1

Introduction to Photovoltaic Systems

With growing concerns about the future and security of the world's energy supply, renewable resources such as solar power are becoming increasingly important. Various solar energy technologies have been used through millennia of human history. However, practical photovoltaics—the direct conversion of solar energy into electricity—has a history of only about 50 years. This field of study and the resulting industry have been rapidly growing and improving and are expected to become a significant part of the world's energy future.

Chapter Objectives

- *Compare the advantages and disadvantages of installing a PV system.*
- *Understand some of the factors that have motivated the growth of PV technology worldwide.*
- *Evaluate the design priorities for PV systems in different types of applications.*
- *Describe the primary levels of the PV industry and how they interact.*
- *Understand why it is important for installers to be well trained.*
- *Differentiate between flat-plate collectors and concentrating collectors.*
- *Understand how the different types of solar energy technologies utilize solar radiation.*

PHOTOVOLTAICS

Photovoltaics is a solar energy technology that uses unique properties of semiconductors to directly convert solar radiation into electricity. Photovoltaic (PV) systems use wafers, typically made of crystalline silicon, that are sensitive to sunlight and produce a small direct current when exposed to light. When these PV cells, also known as solar cells, are combined into larger systems called modules, they produce an appreciable amount of electrical power with no moving parts, noise, or emissions.

A *photovoltaic (PV) system* is an electrical system consisting of an array of one or more PV modules, conductors, electrical components, and one or more loads. These components can be arranged in many ways to design PV systems for different situations, but the most common configuration is a utility-connected system on a residential building. **See Figure 1-1.** These PV systems may or may not include battery storage. The array is usually mounted on a rooftop or nearby on the ground.

Electrical components, such as inverters, charge controllers, and disconnects, control and condition the DC power from the array and either direct it to DC loads or convert it to AC power for use by AC loads. Some of these component functions may instead be combined together into one power conditioning unit (PCU). A *load* is a device that consumes electricity. Examples of loads include lights, pumps, heaters, motors, and electronics.

DOE/NREL, Altair Energy

The most common type of PV system is a utility-connected system on a residential roof.

Advantages

Electricity supplied by a PV system displaces electricity from some other power-generating technology. If the alternative is very expensive, such as a utility connection to a remote location, then the PV system may save the consumer a great deal of money. However, many advantages and benefits of PV systems add value beyond the potential financial savings. Many PV system owners place a high importance on producing clean "green" energy. Photovoltaics is an environmentally friendly technology that produces energy with no noise or pollution. For some owners, operating a PV system makes a statement about protecting the environment and conserving nonrenewable energy sources.

Also, PV systems are very flexible and can be adapted to many different applications. The modular nature of PV arrays and other components make systems easy to expand for increased capacity. Since there are no moving parts, PV systems are extremely reliable and last a long time with minimal maintenance.

PV systems also offer energy independence. A supplemental PV system reduces the consumer's vulnerability to utility power outages, and a stand-alone system eliminates it. Furthermore, sunlight is a renewable energy source that is free and readily available. As conventionally produced electricity is expected to become more expensive and PV system costs are generally decreasing, PV systems can also be used to hedge against future energy rate increases.

Disadvantages

There are, however, some disadvantages to PV systems that have somewhat limited their use. Currently, the most significant issue is the high initial cost of a PV system compared to prices for competing power-generating technologies (when available). PV systems also require a relatively large array area to produce a significant amount of power. The available solar radiation resource at a particular location determines the feasibility of producing appreciable amounts of power.

There is also a lack of knowledge among some groups and in some areas about the potential of solar energy systems, particularly photovoltaics. Consumers may not know what types of systems are available, or even that a solar energy system could be successful for their application or location. Consumers who wish to install a PV system may discover that the industry infrastructure in their area is not yet fully developed to support their installation. It may be difficult to find a qualified installer in their area, or their installation may be hindered by limited knowledge of PV systems and their requirements among the local utilities and code officials.

