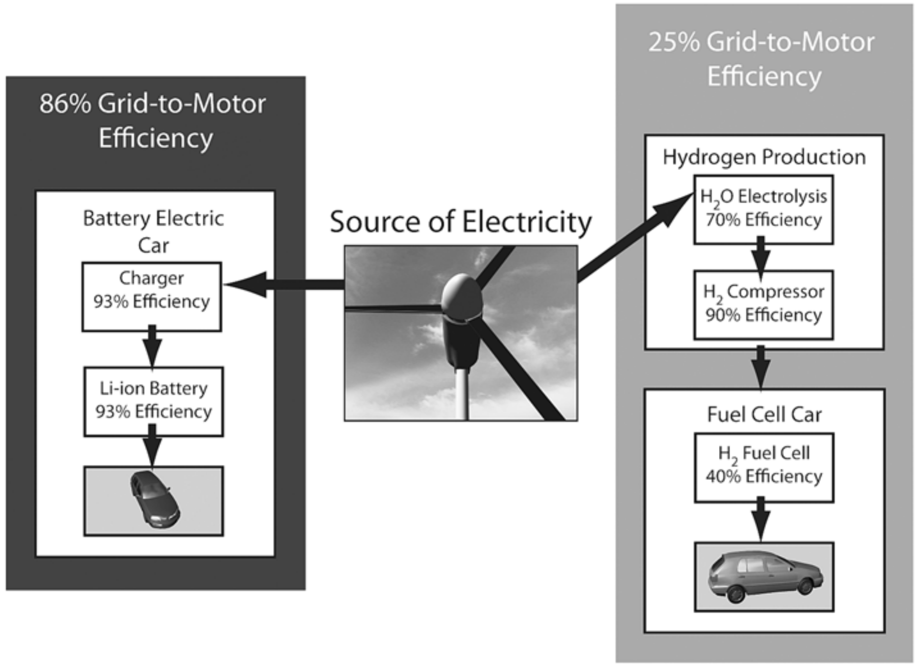


FIGURE 1.10. Efficiency of Direct Solar Vs. Hydrogen Stored Solar. The most fundamental problem with storing electricity in the form of hydrogen, then converting it back to electricity in hydrogen fuel cells is that it involves multiple energy conversions. Each conversion reduces the overall output of the system, as shown here in a system designed to produce electricity to power electric cars. Credit: Anil Rao.

downstate Illinois could provide electricity to Chicago to supplement solar systems in the summer and winter. That's because the winds often blow when the Sun is behind clouds (during storms, for instance). Hydroelectric plants and biomass facilities could also be used to ensure a continuous supply of renewable energy in an electric system finely tuned to switch from one energy source to another. In Canada, for example, hydroelectric facilities are treated as a *dispatchable energy resource*, much like natural gas is today in the United States. That is, they can be turned on and off as needed to meet demand. Such systems could be used to supplement electricity when demand exceeds the capacity of commercial solar systems or at night.

Shortfalls can be offset on a local or a regional scale by transferring electricity from areas of surplus solar and/or wind production to areas of insufficient electrical production. In Colorado, for instance, on cloudy days, wind farms in the northeastern and southeastern parts of the state could supplement locally produced solar electricity along the Front Range, providing electricity to Denver, Colorado Springs, and Fort Collins. The often-sunnier western slope (Grand Junction area) might also provide additional electricity to the Front Range of Colorado from surpluses. If more electricity is needed, it could be shipped via the electrical grid from neighboring Wyoming, Nebraska, and Kansas (Figure 1.12).

FIGURE 1.11. The author's boys, Skyler and Forrest, check out a large wind turbine at a wind farm in Canastota, New York. Wind farms like this one are popping up across the nation—indeed, across the world—producing clean, renewable electricity to power our future. Credit: Dan Chiras.

