Introduction to Solar Energy Technologies

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This course was adapted from the Solar Energy Technologies Office of the U.S. Department of Energy website at https://www.energy.gov/eere/solar/solar-energy-technologies-office, which is in the public domain.

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1. Introduction

The amount of sunlight that strikes the earth's surface in an hour and a half is enough to handle the entire world's energy consumption for a full year. Solar technologies convert sunlight into electrical energy either through photovoltaic (PV) panels or through mirrors that concentrate solar radiation. This energy can be used to generate electricity or be stored in batteries or thermal storage.

Below, you can find information on the basics of solar radiation, photovoltaic and concentrating solar-thermal power technologies, electrical grid systems integration, and the non-hardware aspects (soft costs) of solar energy.

In addition, you can dive deeper into solar energy by going to the U.S. Department of Energy Solar Energy Technologies Office website.

2. Solar Radiation Basics

Solar radiation, often called the solar resource or just sunlight, is a general term for the electromagnetic radiation emitted by the sun. Solar radiation can be captured and turned into useful forms of energy, such as heat and electricity, using a variety of technologies. However, the technical feasibility and economical operation of these technologies at a specific location depends on the available solar resource.

BASIC PRINCIPLES

Every location on Earth receives sunlight at least part of the year. The amount of solar radiation that reaches any one spot on the Earth's surface varies according to:

- Geographic location
- Time of day
- Season
- Local landscape
- Local weather.

Because the Earth is round, the sun strikes the surface at different angles, ranging from 0° (just above the horizon) to 90° (directly overhead). When the sun's rays are vertical, the Earth's surface gets all the energy possible. The more slanted the sun's rays are, the longer they travel through the atmosphere, becoming more scattered and diffuse. Because the Earth is round, the frigid polar regions never get a high sun, and because of the tilted axis of rotation, these areas receive no sun at all during part of the year.

The Earth revolves around the sun in an elliptical orbit and is closer to the sun during part of the year. When the sun is nearer the Earth, the Earth's surface receives a little more solar energy. The

Earth is nearer the sun when it is summer in the southern hemisphere and winter in the northern hemisphere. However, the presence of vast oceans moderates the hotter summers and colder winters one would expect to see in the southern hemisphere as a result of this difference.

The 23.5° tilt in the Earth's axis of rotation is a more significant factor in determining the amount of sunlight striking the Earth at a particular location. Tilting results in longer days in the northern hemisphere from the spring (vernal) equinox to the fall (autumnal) equinox and longer days in the southern hemisphere during the other 6 months. Days and nights are both exactly 12 hours long on the equinoxes, which occur each year on or around March 23 and September 22.

Countries such as the United States, which lie in the middle latitudes, receive more solar energy in the summer not only because days are longer, but also because the sun is nearly overhead. The sun's rays are far more slanted during the shorter days of the winter months. Cities such as Denver, Colorado, (near 40° latitude) receive nearly three times more solar energy in June than they do in December.

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

DIFFUSE AND DIRECT SOLAR RADIATION

As sunlight passes through the atmosphere, some of it is absorbed, scattered, and reflected by:

- Air molecules
- Water vapor
- Clouds
- Dust
- Pollutants
- Forest fires
- Volcanoes.

This is called *diffuse solar radiation*. The solar radiation that reaches the Earth's surface without being diffused is called *direct beam solar radiation*. The sum of the diffuse and direct solar radiation is called *global solar radiation*. Atmospheric conditions can reduce direct beam radiation by 10% on clear, dry days and by 100% during thick, cloudy days.

MEASUREMENT

Scientists measure the amount of sunlight falling on specific locations at different times of the year. They then estimate the amount of sunlight falling on regions at the same latitude with similar climates. Measurements of solar energy are typically expressed as total radiation on a horizontal surface or as total radiation on a surface tracking the sun.

Radiation data for solar electric (photovoltaic) systems are often represented as kilowatt-hours per square meter (kWh/m^2). Direct estimates of solar energy may also be expressed as watts per square meter (W/m^2).

Radiation data for solar water heating and space heating systems are usually represented in British thermal units per square foot (Btu/ft^2).

DISTRIBUTION

The solar resource across the United States is ample for photovoltaic (PV) systems because they use both direct and scattered sunlight. Other technologies may be more limited. However, the amount of power generated by any solar technology at a particular site depends on how much of the sun's energy reaches it. Thus, solar technologies function most efficiently in the southwestern United States, which receives the greatest amount of solar energy.

There are two main types of solar energy technologies—photovoltaics (PV) and concentrating solar-thermal power (CSP).

3. Solar Photovoltaic Technology Basics

A single PV device is known as a cell. An individual PV cell is usually small, typically about 1 or 2 watts of power. To producing boost the power output of PV cells, they are connected together in chains to form larger units known as modules or panels. Modules can be used individually, or several can be connected to form arrays. One or more arrays is then connected to the electrical grid as part of a complete PV system. Because of this modular structure, PV systems can be built to meet almost any electric power need, small or large.

PV modules and arrays are just one part of a PV system. Systems also include mounting structures that point panels toward the sun, along with the components that take the direct-current (DC) electricity produced by modules and convert it to the alternating-current (AC) electricity used to power all of the appliances in your home.

The largest PV systems in the country are located in California and produce power for utilities to distribute to their customers. The Solar Star PV power station produces 579 megawatts of electricity, while the Topaz Solar Farm and Desert Sunlight Solar Farm each produce 550 megawatts.

3.1 Solar Photovoltaic Cell Basics

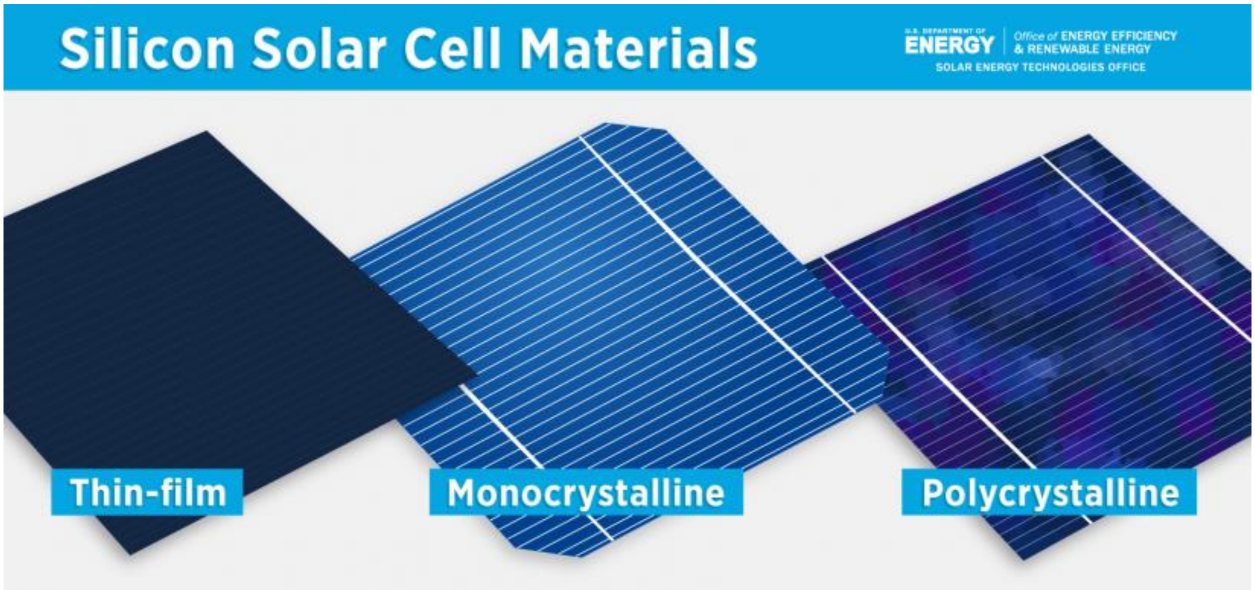
When light shines on a photovoltaic (PV) cell – also called a solar cell – that light may be reflected, absorbed, or pass right through the cell. The PV cell is composed of semiconductor material; the "semi" means that it can conduct electricity better than an insulator but not as well as a good conductor like a metal. There are several different semiconductor materials used in PV cells.

When the semiconductor is exposed to light, it absorbs the light's energy and transfers it to electrons in the material. This extra energy allows the electrons to flow through the material as an electrical current. This current is extracted through conductive metal contacts – the grid-like lines on a solar cell – and can then be used to power your home and the rest of the electric grid.

The efficiency of a PV cell is simply the amount of electrical power coming out of the cell compared to the energy from the light shining on it, which indicates how effective the cell is at converting energy from one form to the other. The amount of electricity produced from PV cells depends on the characteristics (such as intensity and wavelengths) of the light available and multiple performance attributes of the cell.

An important property of PV semiconductors is the bandgap, which indicates what wavelengths of light the material can absorb and convert to electrical energy. If the semiconductor's bandgap matches the wavelengths of light shining on the PV cell, then that cell can efficiently make use of all the available energy.

Learn more below about the most commonly-used semiconductor materials for PV cells.



SILICON

Silicon is, by far, the most common semiconductor material used in solar cells, representing approximately 95% of the modules sold today. It is also the second most abundant material on Earth (after oxygen) and the most common semiconductor used in computer chips. Crystalline silicon cells are made of silicon atoms connected to one another to form a crystal lattice. This lattice provides an organized structure that makes conversion of light into electricity more efficient.

Solar cells made out of silicon currently provide a combination of high efficiency, low cost, and long lifetime. Modules are expected to last for 25 years or more, still producing more than 80% of their original power after this time.

THIN-FILM PHOTOVOLTAICS

A thin-film solar cell is made by depositing one or more thin layers of PV material on a supporting material such as glass, plastic, or metal. There are two main types of thin-film PV semiconductors on the market today: cadmium telluride (CdTe) and copper indium gallium diselenide (CIGS). Both materials can be deposited directly onto either the front or back of the module surface.

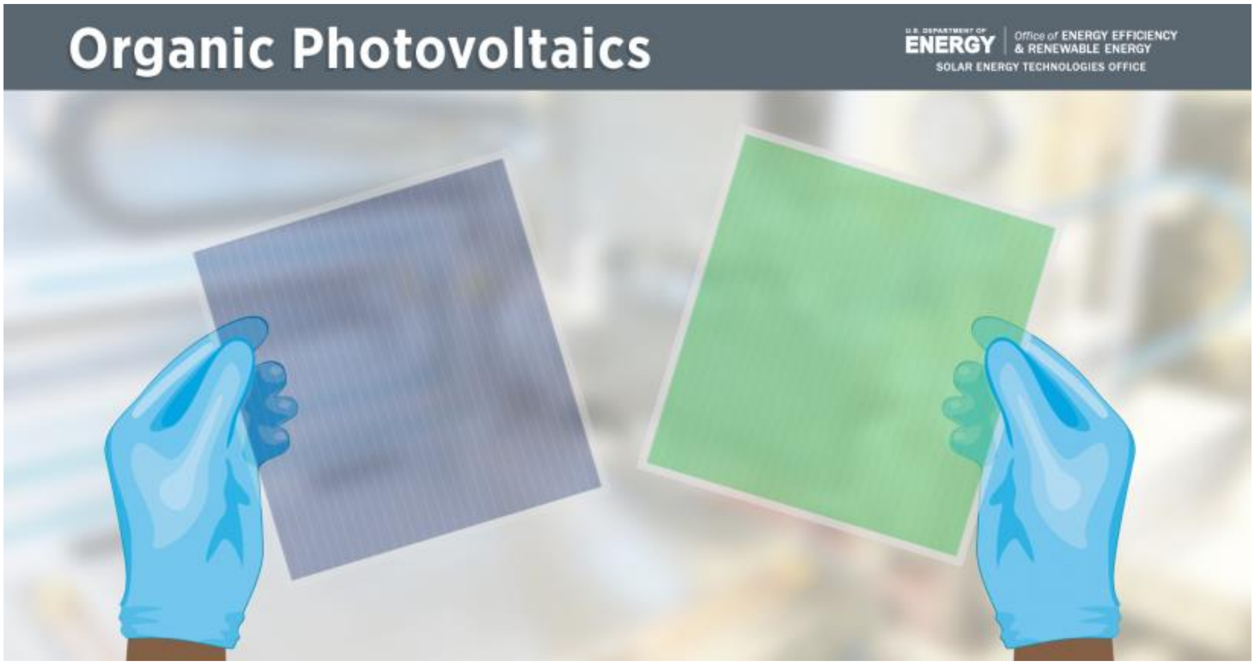
CdTe is the second-most common PV material after silicon, and CdTe cells can be made using low-cost manufacturing processes. While this makes them a cost-effective alternative, their efficiencies still aren't quite as high as silicon. CIGS cells have optimal properties for a PV material and high efficiencies in the lab, but the complexity involved in combining four elements makes the transition from lab to manufacturing more challenging. Both CdTe and CIGS require more protection than silicon to enable long-lasting operation outdoors.

PEROVSKITE PHOTOVOLTAICS

Perovskite solar cells are a type of thin-film cell and are named after their characteristic crystal structure. Perovskite cells are built with layers of materials that are printed, coated, or vacuum-deposited onto an underlying support layer, known as the substrate. They are typically easy to assemble and can reach efficiencies similar to crystalline silicon. In the lab, perovskite solar cell efficiencies have improved faster than any other PV material, from 3% in 2009 to over 25% in 2020. To be commercially viable, highest overall efficiencies are obtained enough to survive 20 years outdoors, so researchers are working on making them more durable and developing large-scale, low-cost manufacturing techniques.

ORGANIC PHOTOVOLTAICS

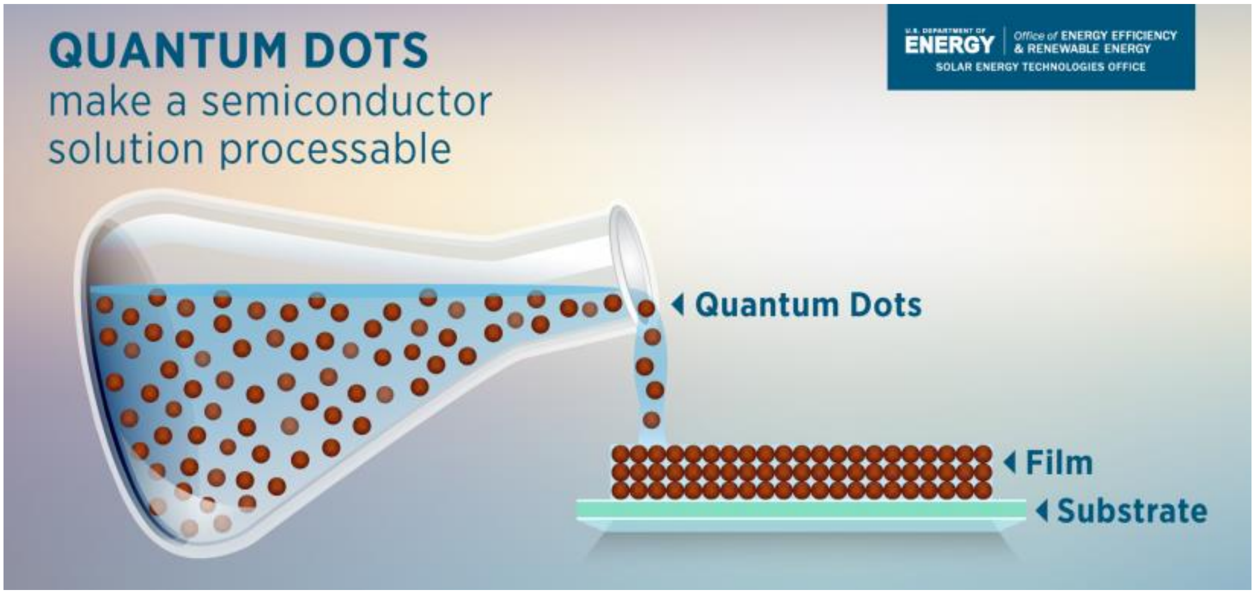
Organic PV or OPV, cells are composed of carbon-rich (organic) compounds and can be tailored to enhance a specific function of the PV cell, such as bandgap, transparency, or color. OPV cells are currently only about half as efficient as crystalline silicon cells and have shorter operating lifetimes, but could be less expensive to manufacture in high volumes. They can also be applied to a variety of supporting materials, such as flexible plastic, making OPV able to serve a wide variety of uses.