Many leaders in the PV industry are addressing these issues in an effort to promote PV systems. Public and private organizations, particularly state and federal governments, are subsidizing PV installations in an effort to offset the additional costs and promote the use of "green" electrical power. Research institutions and manufacturers are working on new PV technologies to increase the efficiency of cells and modules so that more energy can be produced by smaller arrays or in locations with a less-favorable solar radiation resource. Most importantly, the industry as a whole is involved in educating the public and related organizations about solar energy, through publicity, training programs, cooperative projects, legislation, incentives, and other activities.

Electricity Distribution

Most electricity is distributed through an electrical utility grid to millions of customers from a relatively small number of large power plants. A *utility* is a company that produces and/or distributes electricity to consumers in a certain region or state. The *grid* is the utility's network of conductors, substations, and equipment that distributes electricity from its central generation point to the consumer. **See Figure 1-2.** The grid fans out from the power plants to thousands of homes and businesses within a region. Electricity may travel hundreds of miles before it reaches the end user. The grid regions may be connected together so that consumers still have power if part of the distribution system breaks down. Outages, though rare, do still occur, often due to an overloaded system.

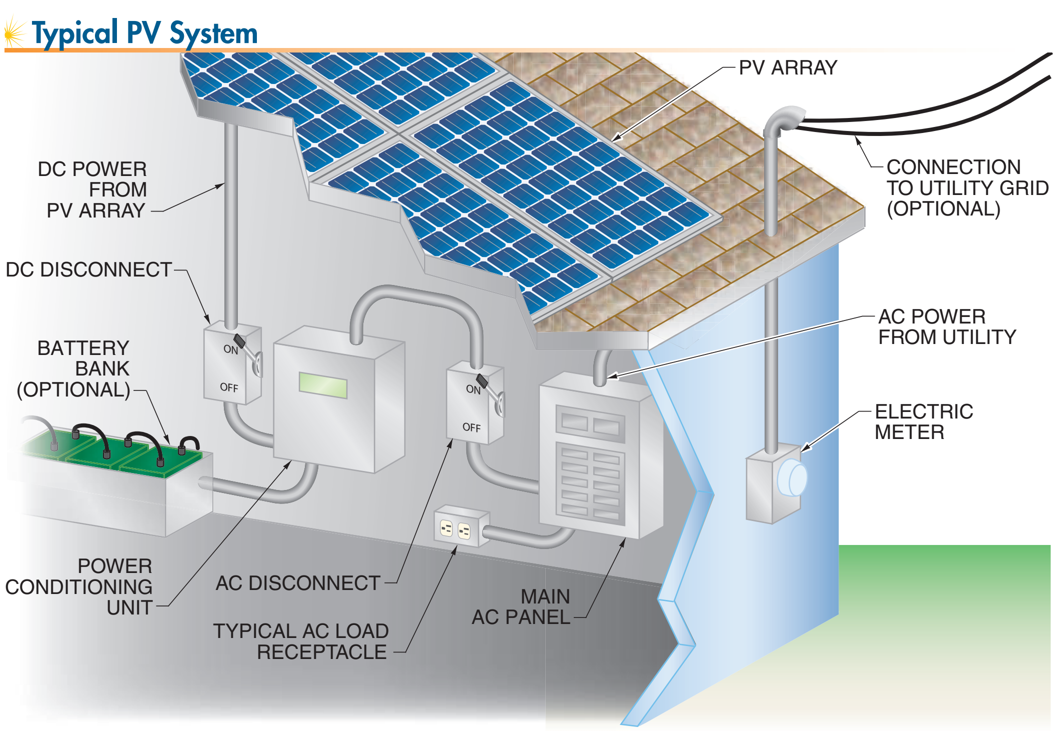


Figure 1-1. *A utility-connected residential PV system is the most common system configuration. Various electrical components control, condition, and distribute the PV power to DC and/or AC loads.*