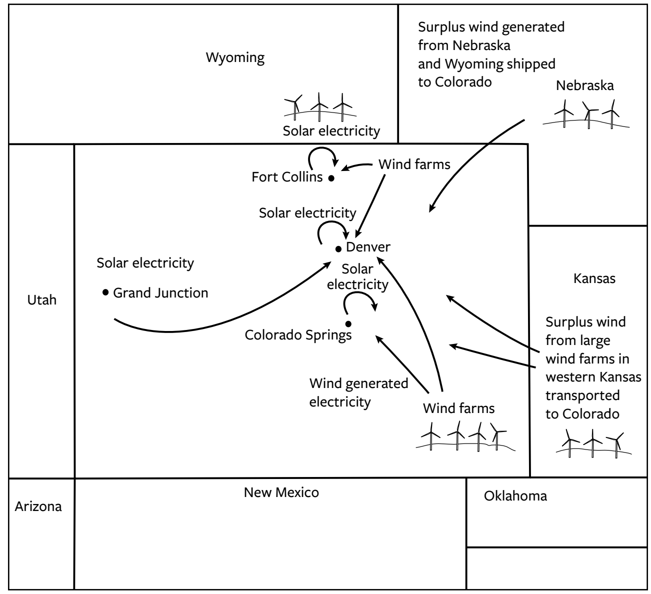


FIGURE 1.12. Electricity can be transported from one state or province to another via the electrical grid, a network of high-voltage transmission lines. As illustrated here, surplus electricity from solar and wind energy systems can be transferred to neighboring states, helping to create a steady supply of electricity through rain and shine. Credit: Forrest Chiras.

Integrating Renewables into America's Electrical Grid

European nations such as Denmark, Germany, and Spain are successfully integrating renewable energy into their electrical grids—and on a large scale. While the electrical grid in the United States is not as finely tuned, efforts are underway to improve and expand the grid, making it more amenable to renewable energy, like solar. Improved weather forecasting and better integration of data on the projected output of large commercial solar and wind systems with projections of customer demand could assist utilities in meeting customers' demands using a mixture of conventional and renewable fuels. Weather projections, for example, allows utilities to step up solar or wind production and scale back production from coal or other fossil fuels or vice versa. Today, thanks to these and other changes, many states are successfully integrating small residential and large commercial solar electric and wind systems with conventional sources of electricity. Further refinements will result in an even greater contribution from renewables—and a cleaner, more sustainable future.

FIGURE 1.13. Solar arrays can be mounted close to the roof to reduce their visibility. Like the arrangement shown here, arrays can be supported by aluminum rails, usually about 6 inches (15 cm) above the surface of the roof (the gap helps cool them in the summer). While attractive, arrays installed this way tend to produce less electricity than pole-mounted or ground-mounted PV arrays, which stay much cooler on hot summer days. Credit: Rochester Solar Technologies.

Solar's availability and variability can also be offset by biomass or natural gas-fired power plants and newer coal-fired plants that burn pulverized coal. Both can be started or stopped, or throttled up or down, to provide electricity at nearly a moment's notice.

Even though solar energy is not available 24 hours a day, there are ways to overcome this problem. That said, we should point out that even though solar energy is variable, it is not unreliable. Just like wind energy, you can count on a certain amount of solar energy each year. With smart planning, forecasting, and careful design and integration of new and existing sources of electricity, we can meet a good portion of our electrical needs from this seemingly capricious resource.

Aesthetics

While many of us view a solar electric array as a thing of great value, even beauty, some don't. Your neighbors, for instance, might think that a PV system detracts from the beauty of the neighborhood. Because not everyone views a PV system the same way, some neighborhood associations have banned PV systems.

Ironically, those who object to solar electric systems rarely complain about other visual blights like cell phone towers, electric transmission lines, and billboards. One reason that these common eyesores draw little attention is that they have been present in our communities for decades. We've grown used to ubiquitous electric lines and cell phone towers. But PV arrays are relatively new, and people aren't used to them yet.

Fortunately, there are ways to mount a solar array so that it blends seamlessly with the roof. As you'll learn in Chapter 8, solar modules can be mounted six inches (15 cm) or so off, and parallel to, the roof surfaces (Figure 1.13). Manufacturers are also producing modules with black frames. They are much less conspicuous than the traditional silver-framed modules. Installations such as these help make solar more appealing to more people. There's also a solar product called PV laminate that is applied directly to certain types of metal roofs, known as *standing seam metal roofs*, resulting in an even lower-profile array (Figure 1.14). Solar arrays can sometimes be mounted on poles or racks anchored to the ground that can be placed in sunny backyards—out of a neighbor's line of sight (Figure 1.15).