QUANTUM DOTS

Quantum dot solar cells conduct electricity through tiny particles of different semiconductor materials just a few nanometers wide, called quantum dots. Quantum dots provide a new way to process semiconductor materials, but it is difficult to create an electrical connection between them, so they're currently not very efficient. However, they are easy to make into solar cells. They can be deposited onto a substrate using a spin-coat method, a spray, or roll-to-roll printers like the ones used to print newspapers.

Quantum dots come in various sizes and their bandgap is customizable, enabling them to collect light that's difficult to capture and to be paired with other semiconductors, like perovskites, to optimize the performance of a multijunction solar cell (more on those below).



MULTIJUNCTION PHOTOVOLTAICS

Another strategy to improve PV cell efficiency is layering multiple semiconductors to make multijunction solar cells. These cells are essentially stacks of different semiconductor materials, as opposed to single-junction cells, which have only one semiconductor. Each layer has a different bandgap, so they each absorb a different part of the solar spectrum, making greater use of sunlight than single-junction cells. Multijunction solar cells can reach record efficiency levels because the light that doesn't get absorbed by the first semiconductor layer is captured by a layer beneath it.

While all solar cells with more than one bandgap are multijunction solar cells, a solar cell with exactly two bandgaps is called a tandem solar cell. Multijunction solar cells that combine semiconductors from columns III and V in the periodic table are called multijunction III-V solar cells.

Multijunction solar cells have demonstrated efficiencies higher than 45%, but they're costly and difficult to manufacture, so they're reserved for space exploration. The military is using III-V solar cells in drones, and researchers are exploring other uses for them where high efficiency is key.

CONCENTRATION PHOTOVOLTAICS

Concentration PV, also known as CPV, focuses sunlight onto a solar cell by using a mirror or lens. By focusing sunlight onto a small area, less PV material is required. PV materials become more efficient as the light becomes more concentrated, so the highest overall efficiencies are obtained with CPV cells and modules. However, more expensive materials, manufacturing techniques, and ability to track the movement of the sun are required, so demonstrating the necessary cost advantage over today's high-volume silicon modules has become challenging.

3.2 Solar Photovoltaic System Design Basics

Solar photovoltaic modules are where the electricity gets generated, but are only one of the many parts in a complete photovoltaic (PV) system. In order for the generated electricity to be useful in a home or business, a number of other technologies must be in place.

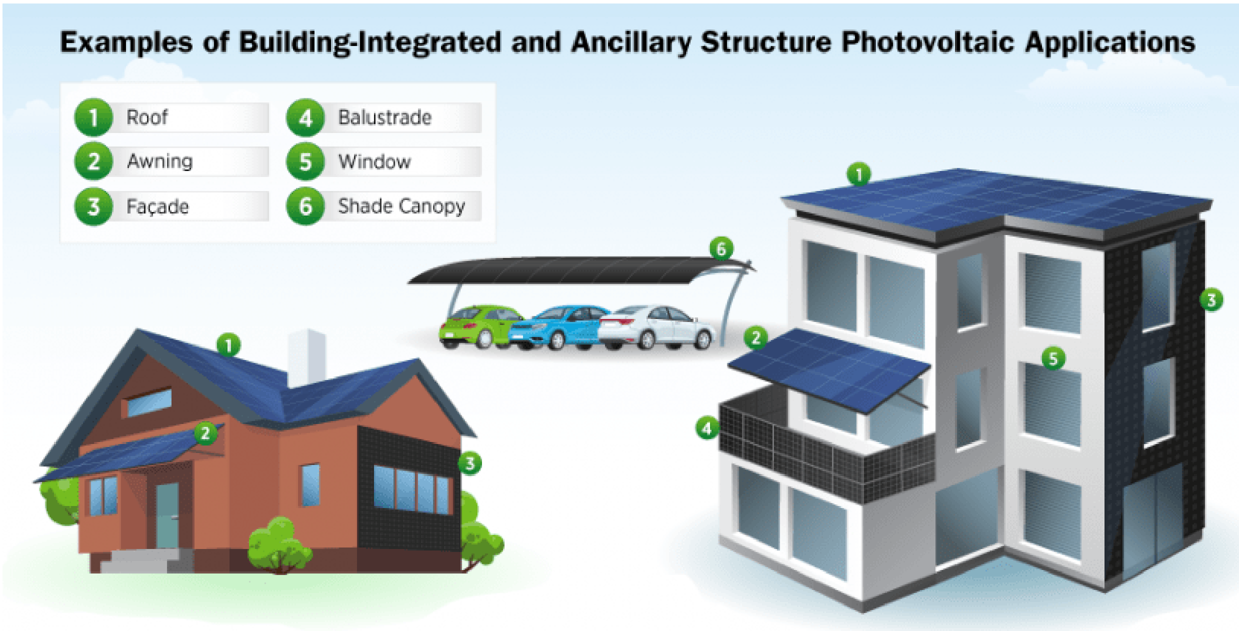
MOUNTING STRUCTURES

PV arrays must be mounted on a stable, durable structure that can support the array and withstand wind, rain, hail, and corrosion over decades. These structures tilt the PV array at a fixed angle determined by the local latitude, orientation of the structure, and electrical load requirements. To obtain the highest annual energy output, modules in the northern hemisphere are pointed due south and inclined at an angle equal to the local latitude. Rack mounting is currently the most common method because it is robust, versatile, and easy to construct and install. More sophisticated and less expensive methods continue to be developed.

For PV arrays mounted on the ground, tracking mechanisms automatically move panels to follow the sun across the sky, which provides more energy and higher returns on investment. One-axis trackers are typically designed to track the sun from east to west. Two-axis trackers allow for modules to remain pointed directly at the sun throughout the day. Naturally, tracking involves more up-front costs and sophisticated systems are more expensive and require more maintenance. As systems have improved, the cost-benefit analysis increasingly favors tracking for ground-mounted systems.

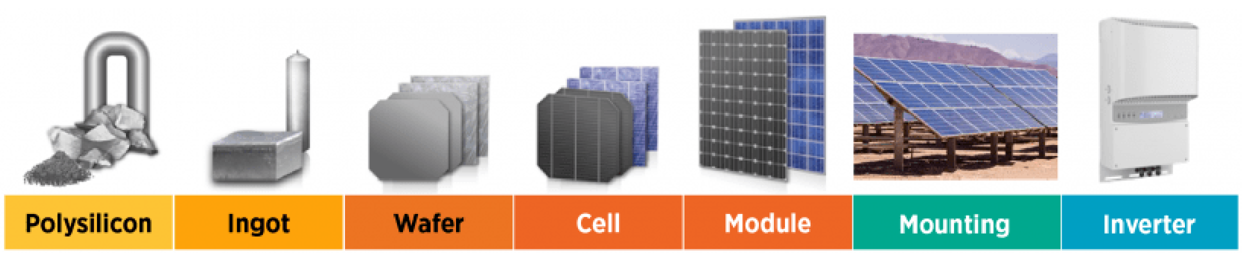
BUILDING-INTEGRATED PV

While most solar modules are placed in dedicated mounting structures, they can also be integrated directly into building materials like roofing, windows, or façades. These systems are known as building-integrated PV (BIPV). Integrating solar into buildings could improve material and supply chain efficiencies by combining redundant parts, and reduce system cost by using existing building systems and support structures. BIPV systems could provide power for direct current (DC) applications in buildings, like LED lighting, computers, sensors, and motors, and support grid-integrated efficient building applications, like electric vehicle charging. BIPV systems still face technical and commercial barriers to widespread use, but their unique value makes them a promising alternative to traditional mounting structures and building materials.



3.3 Solar Photovoltaic Manufacturing Basics

Solar manufacturing encompasses the production of products and materials across the solar value chain. While some concentrating solar-thermal manufacturing exists, most solar manufacturing in the United States is related to photovoltaic (PV) systems. Those systems are comprised of PV modules, racking and wiring, power electronics, and system monitoring devices, all of which are manufactured.



PV Module Manufacturing

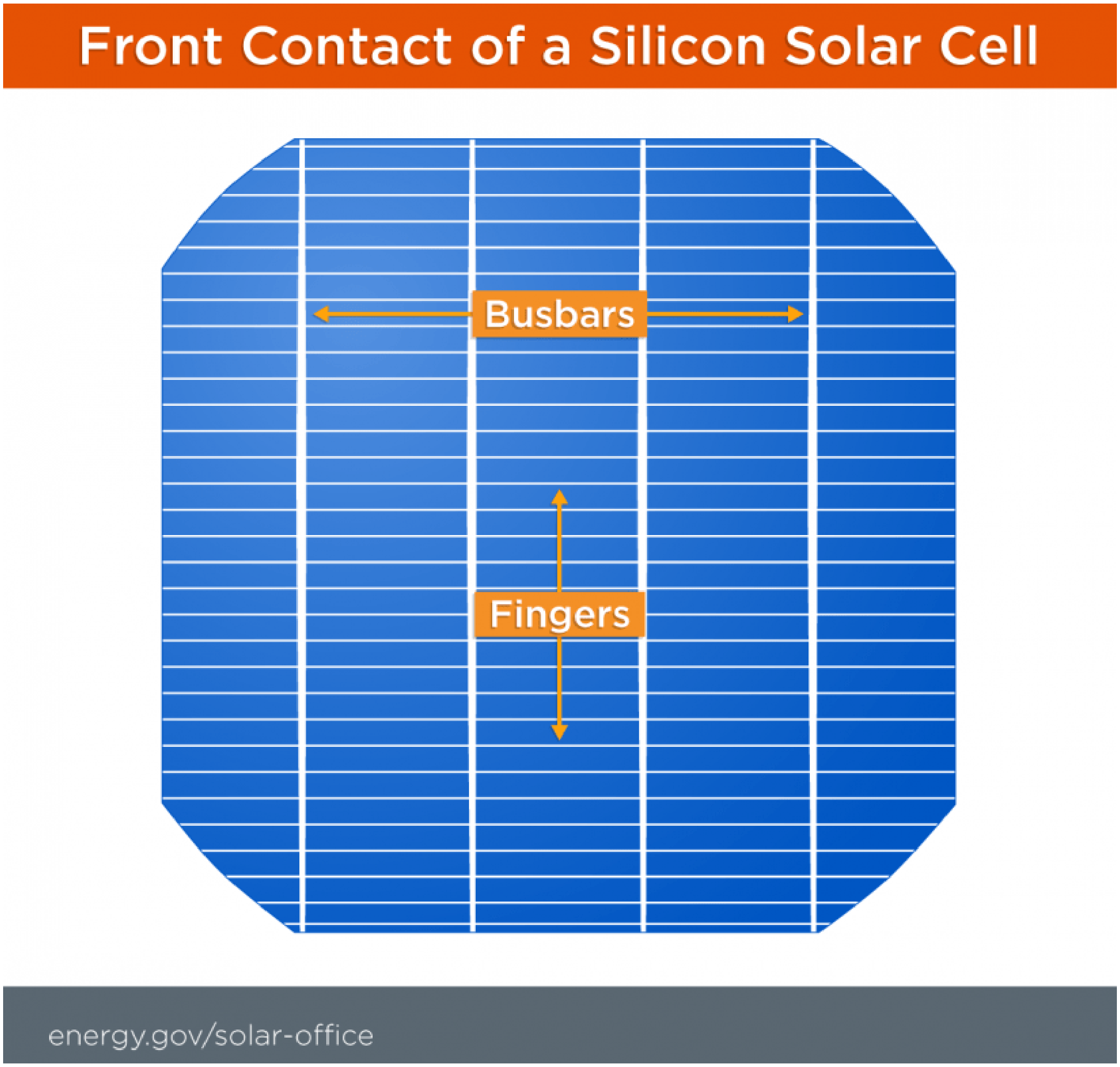
SILICON PV

Most commercially available PV modules rely on crystalline silicon as the absorber material. These modules have several manufacturing steps that typically occur separately from each other.

- **Polysilicon Production** – Polysilicon is a high-purity, fine-grained crystalline silicon product, typically in the shape of rods or beads depending on the method of production. Polysilicon is commonly manufactured using methods that rely on highly reactive gases, synthesized primarily using metallurgical-grade silicon (obtained from quartz sand), hydrogen, and chlorine. In one process, called the Siemens process, the silicon-hydrogen-chlorine compound gas passes over a heated silicon filament, breaking the molecular bonds and depositing the silicon atom on the filament, which ultimately grows into a large U-shaped polysilicon rod. The hydrogen and chlorine atoms are reused in a closed cycle. To keep the filament from contaminating the high-purity poly, the filament itself is also made of pure silicon. In another method, small silicon beads sit at the bottom of an inverted cone-shaped vessel where a compound gas of silicon and hydrogen is pumped in, causing the small beads to float near the surface. Heating the vessel causes the silicon-hydrogen bonds to break, which results in the silicon atoms depositing onto the small beads until they are too heavy to float and drop to the bottom of the vessel where they are harvested, ready for use.

- **Ingot and Wafer Production** – To turn polysilicon into wafers, polysilicon is placed into a container that is heated until the polysilicon forms a liquid mass. In one process, called the Czochralski process, a large cylindrical ingot of monocrystalline silicon is grown by touching a small crystalline seed to the surface of the liquid and slowly pulling it upward. In another process, called directional solidification, the liquid mass is slowly cooled until it solidifies from the bottom up, forming a large-grained multicrystalline-silicon ingot. Silicon ingots are then sliced into very thin wafers using diamond-coated wire saws. The silicon sawdust that is created is called kerf. Though less common, kerfless wafer production can be accomplished by pulling cooled layers off a molten bath of silicon, or by using gaseous silicon compounds to deposit a thin layer of silicon atoms onto a crystalline template in the shape of a wafer.