Cost

For years, the biggest disadvantage of solar electric systems has been their cost. Even in the last edition of this book, which was published in 2009, costs were still rather high, at about $4.00 per watt just for the modules. Those of us who advocated for solar electricity had to appeal to people's sense of right and wrong and to the external economic costs—that is, the environmental costs—of conventional power. I'm delighted to report that those days are over. As noted earlier, solar electricity is now often cost competitive—and sometimes cheaper—over the long haul than electricity from conventional sources, even in rural areas. I'll show you the proof of this assertion in Chapter 4.

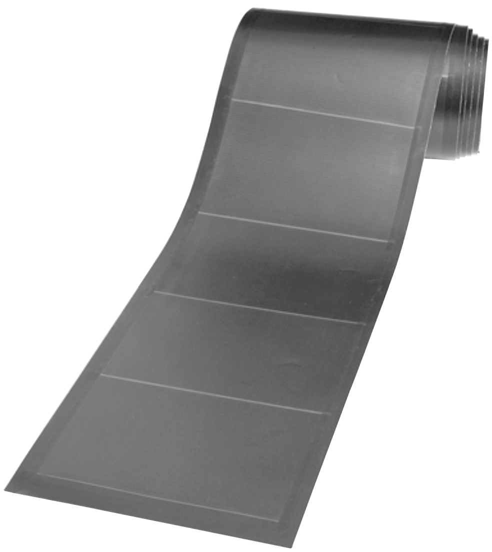


FIGURE 1.14. This product, known as PV laminate, is a plastic-coated flexible material that adheres to standing seam metal roofs. It's best applied to new roof panels *before* they are installed on the building. PV laminate is not as sensitive to high temperatures as conventional silicon-crystal modules used in most solar systems. The company that first developed this product, Uni-Solar is no longer in business, but other companies produce them. Credit: Uni-Solar.

FIGURE 1.15. Ground-mounted solar arrays like this one accommodate numerous modules and can be oriented and angled to maximize production. Because they allow air to circulate freely around the modules, systems such as these stay cooler than many roof-mounted arrays and thus tend to have a higher output. Credit: Dan Chiras.

Solar electricity makes sense in most areas with a decent amount of sunshine. In those areas with lots of sunshine and high electricity costs, like southern California, it makes even more sense. Solar electricity may also make sense for those who are building a home more than a few tenths of a mile from a power line. That's because utility companies often charge customers a gargantuan fee to connect their power lines. You could, for instance, pay $20,000 to connect to an electric line, even if you are building a home 0.2 miles from a power line. Bear in mind, too, that these line extension fees don't pay for a single kilowatt-hour of electricity. They only cover the cost of the transformer, poles, wires, electrical meter, and installation. A homeowner pays the cost of this connection up front or, more commonly, prorated over many years, with the extra amount showing up on the monthly electrical bill.

Another common complaint about solar electricity is that it requires costly, inefficient batteries. Nothing could be further from the truth. Most PV systems installed these days require no batteries. These systems produce electricity that feeds active loads in our homes (that is, things like our TVs and lights). When the system produces more electricity than is needed, the surplus is backfed onto the grid, running the customer's meter backward. However, when the homeowner needs that electricity back, it is his or hers for free—within the billing cycle. (More on this in Chapter 5.) So, batteries are generally not needed.

The Advantages of Solar Electric Systems

Although solar electricity, like any fuel, has some downsides, they're clearly not insurmountable and are outweighed by many advantages. One of the most important advantages is that solar energy is an abundant, renewable resource—one that will be with us for hundreds of thousands of years. While natural gas, oil, coal, and nuclear fuels are limited and on the decline, solar energy will be available to us for about 1 billion years.

Solar energy is a clean resource, too. By reducing the world's reliance on coal-fired power plants, solar electricity could help us reduce our contribution to a host of environmental problems, among them acid rain, global climate disruption, habitat destruction, species extinction, and cropland loss caused by desertification. Solar electricity could even replace costly, risky nuclear power plants. Solar energy could help us decrease our reliance on declining and costly supplies of fossil fuels like coal, natural gas, and oil. (Although very little electricity in the United States comes from oil, electricity generated by solar electric systems could someday be used to power electric or plug-in gas-electric hybrid vehicles [Figure 1.16] like the Ford Fusion Energi.) And, although the production of solar electric systems does have its impacts, all in all it is a relatively benign technology compared to fossil-fuel and nuclear power plants.

Another benefit of solar electricity is that, unlike oil, coal, natural gas, and nuclear energy, the fuel is free. Moreover, solar energy is not owned or controlled by hostile foreign states or one of the dozen or so major energy companies that dictate global energy policy. Because the fuel is free and will remain free, solar energy can provide a hedge against inflation, fueled in part by ever-increasing fuel costs. That's why solar is popular among many businesses and some school districts. Solar is a one-time investment for a lifetime of inexpensive electricity not subjected to annual price hikes.

FIGURE 1.16. Plug-in hybrids, like this one, and electric cars will very likely play a huge role in personal transportation in the future. Electric cars with longer-range battery banks could be used for commuting and for short trips under 200 miles, while plug-in hybrids could be used for commuting and long-distance trips. Credit: Calcars.org.

An increasing reliance on solar and wind energy could also ease political tensions worldwide. Solar and other renewable energy resources could alleviate the perceived need for costly military operations aimed at stabilizing (controlling the politics of) the Mideast, a region where the largest oil reserves reside. Because the Sun is not owned or controlled by any nation in the Middle East, we'll never fight a war over solar or other renewable energy resources. Not a drop of human blood will be shed to ensure the steady supply of solar energy to fuel our economy—or at least, I hope not.

Yet another advantage of solar-generated electricity is that it uses existing infrastructure (the electrical grid). A transition to solar electricity could occur fairly seamlessly.

Solar electricity is also modular. (That's one reason why solar "panels" are called "modules.") That is, you can build a system over time. If you can only afford a small system, you can start small and expand your system as money becomes available. Expandability has been made easier by the invention of *microinverters*, small inverters that are wired to each solar module in a PV system. (For years, most solar systems were designed with one inverter, known as a *string inverter*. If you wanted to expand your system, you'd buy more modules and have to buy a larger, more expensive inverter. With microinverters, a homeowner can add one module and one microinverter at a time. It is much more economical to expand this way.)

Solar electricity could provide substantial economic benefits for local, state, and regional economies. Moreover solar electricity does not require extensive use of water; reliance on water is an increasing problem for coal, nuclear, and gas-fired power plants, particularly in the western United States and other arid regions.

On a personal level, solar electric systems offer considerable economic savings over their lifetime, a topic discussed in Chapter 4. They also create a sense of pride and accomplishment, and they generate tremendous personal satisfaction. A 2015 report by the Lawrence Berkeley National Laboratory on home sales in eight states from 2002 to 2013 showed that solar electric system boosted selling prices. Sales prices on homes with PV systems were about $4.17 per watt higher than comparable "solarless" homes. If you had a 10-kW PV array on your home, you would have made an additional $41,700. That's amazing, especially when you take into account that the cost of a PV system nationwide is currently $3.46 per watt, installed. That system would cost $34,600 up front. Had you availed yourself to the 30% federal tax credit, the cost would have been $24,200. So not only would you have you doubled your money, the systems would have generated a ton of electricity free of charge.

Purpose of this Book

This book focuses primarily on solar electric systems for homes and small businesses. It is written for individuals who aren't well versed in electricity. I'll teach you much of what you need to know about electricity. Rest assured, you don't need a master's degree in electrical engineering to understand this material.

In this book, I've strived to explain facts and concepts clearly and accurately, introducing key terms and concepts as needed, and repeating them as often as prudent to make my points clearly and accurately. My overarching goal is always to create a very user-friendly book.

When you finish reading and studying the material in this book, you'll know an amazing amount about solar energy and solar electric systems. You will have the knowledge required to assess your electrical consumption and the solar resource at your site. You will also be able to determine if a solar electric system will meet your needs and if it makes sense for you. You will know what kind of system you should install, and you'll have a good working knowledge of the key components of PV systems. In keeping with my long-standing goal of creating savvy and knowledgeable buyers, this book will help you know what to look for when shopping for a PV system or an installer. You'll also know how PV systems are installed and what their maintenance requirements are.