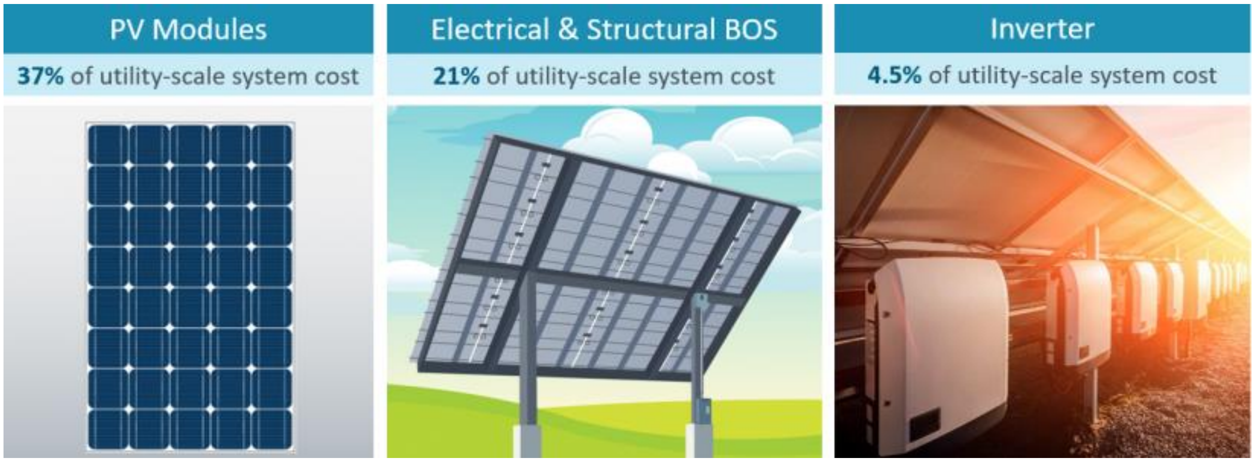
- **Cell Fabrication** – Silicon wafers are then fabricated into photovoltaic cells. The first step is chemical texturing of the wafer surface, which removes saw damage and increases how much light gets into the wafer when it is exposed to sunlight. The subsequent processes vary significantly depending on device architecture. Most cell types require the wafer to be exposed to a gas containing an electrically active dopant, and coating the surfaces of the wafer with layers that improve the performance of the cell. Screen printing of silver metallization for electrical contacts is also very common among cell types.



- **Module Assembly** – At a module assembly facility, copper ribbons plated with solder connect the silver busbars on the front surface of one cell to the rear surface of an adjacent cell in a process known as tabbing and stringing. The interconnected set of cells is arranged face-down on a sheet of glass covered with a sheet of polymer encapsulant. A second sheet of encapsulant is placed on top of the face-down cells, followed by a tough polymer backsheet or another piece of glass. The whole stack of materials is laminated in an oven to make the module waterproof, then fitted with an aluminum frame, edge sealant, and a junction box in which the ribbons are connected to diodes that prevent any backward flow of electricity. Electrical cables from the junction box convey the current produced by the module to an adjacent module or to the system's power electronics.

THIN FILM PV

Thin film PV can refer to a number of different absorber materials, the most common of which is cadmium telluride (CdTe). Thin film PV modules are typically processed as a single unit from beginning to end, where all steps occur in one facility. The manufacturing typically starts with float glass coated with a transparent conductive layer, onto which the photovoltaic absorber material is deposited in a process called close-spaced sublimation. Laser scribing is used to pattern cell strips and to form an interconnect pathway between adjacent cells. Copper ribbons are applied, an encapsulant sheet and second sheet of glass are placed on top, and the stack is laminated to make it waterproof. Finally, a junction box is attached to the rear of the module. There, the module's electrical cables are attached to the copper ribbons, which pass into the junction box through holes in the rear glass.



Racking Systems

The support structures that are built to support PV modules on a roof or in a field are commonly referred to as racking systems. The manufacture of PV racking systems varies significantly depending on where the installation will occur. Ground-mounted racking is made from steel, which is typically coated or galvanized to protect from corrosion and requires concrete foundations. Large ground-mounted systems typically use a one-axis tracking mechanism, which helps solar panels follow the sun as it moves from east to west. Tracking requires mechanical parts like motors and bearings. Stationary racking (referred to as "fixed tilt") can be used as well. Roof-mounted racking depends on the type of roof. For flat roofs, like those on large commercial or industrial buildings, fixed-tilt steel racking is used. It is commonly attached to heavy blocks that sit on the roof. For pitched residential roofs, racking is designed to attach securely to the rafters and hold the modules a few inches above the roof. This allows airflow to cool the rear of the modules, improving their performance.

POWER ELECTRONICS

Power electronics for PV modules, including power optimizers and inverters, are assembled on electronic circuit boards. This hardware converts direct current (DC) electricity, which is what a solar panel generates, to alternating current (AC) electricity, which the electrical grid uses.

Assembly starts with a circuit board template. A solder-paste is printed where small components, like transistors and diodes, are placed using robotics. Sometimes, larger components such as capacitors and transformers are placed by hand on the board. Once all components are in place, the board passes across a solder bath in a furnace to connect the components. The entire board is coated with lacquer and sealed into a waterproof housing with ports for external connections.

3.4 Solar Performance and Efficiency

The conversion efficiency of a photovoltaic (PV) cell, or solar cell, is the percentage of the solar energy shining on a PV device that is converted into usable electricity. Improving this conversion efficiency is a key goal of research and helps make PV technologies cost-competitive with conventional sources of energy.

FACTORS AFFECTING CONVERSION EFFICIENCY

Not all of the sunlight that reaches a PV cell is converted into electricity. In fact, most of it is lost. Multiple factors in solar cell design play roles in limiting a cell's ability to convert the sunlight it receives. Designing with these factors in mind is how higher efficiencies can be achieved.

- **Wavelength**—Light is composed of photons—or packets of energy—that have a wide range of wavelengths and energies. The sunlight that reaches the earth's surface has wavelengths from ultraviolet, through the visible range, to infrared. When light strikes the surface of a solar cell, some photons are reflected, while others pass right through. Some of the absorbed photons have their energy turned into heat. The remainder have the right amount of energy to separate electrons from their atomic bonds to produce charge carriers and electric current.
- **Recombination**—One way for electric current to flow in a semiconductor is for a "charge carrier," such as a negatively-charged electron, to flow across the material. Another such charge carrier is known as a "hole," which represents the absence of an electron within the material and acts like a positive charge carrier. When an electron encounters a hole, they may recombine and therefore cancel out their contributions to the electrical current. Direct recombination, in which light-generated electrons and holes encounter each other, recombine, and emit a photon, reverses the process from which electricity is generated in a solar cell. It is one of the fundamental factors that limits efficiency. Indirect recombination is a process in which the electrons or holes encounter an impurity, a defect in the crystal structure, or interface that makes it easier for them to recombine and release their energy as heat.

- **Temperature**—Solar cells generally work best at low temperatures. Higher temperatures cause the semiconductor properties to shift, resulting in a slight increase in current, but a much larger decrease in voltage. Extreme increases in temperature can also damage the cell and other module materials, leading to shorter operating lifetimes. Since much of the sunlight shining on cells becomes heat, proper thermal management improves both efficiency and lifetime.
- **Reflection**—A cell's efficiency can be increased by minimizing the amount of light reflected away from the cell's surface. For example, untreated silicon reflects more than 30% of incident light. Anti-reflection coatings and textured surfaces help decrease reflection. A high-efficiency cell will appear dark blue or black.

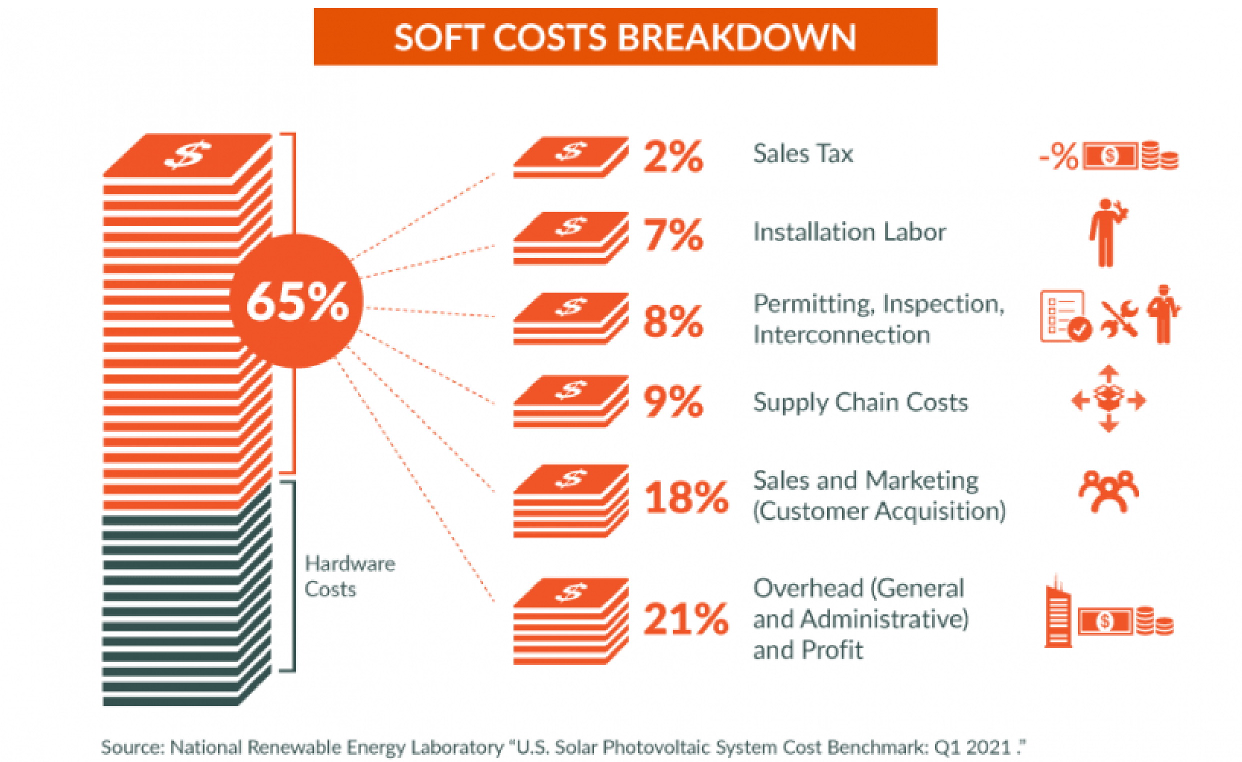
DETERMINING CONVERSION EFFICIENCY

Researchers measure the performance of a photovoltaic (PV) device to predict the power the cell will produce. Electrical power is the product of current and voltage. Current-voltage relationships measure the electrical characteristics of PV devices. If a certain "load" resistance is connected to the two terminals of a cell or module, the current and voltage being produced will adjust according to Ohm's law (the current through a conductor between two points is directly proportional to the potential difference across the two points). Efficiencies are obtained by exposing the cell to a constant, standard level of light while maintaining a constant cell temperature, and measuring the current and voltage that are produced for different load resistances.

3.5 Solar Soft Costs Basics

Dennis Schroeder / NREL

What are solar energy soft costs and why do they matter? Soft costs are the non-hardware costs associated with going solar. These costs include permitting, financing, and installing solar, as well as the expenses solar companies incur to acquire new customers, pay suppliers, and cover their bottom line. These soft costs become a portion of the overall price a customer pays for a solar energy system. While solar hardware costs have fallen in recent years, soft costs represent a growing share of total solar system costs. Because there are so many contributing factors, these costs can be hard to pinpoint and require a variety of solutions.



ROADBLOCKS TO GOING SOLAR

Soft costs are driven up when processes for going solar are slow or inefficient. There isn't a single process or system to get solar customers online because there are many jurisdictions, utilities, and differing state and local laws involved. As a result, customers experience a lag time between when they buy a solar system and when it actually gets installed—a frustrating experience that also adds costs.

RED TAPE

State and local governments that are new to solar or are developing solar adoption processes for the first time can have high costs due to inefficiencies in permitting, inspection, and grid interconnection, among other things—also known as "red tape." Technical assistance programs can help to increase efficiency and decrease these costs by engaging experienced solar professionals to provide governing bodies the knowledge and tools they need to start their own programs.

SOLAR COMPANIES AND INDUSTRY PROFESSIONALS

Streamlining the solar adoption process for solar companies also impacts soft costs. Software improvements can help solar companies save money by improving sales leads, better managing their portfolios, and making financing more accessible. These savings can then be passed along to customers. In addition, solar companies can’t grow without highly skilled workers. Minimizing training gaps allows solar companies to easily recruit new hires and expand at their own pace, which minimizes labor costs.

Solar also impacts professionals working in neighboring industries—such as real estate agents, code officials, and firefighters—who need to understand how solar energy affects their day-to-day jobs. Educating these professionals lowers costs by improving solar sales transactions and speeding up installations.

AFFORDABLE, ACCESSIBLE SOLAR ENERGY

Increasing access to affordable solar energy for customers also plays a role in soft costs. Several factors limit certain customers from adopting solar, including the high cost and up-front expense of solar systems, the lack of competitive interest rates, low credit scores, and the inability of tax-exempt businesses and certain low- and moderate-income populations to use the Solar Investment Tax Credit. One strategy for addressing these barriers is community solar, where multiple participants subscribe to a single solar energy system. Enabling local financial institutions, such as community banks, credit unions, and community development financial institutions, to fund solar projects in their local areas can increase access to affordable solar energy for businesses and individuals in low- and moderate-income communities.

3.6 Solar Rooftop Potential

Solar rooftop potential for the entire country is the number of rooftops that would be suitable for solar power, depending on size, shading, direction, and location. Rooftop potential is not equivalent to the economic or market potential for rooftop solar—it doesn’t consider availability or cost. Rather, it is the upper limit of solar deployment on rooftops across the country.

Solar rooftop potential for an individual rooftop is the amount of solar that could be installed on that rooftop, based on its size, shading, tilt, location, and construction. Satellite maps, irradiance data, equipment specifications, and other factors inform the bids that installers present to customers to assist them in understanding the potential costs and benefits of solar panels on their roof.

NATIONAL ROOFTOP POTENTIAL

According to National Renewable Energy Laboratory (NREL) analysis in 2016, there are over 8 billion square meters of rooftops on which solar panels could be installed in the United States, representing over 1 terawatt of potential solar capacity. With improvements in solar conversion efficiency, the rooftop potential in the country could be even greater. Residential and other small rooftops represent about 65% of the national rooftop potential, and 42% of residential rooftops are households with low-to-moderate income.

NREL estimates that an average of 3.3 million homes per year will be built or will require roof replacement—representing a potential of roughly 30 gigawatts (GW) of solar capacity per year. If even a small fraction of these new roofs had solar installations, it could have a significant impact on U.S. solar power generation.

4. Concentrating Solar-Thermal Power Basics

What is concentrating solar-thermal power (CSP) technology and how does it work? CSP technologies use mirrors to reflect and concentrate sunlight onto a receiver. The energy from the concentrated sunlight heats a high temperature fluid in the receiver.

This heat - also known as thermal energy - can be used to spin a turbine or power an engine to generate electricity. It can also be used in a variety of industrial applications, like water desalination, enhanced oil recovery, food processing, chemical production, and mineral processing.

Concentrating solar-thermal power systems are generally used for utility-scale projects. These utility-scale CSP plants can be configured in different ways. Power tower systems arrange mirrors around a central tower that acts as the receiver. Linear systems have rows of mirrors that concentrate the sunlight onto parallel tube receivers positioned above them.

Smaller CSP systems can be located directly where power is needed. For example, single dish/engine systems can produce 5 to 25 kilowatts of power per dish and be used in distributed applications.

4.1 Linear Concentrator System

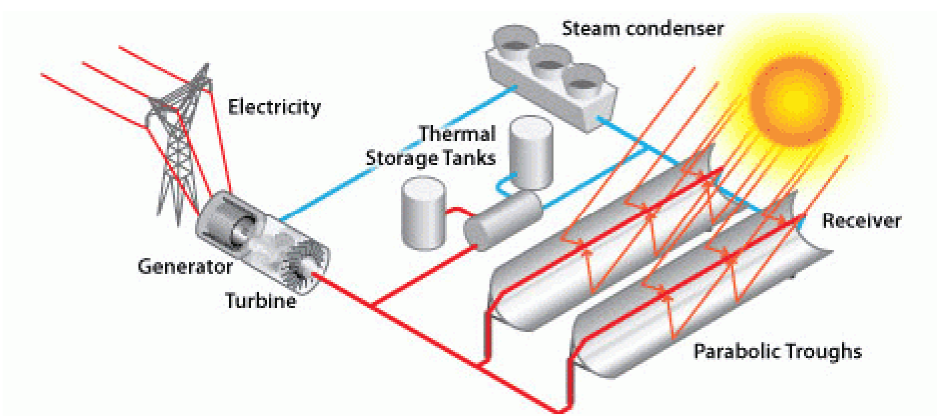
Linear concentrating solar power (CSP) collectors capture the sun's energy with large mirrors that reflect and focus the sunlight onto a linear receiver tube. The receiver contains a fluid that is heated by the sunlight and then used to heat a traditional power cycle that spins a turbine that drives a generator to produce electricity. Alternatively, steam can be generated directly in the solar field, which eliminates the need for costly heat exchangers.

Linear concentrating collector fields consist of a large number of collectors in parallel rows that are typically aligned in a north-south orientation to maximize annual and summer energy collection. With a single-axis sun-tracking system, this configuration enables the mirrors to track the sun from east to west during the day, which ensures that the sun reflects continuously onto the receiver tubes.

Linear systems may incorporate thermal storage. In these systems, the collector field is oversized to heat a storage system during the day so the additional steam it generates can be used to produce electricity in the evening or during cloudy weather. These plants can also be designed as hybrids, meaning that they use fossil fuel to supplement the solar output during periods of low solar radiation. In such a design, a natural gas-fired heater or gas-steam boiler/reheater is used. In the future, linear systems may be integrated with existing or new combined-cycle natural-gas- and coal-fired plants.

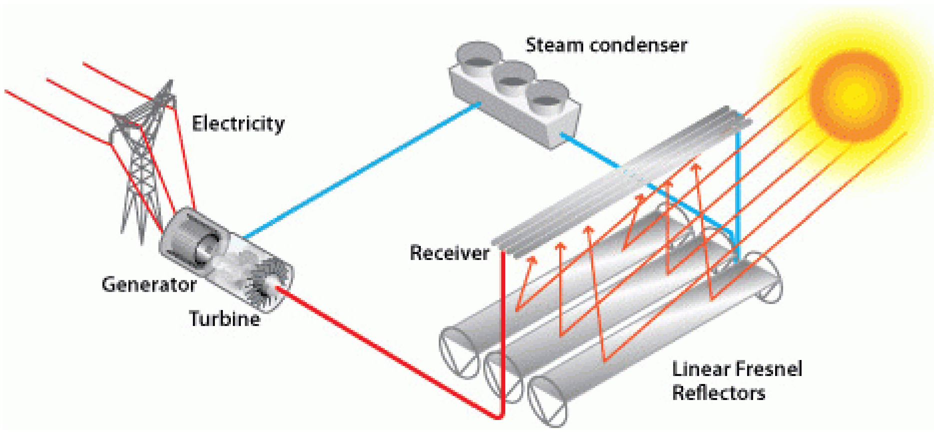
PARABOLIC TROUGH SYSTEMS

The most common CSP system in the United States is a linear concentrator that uses parabolic trough collectors. In such a system, the receiver tube is positioned along the focal line of each parabola-shaped reflector. The tube is fixed to the mirror structure and the heat transfer fluid flows through and out of the field of solar mirrors to where it is used to create steam (or, in the case of a water/steam receiver, it is sent directly to the turbine).

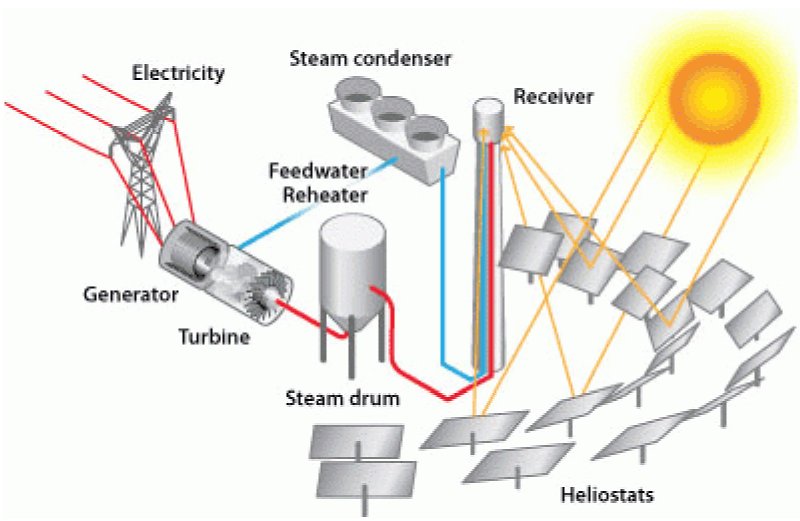


LINEAR FRESNEL REFLECTOR SYSTEMS

A second linear concentrator technology is the linear Fresnel reflector system. Flat or slightly curved mirrors mounted on trackers on the ground are configured to reflect sunlight onto a receiver tube fixed in space above the mirrors. A small parabolic mirror is sometimes added atop the receiver to further focus the sunlight.



4.2 Power Tower System

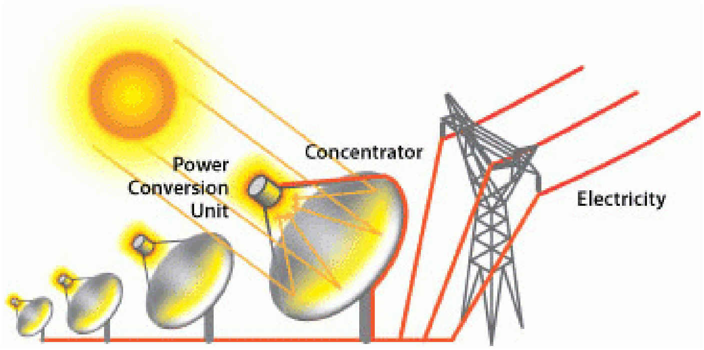


In power tower concentrating solar power systems, a large number of flat, sun-tracking mirrors, known as heliostats, focus sunlight onto a receiver at the top of a tall tower. A heat-transfer fluid heated in the receiver is used to heat a working fluid, which, in turn, is used in a conventional turbine generator to produce electricity. Some power towers use water/steam as the heat-transfer fluid. Other advanced designs are experimenting with high temperature molten salts or sand-like particles to maximize the power cycle temperature.

The Ivanpah Solar Electric Generating System is the largest concentrated solar thermal plant in the U.S. Located in California's Mojave Desert, the plant is capable of producing 392 megawatts of electricity using 173,500 heliostats, each with two mirrors that focus sunlight onto three solar power towers.

Aside from the U.S., Spain has several power tower systems. Planta Solar 10 and Planta Solar 20 are water/steam systems with capacities of 11 and 20 megawatts, respectively. Gemasolar, previously known as Solar Tres, produces nearly 20 megawatts of electricity and utilizes molten-salt thermal storage.

4.3 Dish/Engine System Concentrating Solar-Thermal Power Basics



Dish/engine systems use a parabolic dish of mirrors to direct and concentrate sunlight onto a central engine that produces electricity. The dish/engine system is a concentrating solar power (CSP) technology that produces smaller amounts of electricity than other CSP technologies—typically in the range of 3 to 25 kilowatts—but is beneficial for modular use. The two major parts of the system are the solar concentrator and the power conversion unit.

SOLAR CONCENTRATOR

The solar concentrator, or dish, gathers the solar energy coming directly from the sun. The resulting beam of concentrated sunlight is reflected onto a thermal receiver that collects the solar heat. The dish is mounted on a structure that tracks the sun continuously throughout the day to reflect the highest percentage of sunlight possible onto the thermal receiver.

POWER CONVERSION UNIT

The power conversion unit includes the thermal receiver and the engine/generator. The thermal receiver is the interface between the dish and the engine/generator. It absorbs the concentrated beams of solar energy, converts the energy to heat, and transfers the heat to the engine/generator. A thermal receiver can be a bank of tubes with a cooling fluid—usually hydrogen or helium—that typically is the heat-transfer medium and also the working fluid for an engine. Alternate thermal receivers are heat pipes, where the boiling and condensing of an intermediate fluid transfers the heat to the engine.

The engine/generator system is the subsystem that takes the heat from the thermal receiver and uses it to produce thermal to electric energy conversion. The most common type of heat engine used in dish/engine systems is the Stirling engine. A Stirling engine uses the heated fluid to move pistons and create mechanical power. The mechanical work, in the form of the rotation of the engine's crankshaft, drives a generator and produces electrical power.

4.4 Thermal Storage System

One challenge facing the widespread use of solar energy is reduced or curtailed energy production when the sun sets or is blocked by clouds. Thermal energy storage provides a workable solution to this challenge.

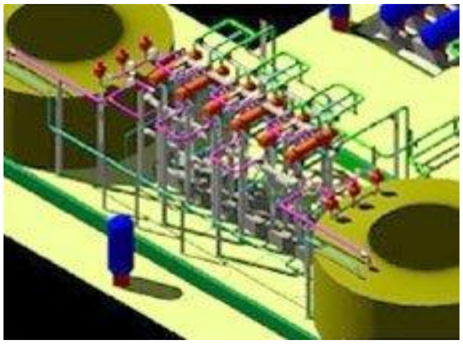
In a concentrating solar power (CSP) system, the sun's rays are reflected onto a receiver, which creates heat that is used to generate electricity that can be used immediately or stored for later use. This enables CSP systems to be flexible, or dispatchable, options for providing clean, renewable energy.

Several sensible thermal energy storage technologies have been tested and implemented since 1985 ("Sensible thermal energy storage" means the temperature of the storage fluid changes, but there is no phase change**)**. These include the two-tank direct system, two-tank indirect system, and single-tank thermocline system.

TWO-TANK DIRECT SYSTEM

Solar thermal energy in this system is stored in the same fluid used to collect it. The fluid is stored in two tanks—one at high temperature and the other at low temperature. Fluid from the low-temperature tank flows through the solar collector or receiver, where solar energy heats it to a high temperature, and it then flows to the high-temperature tank for storage. Fluid from the high-temperature tank flows through a heat exchanger, where it generates steam for electricity production. The fluid exits the heat exchanger at a low temperature and returns to the low-temperature tank.

Two-tank direct storage was used in early parabolic trough power plants (such as Solar Electric Generating Station I) and at the Solar Two power tower in California. The trough plants used mineral oil as the heat-transfer and storage fluid; Solar Two used molten salt.

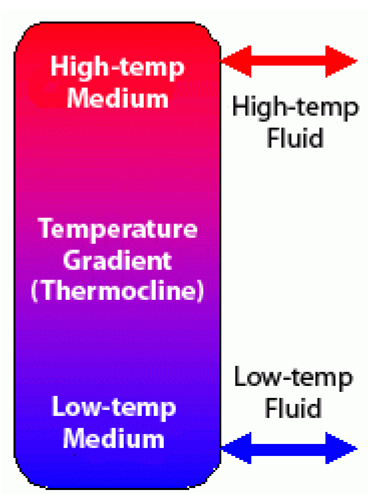


TWO-TANK INDIRECT SYSTEM

Two-tank indirect systems function in the same way as two-tank direct systems, except different fluids are used as the heat-transfer and storage fluids. This system is used in plants in which the heat-transfer fluid is too expensive or not suited for use as the storage fluid.

The storage fluid from the low-temperature tank flows through an extra heat exchanger, where it is heated by the high-temperature heat-transfer fluid. The high-temperature storage fluid then flows back to the high-temperature storage tank. The fluid exits this heat exchanger at a low temperature and returns to the solar collector or receiver, where it is heated back to a high temperature. Storage fluid from the high-temperature tank is used to generate steam in the same manner as the two-tank direct system. The indirect system requires an extra heat exchanger, which adds cost to the system.

This system will be used in many of the parabolic power plants in Spain and has also been proposed for several U.S. parabolic plants. The plants will use organic oil as the heat-transfer fluid and molten salt as the storage fluid.



SINGLE-TANK THERMOCLINE SYSTEM

Single-tank thermocline systems store thermal energy in a solid medium—most commonly, silica sand—located in a single tank. At any time during operation, a portion of the medium is at high temperature, and a portion is at low temperature. The hot- and cold-temperature regions are separated by a temperature gradient or thermocline. High-temperature heat-transfer fluid flows into the top of the thermocline and exits the bottom at low temperature. This process moves the thermocline downward and adds thermal energy to the system for storage. Reversing the flow moves the thermocline upward and removes thermal energy from the system to generate steam and electricity. Buoyancy effects create thermal stratification of the fluid within the tank, which helps to stabilize and maintain the thermocline.

Using a solid storage medium and only needing one tank reduces the cost of this system relative to two-tank systems. This system was demonstrated at the Solar One power tower, where steam was used as the heat-transfer fluid and mineral oil was used as the storage fluid.

5. Solar Systems Integration Basics

What is solar systems integration and how does it work? Solar systems integration involves developing technologies and tools that allow solar energy onto the electricity grid, while maintaining grid reliability, security, and efficiency.

THE ELECTRICAL GRID

For most of the past 100 years, electrical grids involved large-scale, centralized energy generation located far from consumers. Modern electrical grids are much more complex. In addition to large utility-scale plants, modern grids also involve variable energy sources like solar and wind, energy storage systems, power electronic devices like inverters, and small-scale energy generation systems like rooftop installations and microgrids. These smaller-scale and dispersed energy sources are generally known as distributed energy resources (DER).