I should point out, however, that this book is not an installation manual. When you're done reading, you won't be qualified to install a solar electric system. Even so, this book is a good start. You'll understand much of what's needed to design and install a system or launch a career in PVs. Many people who have read this book and taken my workshops have gone on to careers in solar electricity.

If you choose to hire a solar energy professional to install a system, you'll be thankful you've read and studied the material in this book. The more you know, the more informed input you will have into your system design, components, siting, and installation—and the more likely you'll be happy with your purchase.

This book should also help you develop realistic expectations. Knowing the shortcomings and pitfalls of solar electric systems helps us avoid mistakes and prevent disappointments that are often fueled by unrealistic expectations. By the same token, the more you know about these systems, the more likely you are to install an efficient high-output system. Paying attention to small details can result in huge increases in output.

Organization of this Book

Let's begin our exploration of solar electricity. We'll start in the next chapter by studying the Sun and solar energy. I will discuss important terms and concepts such as average peak sun hours. You'll learn why solar energy varies during the year, and how to calculate the proper orientation and tilt angle of your array to achieve optimal performance.

In Chapter 3, we'll explore solar electricity—the history of PVs, the types of solar cells on the market today, their efficiency, how solar cells generate electricity, and what new solar electric technologies are being developed.

In Chapter 4, we will explore the feasibility of tapping into solar energy to produce electricity at your site. I'll tell you how to assess your electrical energy needs and determine the size of the solar system you'll need to meet them. You'll also learn why it is so important to make your home as energy efficient as possible before you install a solar electric system.

In Chapter 5, we'll examine three types of residential solar electric systems: (1) off-grid, (2) batteryless grid-tied, and (3) grid-connected with battery backup. You'll learn the basic components and the pros and cons of each system. We will also examine hybrid systems—for example, wind-PV systems. You will see how they complement each other and can provide a reliable, year-round supply of electricity. That said, you will also learn whether it makes sense to hybridize or simply expand your solar system. In this chapter, you will also learn the ins and outs of connecting to the electric grid. And I will discuss the sometimes-confusing process called *net metering*. I'll also show you ways to make solar electricity affordable. And, we'll explore ways to expand a solar electric system and ways to economically add batteries to a grid-tied system. This is a strategy that many of us are contemplating as utility companies are starting to charge PV system owners more for electricity they buy from the grid. (More on that revolting development shortly!)

Chapter 6 introduces readers to inverters, string inverters, and microinverters, vital components of most solar electric systems. You'll learn what they do and how they operate. I'll also discuss some recent innovations in inverter design and provide some shopping tips—ideas on what you should look for when buying an inverter.

In Chapter 7, I'll tackle storage batteries for off-grid solar or grid-connected systems with battery backup. You will learn about the types of batteries you can install, how to install batteries correctly, battery maintenance, and ways to reduce battery maintenance. I will point out common mistakes people make with their batteries—and there are many—and give you ways to avoid making those same, often costly mistakes. You will also learn about battery safety and how to size a battery bank for a PV system. I'll finish with a discussion of charge controllers, an essential component of virtually all battery-based PV systems. We'll examine some recent innovations in charge controllers and explore backup generators, providing information on what your options are and what to look for when buying a generator.

In Chapter 8, I'll provide an overview of the steps in a solar electric system installation—so you know what to expect. I'll also discuss system maintenance. You'll learn various mounting options—for example, pole-mounts and roof racks. We'll explore pole-mounted racks that enable PV arrays to track the Sun from sunrise to sunset and discuss the economics of this option.

In Chapter 9, we'll explore a range of issues such as permits, covenants, and utility interconnection. I'll discuss whether you should install a system yourself or hire a professional and, if you choose the latter, how to locate a competent installer.

Finally, as all of my books do, this book includes a comprehensive resource guide. It contains a list of books, articles, videos, associations, organizations, workshops, and websites of manufacturers of the components of PV systems.