The electrical grid is separated into transmission and distribution systems. The transmission grid is the network of high-voltage power lines that carry electricity from centralized generation sources like large power plants. These high voltages allow power to be transported long distances without excessive loss. The distribution grid refers to low-voltage lines that eventually reach homes and businesses. Substations and transformers convert power between high and low voltage. Traditionally, electricity only needed to flow one way through these systems: from the central generation source to the consumer. However, systems like rooftop solar now require the grid to handle two-way electricity flow, as these systems can inject the excess power that they generate back into the grid.

5.1 Solar and Resilience Basics

WHAT IS ELECTRIC POWER RESILIENCE?

A resilient power system, as defined by the U.S. Department of Energy (DOE)'s Grid Modernization Initiative and the National Academy of Sciences, must be capable of lessening the likelihood of long-duration electrical outages occurring over large service areas, limiting the scope and impact of outages when they do occur, and rapidly restoring power after an outage.

Here is an example of a resilient power system scenario: A flood forces a local utility substation to shut down, interrupting electric service. Within seconds, residential photovoltaic (PV) solar panel systems with battery storage automatically detect the loss of grid power and switch to an "islanded" mode to keep the power on. At the same time, a backup battery system at a local fire station enables the utility company to keep its communication equipment on so it can coordinate rescue operations. When the utility company is able to restore service, these backup resources will seamlessly reconnect to the grid, ready to be used during the next incident.

A completely resilient electric grid will help communities keep the power on during man-made or natural disruptions.

HOW DOES SOLAR IMPROVE RESILIENCE?

Solar energy technologies can play an important role in strengthening our energy system's resilience. Two key attributes make solar a unique asset for resilience. The first is that solar generation can be distributed, as opposed to centralized. This means individual buildings can host their own solar systems to meet some or all of their power needs. Communities can combine solar with storage and other technologies to create a microgrid that will provide power to critical infrastructure when it is needed.

Most electric power is generated in large, centralized power plants—which then send the electricity to homes and businesses through power lines. This power can be disrupted if the transmission or distribution system gets damaged. Distributed generation in combination with local energy storage allows power to be generated locally, near the customers, and could be used even if the centralized system experiences interference or disruption.

The second attribute that makes solar energy a key contributor to resilience is that sunlight-generated electricity can be stored and discharged without the need for fuel deliveries, unlike conventional diesel generators, which are the most common source of emergency backup power. In a long outage, solar and its associated energy storage can continue delivering power, even at night, to homes and businesses.

HOW DOES RESILIENCE FIT INTO THE SOLAR ENERGY LANDSCAPE?

Adoption of distributed energy resources, such as rooftop solar generation, is increasing. There are over 2 million solar generators on the U.S. distribution system, representing about 40% of total PV capacity, with steady growth expected into the future. In addition to providing energy savings, solar energy systems have the potential to make homes, commercial buildings, and entire communities more resilient. By identifying the critical infrastructure in a community—like hospitals, fire stations, and shelters—and equipping those buildings with solar and energy storage systems, the community can respond better to, and recover faster from, electrical service loss.

Resilient systems like these have been built and demonstrated in regions prone to outages, fuel-supply constraints, and natural disasters. For example, the DOE's SunSmart program helped equip more than 100 schools with backup solar and storage systems. In response to power system vulnerabilities revealed by Superstorm Sandy, the New York Governor's Office of Storm Recovery announced a project in 2019 to place solar panels and energy storage systems in flood-prone areas.

The DOE has also launched major initiatives to address the increasing resilience challenges, including:

- A partnership with the National Laboratories to provide technical support to Puerto Rico after Hurricane Maria in 2017
- The North American Energy Resilience Model
- The Grid Modernization Laboratory Consortium (GMLC)'s Resilient Distribution Systems research programs
- The Solar Energy Technologies Office's Advanced Systems Integration for Solar Technologies (ASSIST): Situational Awareness and Resilient Solutions for Critical Infrastructure funding program

Technically, residential solar panels alone are not enough to make your home resilient. This is because solar systems generally depend on the electrical grid to produce power—and, for safety reasons, they're designed to switch off if the grid power cuts out. For solar panels to produce power on their own, they need two things: a properly configured inverter and a storage system. The solar inverter generates alternating-current power from the solar panel's direct-current output, while the storage system, like a battery, can keep power steady amid changes in output and building loads.

Communities can become more resilient with advanced solar technologies. Pairing solar with storage can help make solar energy available during outages. With new grid-forming inverters, a solar-plus-storage system may be able restart the grid after disruptions if the system is large enough. Microgrids could also provide resiliency benefits. Microgrids are a smaller version of the electrical grid that can help a large building, campus, or neighborhood balance its electrical supply and demand when the larger grid is down. By combining solar with these new technologies, we can build a robust energy system that responds to whatever threats and disruptions might lie ahead.

HOW CAN I HELP BUILD COMMUNITY RESILIENCE?

- Community officials can use the Federal Emergency Management Agency (FEMA)'s electric power mitigation guide to work with public and private actors to mitigate hazards while planning and developing projects. FEMA also provides guides to expanding mitigation to build preparedness in disproportionately at-risk communities and in transportation and other sectors.
- This GMLC metrics report defines how resilience should be assessed when making decisions about grid modernization.
- The National Renewable Energy Laboratory promotes resilience in remote communities, as well as at the building, community, regional, and national levels. The lab has published the Power Sector Resilience Planning Guidebook: A Self-Guided Reference for Practitioners.
- At the regional level, the Resilience Roadmap: A Collaborative Approach to Multi-Jurisdictional Planning provides holistic planning guidance for local, state, and federal entities.
- Organizations can use the Technical Resilience Navigator to identify their resilience gaps and prioritize solutions that reduce risk from disruptions to energy and water services.
- Visit Solar Market Pathways for resources, tools, and real-world examples that help local governments, community advocates, solar project developers, emergency management professionals, facilities managers, and others understand all the aspects of implementing resilient solar.

5.2 Solar Integration: Distributed Energy Resources and Microgrids

Rooftop photovoltaics in Boulder, CO. Photo by Dennis Schroeder.

Simply put, we need a reliable and secure energy grid. Two ways to ensure continuous electricity regardless of the weather or an unforeseen event are by using distributed energy resources (DER) and microgrids. DER produce and supply electricity on a small scale and are spread out over a wide area. Rooftop solar panels, backup batteries, and emergency diesel generators are examples of DER. While traditional generators are connected to the high-voltage transmission grid, DER are connected to the lower-voltage distribution grid, like residences and businesses are.

Microgrids are localized electric grids that can disconnect from the main grid to operate autonomously. Because they can operate while the main grid is down, microgrids can strengthen grid resilience, help mitigate grid disturbances, and function as a grid resource for faster system response and recovery.

DISTRIBUTED ENERGY RESOURCES

Solar DER can be built at different scales—even one small solar panel can provide energy. In fact, about one-third of solar energy in the United States is produced by small-scale solar, such as rooftop installations. Household solar installations are called behind-the-meter solar; the meter measures how much electricity a consumer buys from a utility. Since distributed solar is "behind" the meter, customers do not pay the utility for the solar power generated.

The cost of owning DER varies from state to state and among utility companies. One way the electric bill is determined is through net metering, where utilities calculate the total power generated by the customer's solar system and subtract it from the total power the customer consumes. Customers are credited for the amount of power they supply to the grid.

DER could fundamentally change the way the electric grid works. With DER, power is generated right where it is used and can be connected with other DER to optimize its use. Households and other electricity consumers are also part-time producers, selling excess generation to the grid and to each other. Energy storage, such as batteries, can also be distributed, helping to ensure power when solar or other DER don't generate power. Electric cars can even store excess energy in the batteries of idle cars. DER can also include controllable loads, like water heaters or air-conditioning units that the utility can use to shift power consumption away from peak hours. While the grid was designed to generate power at large facilities and move it through the transmission grid to the distribution grid for consumption, DER enable local generation and consumption of electricity.

ISLANDS AND MICROGRIDS

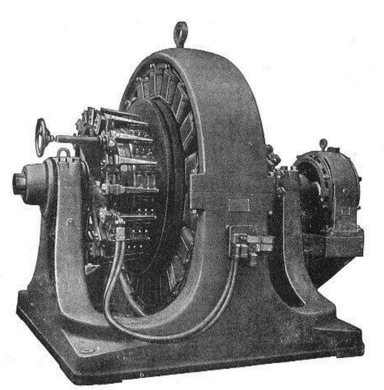
Distribution grids are vulnerable to outages that can affect large regions and millions of people and businesses, particularly as a consequence of extreme, destructive weather events. When parts of the grid are equipped with DER, they can continue serving other loads on the same distribution network, meeting local needs with local generation. This is called islanding. Electrical systems that can disconnect from the larger grid, engaging in intentional islanding, are often called microgrids.

Microgrids vary in size from a single-customer microgrid to a full-substation microgrid, which may include hundreds of individual generators and consumers of power. Small, off-the-grid electrical systems are not a recent invention. Ships, military bases, remote outposts, and communities around the world have long relied on local generation and electricity management to meet their energy needs. DER make microgrids a more widespread option, because the means of energy production are now more easily obtained and sited in neighborhoods. Community-scale microgrids may provide resiliency and backup during and after disasters like hurricanes.

Technology is advancing to manage the risks caused by islanding with better control software and to provide grid services. Without the larger grid to help stabilize the power supply, an islanded grid could damage connected equipment or injure workers who think it is disconnected from power. For this reason, many solar energy systems are programmed to detect islanding and disconnect from the grid if it occurs. Beyond microgrids, some researchers are studying nanogrids—smart electricity systems on the scale of a single building.

5.3 Solar Integration: Inverters And Grid Services Basics

The first inverters were created in the 19th century and were mechanical. A spinning motor, for example, would be used to continually change whether the DC source was connected forward or backward. Today we make electrical switches out of transistors, solid-state devices with no moving parts. Transistors are made of semiconductor materials like silicon or gallium arsenide. They control the flow of electricity in response to outside electrical signals.



A 1909 500-kilowatt Westinghouse “rotary converter,” an early type of inverter. Illustration courtesy of Wikimedia.

If you have a household solar system, your inverter probably performs several functions. In addition to converting your solar energy into AC power, it can monitor the system and provide a portal for communication with computer networks. Solar-plus–battery storage systems rely on advanced inverters to operate without any support from the grid in case of outages, if they are designed to do so.

TOWARD AN INVERTER-BASED GRID

Historically, electrical power has been predominantly generated by burning a fuel and creating steam, which then spins a turbine generator, which creates electricity. The motion of these generators produces AC power as the device rotates, which also sets the frequency, or the number of times the sine wave repeats. Power frequency is an important indicator for monitoring the health of the electrical grid. For instance, if there is too much load—too many devices consuming energy—then energy is removed from the grid faster than it can be supplied. As a result, the turbines will slow down and the AC frequency will decrease. Because the turbines are massive spinning objects, they resist changes in the frequency just as all objects resist changes in their motion, a property known as inertia.

As more solar systems are added to the grid, more inverters are being connected to the grid than ever before. Inverter-based generation can produce energy at any frequency and does not have the same inertial properties as steam-based generation, because there is no turbine involved. As a result, transitioning to an electrical grid with more inverters requires building smarter inverters that can respond to changes in frequency and other disruptions that occur during grid operations, and help stabilize the grid against those disruptions.

GRID SERVICES AND INVERTERS

Grid operators manage electricity supply and demand on the electric system by providing a range of grid services. Grid services are activities grid operators perform to maintain system-wide balance and manage electricity transmission better.

When the grid stops behaving as expected, like when there are deviations in voltage or frequency, smart inverters can respond in various ways. In general, the standard for small inverters, such as those attached to a household solar system, is to remain on during or "ride through" small disruptions in voltage or frequency, and if the disruption lasts for a long time or is larger than normal, they will disconnect themselves from the grid and shut down. Frequency response is especially important because a drop in frequency is associated with generation being knocked offline unexpectedly. In response to a change in frequency, inverters are configured to change their power output to restore the standard frequency. Inverter-based resources might also respond to signals from an operator to change their power output as other supply and demand on the electrical system fluctuates, a grid service known as automatic generation control. In order to provide grid services, inverters need to have sources of power that they can control. This could be either generation, such as a solar panel that is currently producing electricity, or storage, like a battery system that can be used to provide power that was previously stored.

Another grid service that some advanced inverters can supply is grid-forming. Grid-forming inverters can start up a grid if it goes down—a process known as black start. Traditional "grid-following" inverters require an outside signal from the electrical grid to determine when the switching will occur in order to produce a sine wave that can be injected into the power grid. In these systems, the power from the grid provides a signal that the inverter tries to match. More advanced grid-forming inverters can generate the signal themselves. For instance, a network of small solar panels might designate one of its inverters to operate in grid-forming mode while the rest follow its lead, like dance partners, forming a stable grid without any turbine-based generation.

Reactive power is one of the most important grid services inverters can provide. On the grid, voltage— the force that pushes electric charge—is always switching back and forth, and so is the current—the movement of the electric charge. Electrical power is maximized when voltage and current are synchronized. However, there may be times when the voltage and current have delays between their two alternating patterns like when a motor is running. If they are out of sync, some of the power flowing through the circuit cannot be absorbed by connected devices, resulting in a loss of efficiency. More total power will be needed to create the same amount of "real" power—the power the loads can absorb. To counteract this, utilities supply reactive power, which brings the voltage and current back in sync and makes the electricity easier to consume. This reactive power is not used itself, but rather makes other power useful. Modern inverters can both provide and absorb reactive power to help grids balance this important resource. In addition, because reactive power is difficult to transport long distances, distributed energy resources like rooftop solar are especially useful sources of reactive power.

A worker checks an inverter at the 2MW CoServ Solar Station in Krugerville, Texas. Photo by Ken Oltmann/CoServ.

TYPES OF INVERTERS

There are several types of inverters that might be installed as part of a solar system. In a large-scale utility plant or mid-scale community solar project, every solar panel might be attached to a single *central inverter*. *String* inverters connect a set of panels—a string—to one inverter. That inverter converts the power produced by the entire string to AC. Although cost-effective, this setup results in reduced power production on the string if any individual panel experiences issues, such as shading. *Microinverters* are smaller inverters placed on every panel. With a microinverter, shading or damage to one panel will not affect the power that can be drawn from the others, but microinverters can be more expensive. Both types of inverters might be assisted by a system that controls how the solar system interacts with attached battery storage. Solar can charge the battery directly over DC or after a conversion to AC.

5.4 Solar Integration: Solar Energy and Storage Basics

The AES Lawai Solar Project in Kauai, Hawaii has a 100 megawatt-hour battery energy storage system paired with a solar photovoltaic system.

National Renewable Energy Laboratory

Sometimes two is better than one. Coupling solar energy and storage technologies is one such case. The reason: Solar energy is not always produced at the time energy is needed most. Peak power usage often occurs on summer afternoons and evenings, when solar energy generation is falling. Temperatures can be hottest during these times, and people who work daytime hours get home and begin using electricity to cool their homes, cook, and run appliances.

Storage helps solar contribute to the electricity supply even when the sun isn't shining. It can also help smooth out variations in how solar energy flows on the grid. These variations are attributable to changes in the amount of sunlight that shines onto photovoltaic (PV) panels or concentrating solar-thermal power (CSP) systems. Solar energy production can be affected by season, time of day, clouds, dust, haze, or obstructions like shadows, rain, snow, and dirt. Sometimes energy storage is co-located with, or placed next to, a solar energy system, and sometimes the storage system stands alone, but in either configuration, it can help more effectively integrate solar into the energy landscape.

WHAT IS ENERGY STORAGE?

"Storage" refers to technologies that can capture electricity, store it as another form of energy (chemical, thermal, mechanical), and then release it for use when it is needed. Lithium-ion batteries are one such technology. Although using energy storage is never 100% efficient—some energy is always lost in converting energy and retrieving it—storage allows the flexible use of energy at different times from when it was generated. So, storage can increase system efficiency and resilience, and it can improve power quality by matching supply and demand.

Storage facilities differ in both energy capacity, which is the total amount of energy that can be stored (usually in kilowatt-hours or megawatt-hours), and power capacity, which is the amount of energy that can be released at a given time (usually in kilowatts or megawatts). Different energy and power capacities of storage can be used to manage different tasks. Short-term storage that lasts just a few minutes will ensure a solar plant operates smoothly during output fluctuations due to passing clouds, while longer-term storage can help provide supply over days or weeks when solar energy production is low or during a major weather event, for example.

Advantages of Combining Storage and Solar

1. **Balancing electricity loads** – Without storage, electricity must be generated and consumed at the same time, which may mean that grid operators take some generation offline, or "curtail" it, to avoid over-generation and grid reliability issues. Conversely, there may be other times, after sunset or on cloudy days, when there is little solar production but plenty of demand for power. Enter storage, which can be filled or charged when generation is high and power consumption is low, then dispensed when the load or demand is high. When some of the electricity produced by the sun is put into storage, that electricity can be used whenever grid operators need it, including after the sun has set. In this way, storage acts as an insurance policy for sunshine.
2. **"Firming" solar generation** – Short-term storage can ensure that quick changes in generation don't greatly affect the output of a solar power plant. For example, a small

battery can be used to ride through a brief generation disruption from a passing cloud, helping the grid maintain a "firm" electrical supply that is reliable and consistent.

3. **Providing resilience** – Solar and storage can provide backup power during an electrical disruption. They can keep critical facilities operating to ensure continuous essential services, like communications. Solar and storage can also be used for microgrids and smaller-scale applications, like mobile or portable power units.

TYPES OF ENERGY STORAGE

The most common type of energy storage in the power grid is pumped hydropower. But the storage technologies most frequently coupled with solar power plants are electrochemical storage (batteries) with PV plants and thermal storage (fluids) with CSP plants, which was discussed in Section 4.4. Other types of storage, such as compressed air storage and flywheels, may have different characteristics, such as very fast discharge or very large capacity, that make them attractive to grid operators. More information on other types of storage is below.

PUMPED-STORAGE HYDROPOWER

Pumped-storage hydropower is an energy storage technology based on water. Electrical energy is used to pump water uphill into a reservoir when energy demand is low. Later, the water can be allowed to flow back downhill and turn a turbine to generate electricity when demand is high. Pumped hydro is a well-tested and mature storage technology that has been used in the United States since 1929. However, it requires suitable landscapes and reservoirs, which may be natural lakes or man-made by constructing dams, requiring lengthy regulatory permits, long implementation times, and large initial capital. Other than energy arbitrage, pumped hydro's value of services to integrate variable renewables are not fully realized, which can make the financial payback period long. These are some of the reasons pumped hydro has not been built recently, even though interest is evident from requests to the Federal Energy Regulatory Commission for preliminary permits and licenses.

ELECTROCHEMICAL STORAGE

Many of us are familiar with electrochemical batteries, like those found in laptops and mobile phones. When electricity is fed into a battery, it causes a chemical reaction, and energy is stored. When a battery is discharged, that chemical reaction is reversed, which creates voltage between two electrical contacts, causing current to flow out of the battery. The most common chemistry for battery cells is lithium-ion, but other common options include lead-acid, sodium, and nickel-based batteries.

FLYWHEEL STORAGE

A flywheel is a heavy wheel attached to a rotating shaft. Expending energy can make the wheel turn faster. This energy can be extracted by attaching the wheel to an electrical generator, which uses electromagnetism to slow the wheel down and produce electricity. Although flywheels can quickly provide power, they can't store a lot of energy.

COMPRESSED AIR STORAGE

Compressed air storage systems consist of large vessels, like tanks, or natural formations, like caves. A compressor system pumps the vessels full of pressurized air. Then the air can be released and used to drive a turbine that produces electricity. Existing compressed air energy storage systems often use the released air as part of a natural gas power cycle to produce electricity.

SOLAR FUELS

Solar power can be used to create new fuels that can be combusted (burned) or consumed to provide energy, effectively storing the solar energy in the chemical bonds. Among the possible fuels researchers are examining are hydrogen, produced by separating it from the oxygen in water, and methane, produced by combining hydrogen and carbon dioxide. Methane is the main component of natural gas, which is commonly used to produce electricity or heat homes.

VIRTUAL STORAGE

Energy can also be stored by changing how we use the devices we already have. For example, by heating or cooling a building before an anticipated peak of electrical demand, the building can "store" that thermal energy so it doesn't need to consume electricity later in the day. The building itself is acting as a thermos by storing cool or warm air. A similar process can be applied to water heaters to spread demand out over the day.

Ultimately, residential and commercial solar customers, and utilities and large-scale solar operators alike, can benefit from solar-plus-storage systems. As research continues and the costs of solar energy and storage come down, solar and storage solutions will become more accessible to all Americans.

5.5 Solar-Plus-Storage

The ability to store solar energy for later use is important: It helps to keep the balance between electricity generation and demand. Lithium-ion batteries are one way to store this energy—the same batteries that power your phone.

WHY LITHIUM?

There are many ways to store energy: pumped hydroelectric storage, which stores water and later uses it to generate power; batteries that contain zinc or nickel; and molten-salt thermal storage, which generates heat, to name a few. Some of these systems can store large amounts of energy.

Lithium is a lightweight metal that an electric current can easily pass through. Lithium ions make a battery rechargeable because their chemical reactions are reversible, allowing them to absorb power and discharge it later. Lithium-ion batteries can store a lot of energy, and they hold a charge for longer than other kinds of batteries. The cost of lithium-ion batteries is dropping because more people are buying electric vehicles that depend on them.

While lithium-ion battery systems may have smaller storage capacity in comparison to other storage systems, they are growing in popularity because they can be installed nearly anywhere, have a small footprint, and are inexpensive and readily available—increasing their application by utilities. Growth in the electric vehicle market has also contributed to further price decreases given that the batteries are an essential component. In fact, more than 10,000 of these systems have been installed throughout the country, according to "U.S. Energy Storage Monitor: Q3 2018" from GTM Research, and they accounted for 89% of all new energy storage capacity installed in 2015.

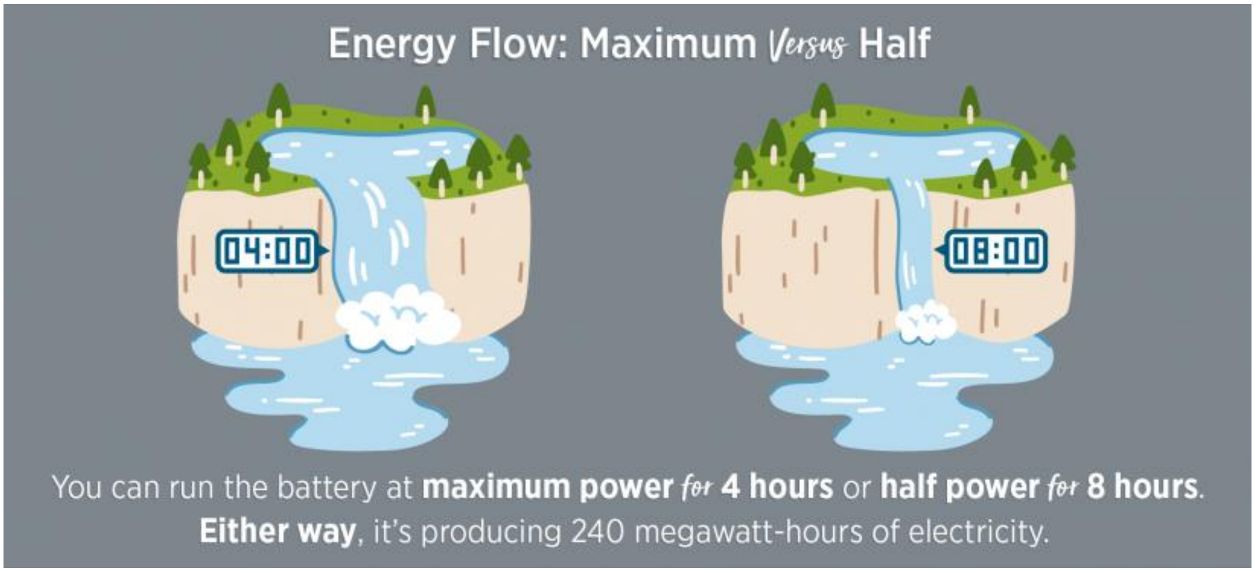
WHAT IS A SOLAR-PLUS-STORAGE SYSTEM?

Many solar-energy system owners are looking at ways to connect their system to a battery so they can use that energy at night or in the event of a power outage. Simply put, a solar-plus-storage system is the integration of a battery with a connected solar system, such as a photovoltaic (PV) one.

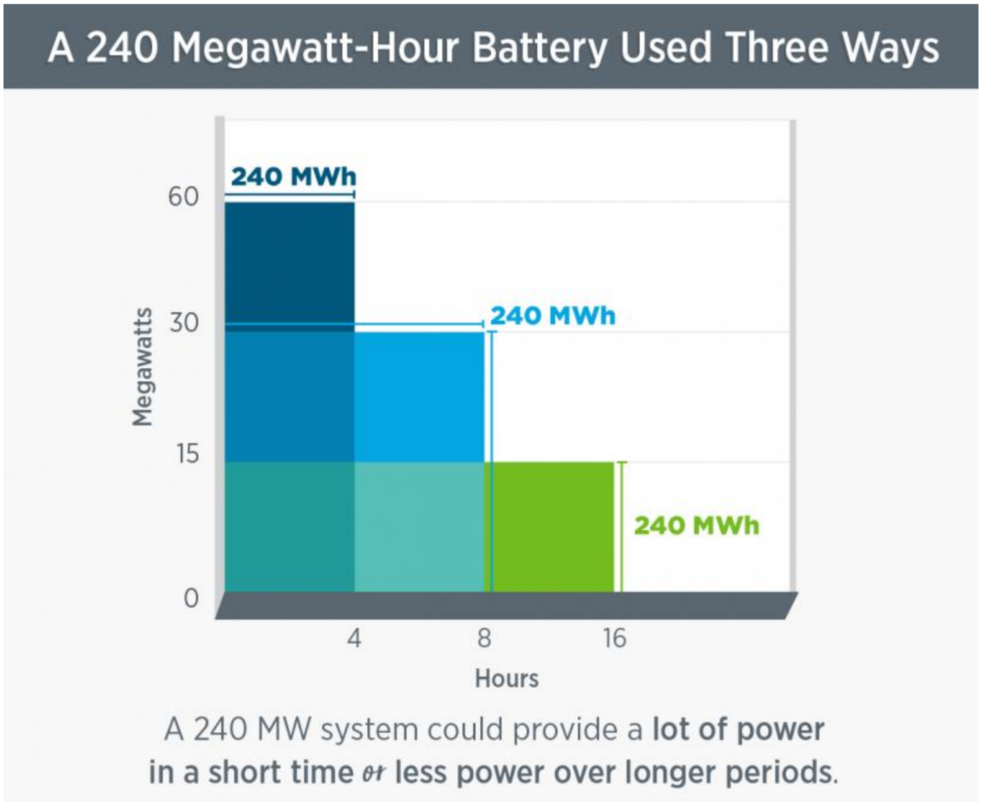
In an effort to track this trend, researchers at the National Renewable Energy Laboratory (NREL) created a first-of-its-kind benchmark of U.S. utility-scale solar-plus-storage systems. To determine the cost of a solar-plus-storage system for this study, the researchers used a 100 megawatt (MW) PV system combined with a 60 MW lithium-ion battery that had 4 hours of storage (240 megawatt-hours). A 100 MW PV system is large, or utility-scale, and would be mounted on the ground instead of on a rooftop.

WHAT IS A MEGAWATT-HOUR?

A megawatt-hour (MWh) is the unit used to describe the amount of energy a battery can store. Take, for instance, a 240 MWh lithium-ion battery with a maximum capacity of 60 MW. Now imagine the battery is a lake storing water that can be released to create electricity. A 60 MW system with 4 hours of storage could work in a number of ways:



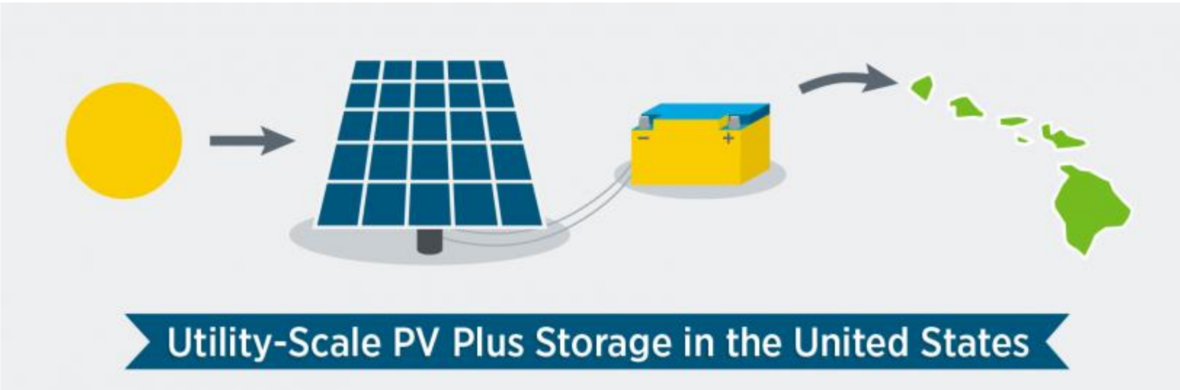
So you can get a lot of power in a short time or less power over a longer time. A 240 MWh battery could power 30 MW over 8 hours, but depending on its MW capacity, it may not be able to get 60 MW of power instantly. That is why a storage system is referred to by both the capacity and the storage time (e.g., a 60 MW battery with 4 hours of storage) or—less ideal—by the MWh size (e.g., 240 MWh).



HOW MUCH UTILITY-SCALE LITHIUM-ION ENERGY STORAGE IS INSTALLED IN THE COUNTRY?

From 2008 to 2017, the United States was the world leader in lithium-ion storage use, with about 1,000 MWh of storage, and 92% of it, or about 844 MWh, is deployed by utilities, according to the benchmark report. The average duration of utility-scale lithium-ion battery storage systems is 1.7 hours, but it can reach 4 hours. Batteries account for the biggest share of a storage system's cost right now—a storage system contains an inverter and wiring in addition to the battery—and utilities will need big battery packs if they're going to provide backup power for all of their customers.

HOW MANY PV-PLUS-STORAGE SYSTEMS ARE INSTALLED IN THE COUNTRY?

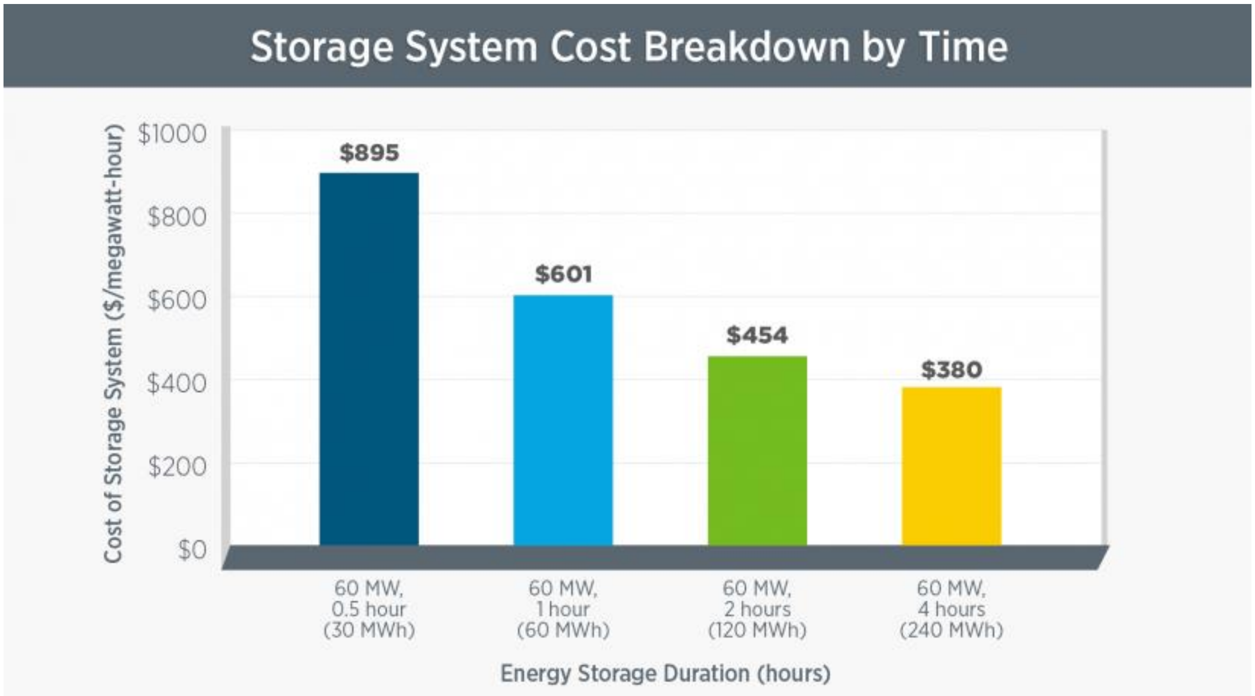


According to NREL, there's only one utility-scale PV system in the United States connected to storage, and it's a 13 MW PV plant with 52 MWh of storage in Kauai, Hawaii. There are more systems that have storage co-located with a solar array, but those batteries can be charged by other sources of power on the grid. According to GTM Research's "U.S. Energy Storage Monitor 2017 Year in Review," more than 5,500 energy storage systems are installed in the U.S., in the residential and commercial sectors with over 95% connected to PV in the residential sector at the end of 2017, which amounts to about 4,700 systems. By the end of 2018, GTM estimates that solar-plus-storage will have accounted for about 4% of distributed PV and could reach 27% by 2023.

SO, WHAT WILL IT COST TO BUILD A SOLAR-PLUS-STORAGE PLANT?

That depends on how long you want your storage to last and how much power you want to use.

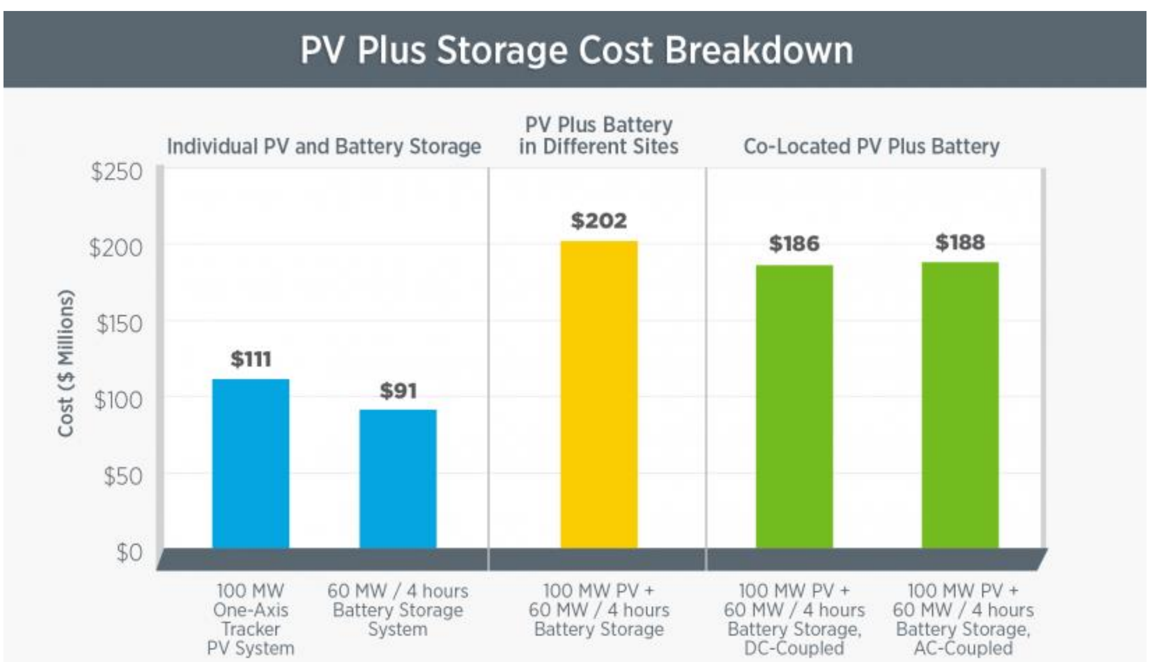
A standalone 60 MW storage system will decrease in cost per megawatt-hour (MWh) as duration increases. Meaning, the longer your storage lasts, the lower the cost per MWh. That's because the cost of inverters and other hardware account for more of the system's costs over a shorter period.



The system costs range from $380 per kWh for those that can provide electricity for 4 hours to $895 per kWh for 30-minute systems.

ALL RIGHT, SO WHAT WILL A 100-MEGAWATT PV SYSTEM WITH A 60-MEGAWATT LITHIUM-ION BATTERY WITH 4 HOURS OF STORAGE COST?

Well, we have some options there too:



Putting a PV system and a storage system in the same place, known as co-location, enables the two systems to share some hardware components, which can lower costs. Co-location can also reduce costs related to site preparation, land acquisition, labor for installation, permitting, interconnection, and developer overhead and profit.

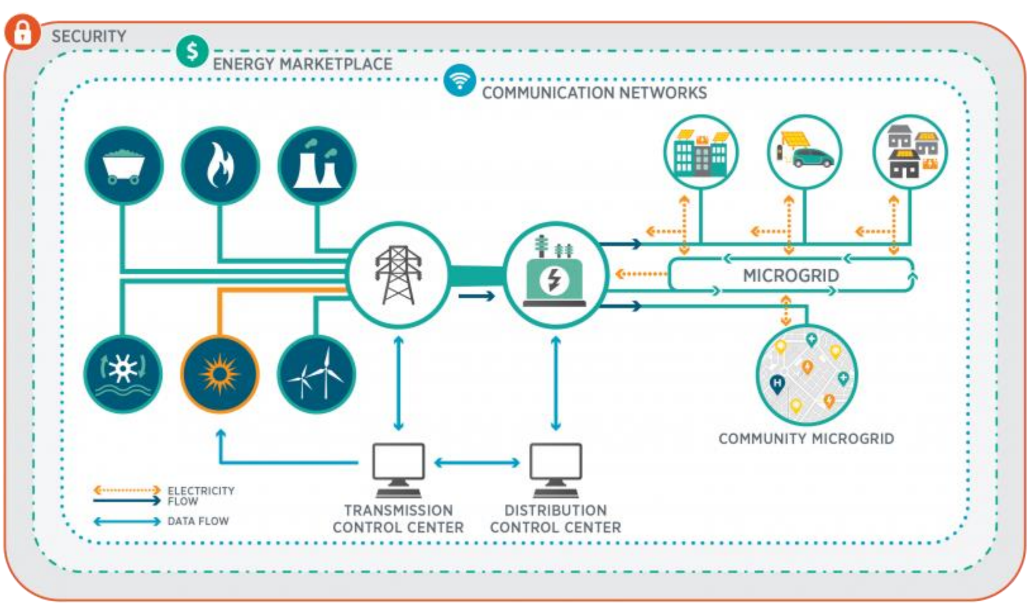
When PV and battery storage are co-located, they can be connected by either a DC-coupled or an AC-coupled configuration. DC, or direct current, is the form produced by solar panels and also the form that batteries use to store energy. On the other hand, AC, or alternating current, is the form that is needed to power household appliances and also the form accepted by the electric grid. Various factors figure into the choice of a DC- or AC-coupled system, and it's up to the owner to decide which would work best.

When choosing between DC and AC, the technical factors that affect the system's performance must be considered, as well as costs. The cost of the co-located, DC-coupled system is 8% lower than the cost of the system with PV and storage sited separately, and the cost of the co-located, AC-coupled system is 7% lower. NREL's new cost model can be used to assess the costs of utility-scale solar-plus-storage systems and help guide future research and development to reduce costs.

WHERE IS THIS ALL GOING?

As solar energy becomes cheaper and more widely used, the market potential for energy-storage devices grows. The challenge is making storage affordable too, with cheaper batteries while improving management and integration techniques. The goal, of course, is to make sure the U.S. electric grid can deploy enough energy to accommodate everyone during peak times at an affordable cost, ensuring the reliability of the grid.

5.6 Solar Grid Planning Operation Basics



WHAT ARE GRID PLANNING AND OPERATION?

When it comes to systems integration, “planning” refers to near- and long-term power system designs under various generation and load scenarios; “operation” refers to real-time sensing, communication, and control that ensure system reliability. Many organizations work together to maintain the grid’s performance through planning and operation. Private, cooperative, and public utility companies, federal and state agencies, independent system operators, and others work to ensure safe, reliable electricity is delivered to consumers.

The technologies necessary to achieve safe, secure, reliable, and affordable power delivery fall into four categories: balancing, protection, situational awareness, and utility management tools.

BALANCING

Balancing is the task of making sure electricity generation matches consumption. The electrical grid is not like a grocery store, where products are stocked on the shelf then sold. Electrical power is generated and then almost instantly consumed by devices in homes and businesses. Therefore, utilities must carefully balance generation, minute to minute, with power that is being used, also known as load.

Consumers change the load when they turn their devices on and off. Generators ramp up and down, and may go offline owing to an equipment fault. With renewables like solar, weather conditions and the daily passage of the sun across the sky introduce additional variability in generation. If there is too much or too little generation to serve the current load, over- or under-generation occurs.

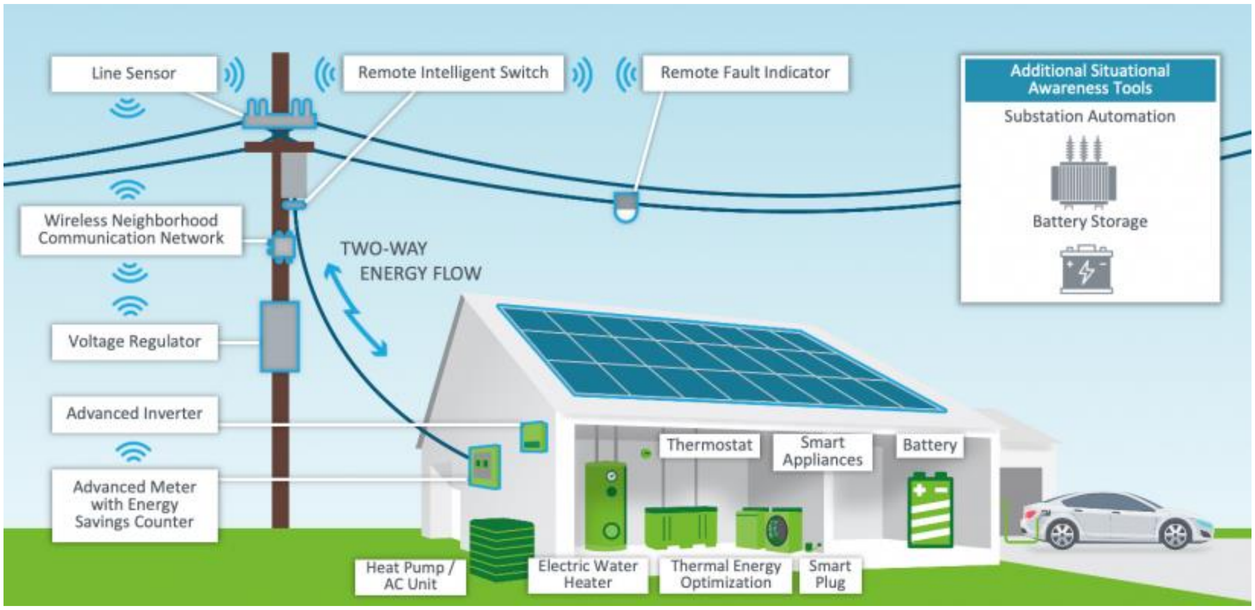
A temporary drop in generation might need to be compensated by ramping up other generators, by reducing load, or by tapping stored energy. Solar can help balance the grid by keeping some generating capacity in reserve. Solar plants can then respond to increasing demand by releasing the power they were holding back. Because a solar plant doesn’t have a lot of mechanical inertia like traditional fossil-fueled turbines, it can respond much more quickly to changes. Solar can therefore provide grid operators with a fast, almost instantaneously available resource to help balance the grid, potentially distributed across millions of homes in an area.

PROTECTION

Protection refers to the use of devices such as relays, breakers, and fuses that protect people and equipment from unsafe electricity. For instance, if a power line is down, creating a condition known as a line-to-ground fault, large amounts of current will flow into the ground. This is dangerous for people near the power line, but it’s also dangerous to electrical equipment that is not designed to carry as much current as the line will carry when it’s lying on the ground. Therefore, automated systems must be installed to disconnect the line quickly when necessary. Effective protection will allow the system to isolate and clear the fault while the rest of the grid remains operational during a disruption.

Distributed energy resources (DER), such as household solar panels, present new challenges to grid protection measures, simply because they provide new sources of generation that need to be monitored and safely disconnected during faults. On the other hand, DER represent a new fleet of smart, connected devices that can serve as gateways for monitoring and control, giving grid operators a new window onto the condition of the grid for identifying problems faster than ever. In addition, because DER produce power where it will be used, communities are better equipped to deal locally with the consequences of failures in the power system.

SITUATIONAL AWARENESS



All these issues highlight the need for improved sensing, communications, and control in electrical grids with large amounts of solar generation, especially distributed rooftop solar. Situational awareness refers to the utilities' awareness of the current load, the current generation, and where that generation and consumption is occurring.

As the electricity system modernizes, the instrumentation and technology required to observe and control it has become more complex. Advanced power electronics and other smart devices in your home can give utilities information so they can better manage loads. Line sensors and other devices on utility poles can provide information on a neighborhood level. Power lines can be equipped with fault indicators, and digital substations can also present important information.

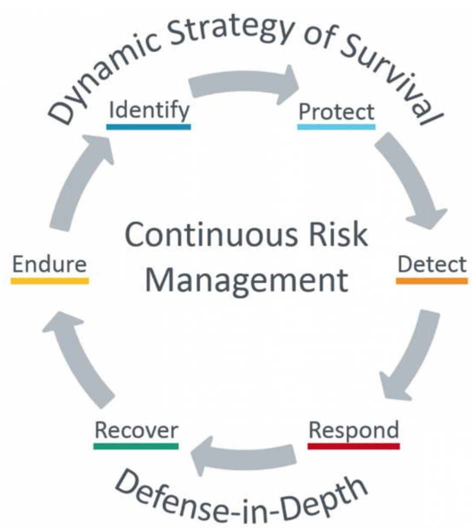
Situational awareness is always important, but it becomes especially important when there is a disaster or an accident that requires a fast, smart response. Historically, utilities have not had fine-grained insight into the distributed grid. For instance, grid operators are unlikely to have access to real-time information about how much electricity individual households are using, nor are they aware of downed power lines unless a customer reports it. In a disaster, understanding where a problem is occurring is the first step to solving it.

UTILITY MANAGEMENT TOOLS

To realize the benefits of DER for grid operation, utilities need a way to interface with these generators. That means they need a software platform that allows DER to be seen, managed, and controlled effectively and efficiently while maintaining privacy and security. That's where a distributed energy resource management system (DERMS) comes in. A DERMS allows a grid operator to securely monitor and control distributed resources and make better decisions about what resources to tap in different situations.

DERMS is an active area of software engineering and research. A good DERMS should be able to deal with demand-response resources (loads the utility can control to reduce demand, like water heaters or smart thermostats), distributed generation (such as solar), electric vehicles, and energy storage (like batteries). It should also be aware of grid conditions so that decisions can be made based on real-time power flow. Building a software platform that allows operators and DER aggregators to conduct this orchestra of energy resources is difficult, but it can lead to more efficient, cleaner, and more cost-effective grid operation.

5.7 Solar Cybersecurity Basics



A dynamic survival strategy applies a defense-in-depth approach and continuous risk management.

Solar energy technologies can be vulnerable to cyberattack through inverters and control devices that are designed to help manage the electric power grid. Operating-technology (OT) devices like solar photovoltaic inverters, when connected to the Internet, are at higher risk relative to stand-alone OT devices. They must be able to prevent, detect, and respond to unauthorized access or attack. While some cyberattacks manipulate information-technology (IT) systems, cyberattacks on electric-grid devices can cause physical impacts like loss of power and fires.

The electric grid is becoming increasingly digitized and connected, so maintaining cybersecurity is a top priority for the U.S. Department of Energy (DOE). There are daily attempts to attack the grid, but the majority are not successful. In March 2019, however, hackers breached a utility's web-portal firewall, causing operators to lose visibility of parts of the grid intermittently for 10 hours.

WHAT IS A CYBER ATTACK?

You may envision lone hackers furiously entering commands in dark rooms, illegally breaching and controlling sensitive systems, but many cyberattacks are more ordinary. For example, phishing scams use emails that appear to come from reputable sources and trick people into giving important information to a malicious actor. This type of manipulative, fraudulent practice is called social engineering. Failure to recognize such deceptions is the entry point into many systems.

Outdated software is another risk: A novice hacker could take advantage of a system's known vulnerabilities by running code downloaded from the Internet to attack it. Advanced hackers might discover problems so new that they're called "zero-day attacks," meaning security professionals have had no time to prepare for them.

A cyberattack on a cyber-physical system is different from one on an enterprise IT system because of the physical consequences. Cyber-physical systems are engineered systems that are built from, and depend upon, the seamless integration of computation and physical components.

HOW COULD HACKERS ATTACK SOLAR POWER SYSTEMS?

Historically, cyber risk for solar was relatively minor, given how few systems were deployed and because most solar inverters did not communicate for monitoring or control. However, as more solar is installed and inverters become more advanced, this risk grows. Inverters are the interface between solar panels and the grid. If the inverter's software isn't updated and secure, its data could be intercepted and manipulated. An attacker could also embed code in an inverter that could spread malware into the larger power system.

A cyberattack that introduces instabilities or false information into the power system can cause physical as well as financial damage. For example, a security breach could make an unauthorized change in power delivery. Unauthorized changes to inverter controls or communications like these are called cyber-physical security breaches, because the result is a change in the voltage or the electric current that the inverter injects into homes or the grid.

Microgrids are also a potential target for cyberattacks. Microgrids are local power systems that can operate independently of the larger grid in case of a power outage. Protecting them from cyberattack becomes part of an overall resilience strategy to maintain critical electrical infrastructure in emergencies.

MANAGING VULNERABILITIES

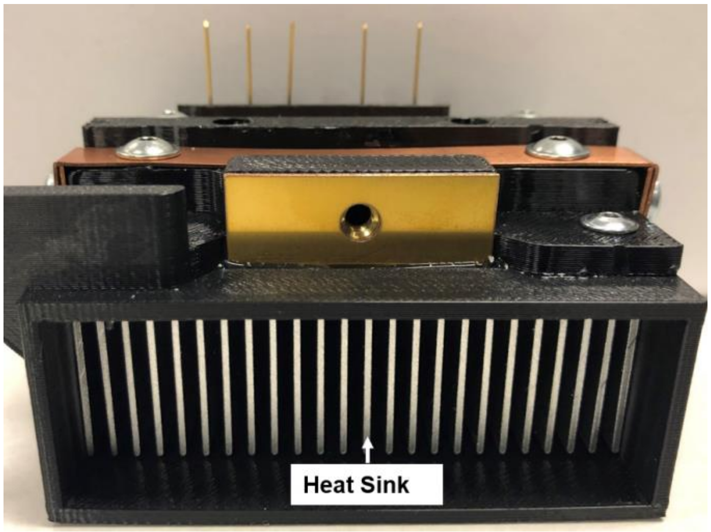
The introduction of widespread digitization and interconnectivity across the modern grid presents a great challenge for grid operators. As more solar and other distributed energy resources (DER) are added to the grid, so are more tools that provide utilities with real-time solar power generation and other information. These tools must be secured, or the grid will become more vulnerable to cyberattack.

Security software can help utilities maintain control of their DER and prevent attackers from injecting false information into the system. Most attempted attacks on the grid are mitigated by intrusion-detection software that alerts grid operators to abnormal behavior.

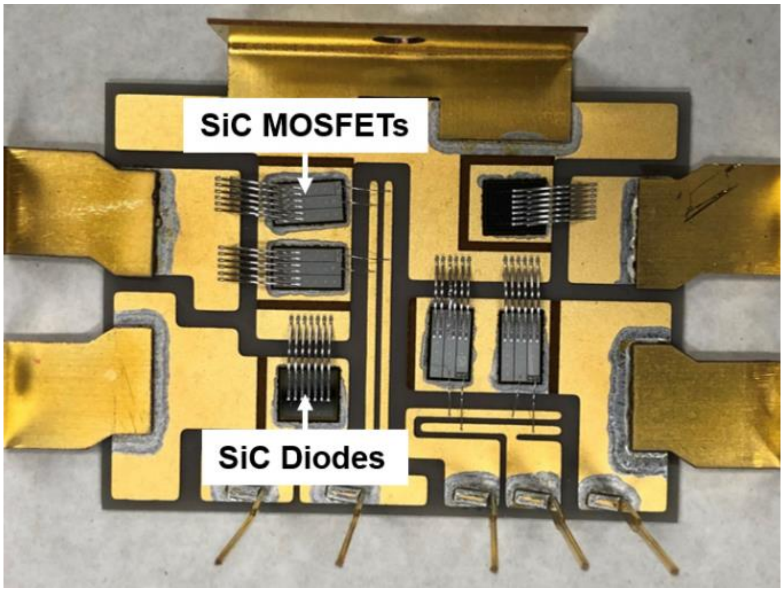
Utilities and solar system owners and operators can use a dynamic survival strategy based on defense-in-depth measures, which are basically diverse layers of security that cover everything from individual components to entire systems. For example, installing anti-virus software in DER systems, such as solar inverters and battery controllers, is one layer of protection. Installing virus protection and detection on the firewalls and servers that integrate DER into the broader system of grid operation is another layer. This strategy for DER is complex, considering the number of owners, operators, and systems involved, but it’s crucial to reduce the chance of cyberattack.

The DOE Solar Energy Technologies Office (SETO) is working to ensure the electric grid is smart, secure, and capable of integrating more solar power systems and other DER. SETO has developed a Roadmap for Photovoltaic Cybersecurity, supports ongoing efforts in DER cybersecurity standards, and is involved in the Office of Energy Efficiency and Renewable Energy (EERE) Cybersecurity Multiyear Program Plan and DOE’s broader cybersecurity research activities.

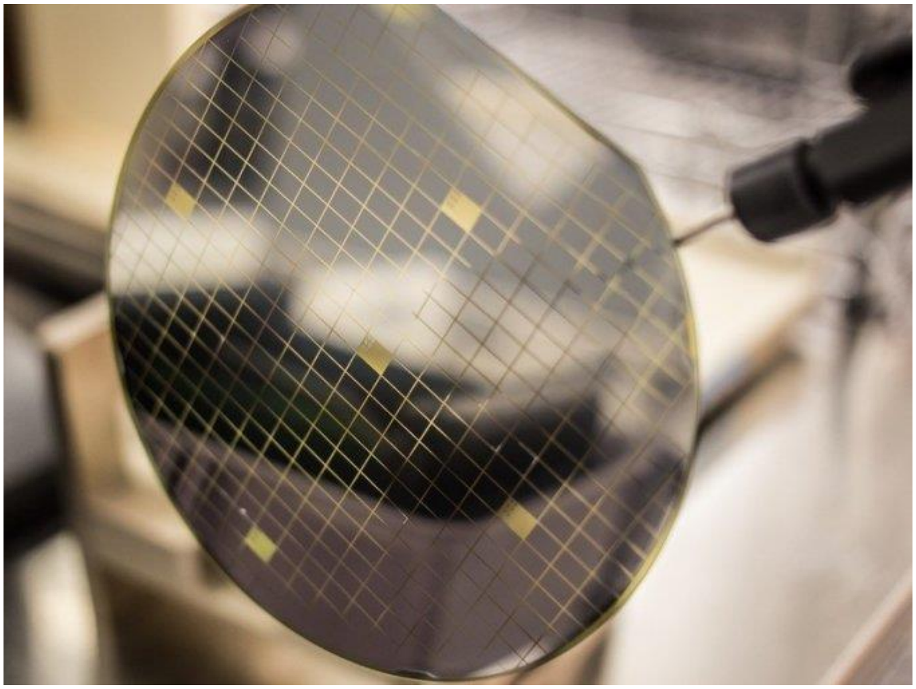
5.8 Silicon Carbide in Solar Energy



Prototype of a PV inverter developed by researchers at Oak Ridge National Laboratory and the National Renewable Energy Laboratory. Photo courtesy of Oak Ridge National Laboratory



An inside look from the national laboratory reserch team. MOSFETS and diodes are components that act as switches. Photo courtesy of Oak Ridge National Laboratory



A silicon carbide wafer processed at X-Fab. Photo courtesy of X-Fab

The Solar Energy Technologies Office (SETO) supports research and development projects that advance the understanding and use of the semiconductor silicon carbide (SiC). SiC is used in power electronics devices, like inverters, which deliver energy from photovoltaic (PV) arrays to the electric grid, and other applications, like heat exchangers in concentrating solar power (CSP) plants and electric vehicles.

When PV modules generate electricity, energy first flows through a power electronics device that contains a semiconductor. Until around 2011, silicon was the preferred semiconductor used to make these devices, but research has shown that SiC can be smaller, faster, tougher, more efficient, and more cost-effective.

SiC withstands higher temperatures and voltages than silicon, making it a more reliable and versatile inverter component. Inverters convert direct current electricity generated by solar panels from to grid-compatible alternating current. During the conversion process, some energy is lost as heat. State-of-the-art silicon inverters operate at 98% efficiency, whereas SiC inverters can operate at about 99% over wide-ranging power levels and can produce optimal quality frequency. While the 1% increase in efficiency might seem small, it represents a 50% reduction in energy loss. With 60 gigawatts of solar installed in the United States, a 1% increase in efficiency would amount to 600 megawatts of additional solar power each year and cost savings over the device's lifetime.

BENEFITS OF SILICON CARBIDE

SiC has an edge over silicon because it enables the following:

- Higher temperatures: SiC-based power electronics devices can theoretically endure temperatures of up to 300° Celsius, while silicon devices are generally limited to 150°C.
- Higher voltage: Compared with silicon devices, SiC devices can tolerate nearly 10 times the voltage, take on more current, and move more heat away from the energy system.
- Faster switching: A power electronics device needs a switch that turns on to convert low voltage to higher voltage. SiC can switch on and off quickly, and although some energy is lost during switching, faster switching limits that loss and improves device efficiency.
- Less-costly equipment: SiC translates to lower system costs because it allows for smaller, more affordable equipment. For example, the heat sink, which protects the rest of the components by taking on excess heat, can be smaller because with less energy loss, less heat is produced.

THE WIDE-BANDGAP ADVANTAGE

One attribute is responsible for these benefits: SiC's wide bandgap. The bandgap is a measure of energy that signifies the distance between two states—an electron's starting point in the valence band, which is the nonconduction state, and the level it has to move to in order for electricity to flow. The wide bandgap allows for high voltage, which means SiC can better tolerate voltage spikes, and because devices can be thinner, they perform faster.