Centralized Electricity Distribution

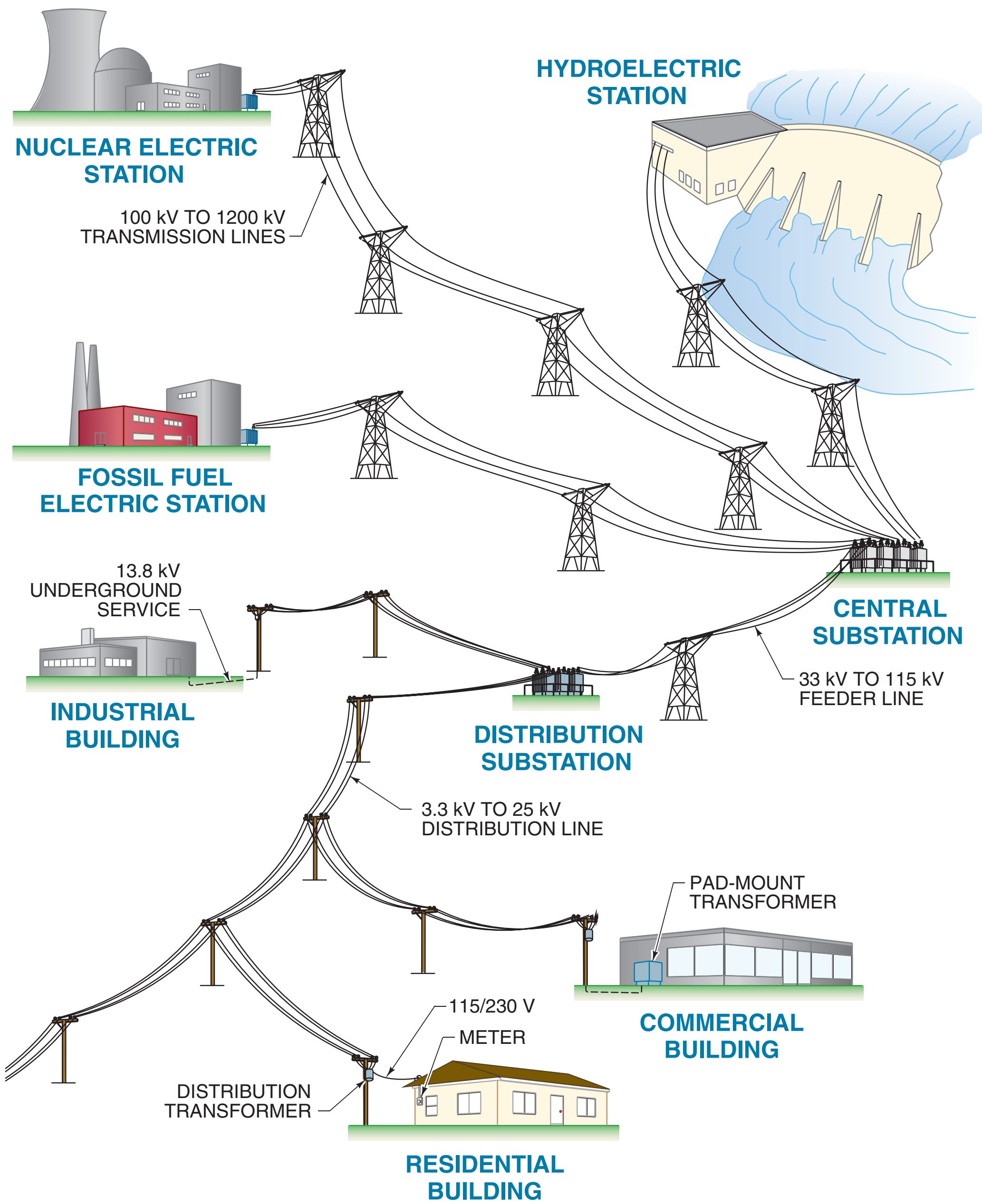


Figure 1-2. *An electric utility produces electricity at a power plant and distributes it to consumers through power lines, substations, and transformers.*

Distributed generation is a system in which many smaller power-generating systems create electrical power near the point of consumption. The electricity may travel only a few feet to the loads. Distributed generation systems can include PV systems, wind turbines, engine generators, or other relatively small-scale power systems. **See Figure 1-3.** A distributed generation system may serve as the only source of power for the consumer (a stand-alone system), or as backup or supplemental power for a utility grid connection. If consumers are connected to the utility grid, excess power can be distributed to the grid if it is not needed by the on-site loads.

Distributed Generation

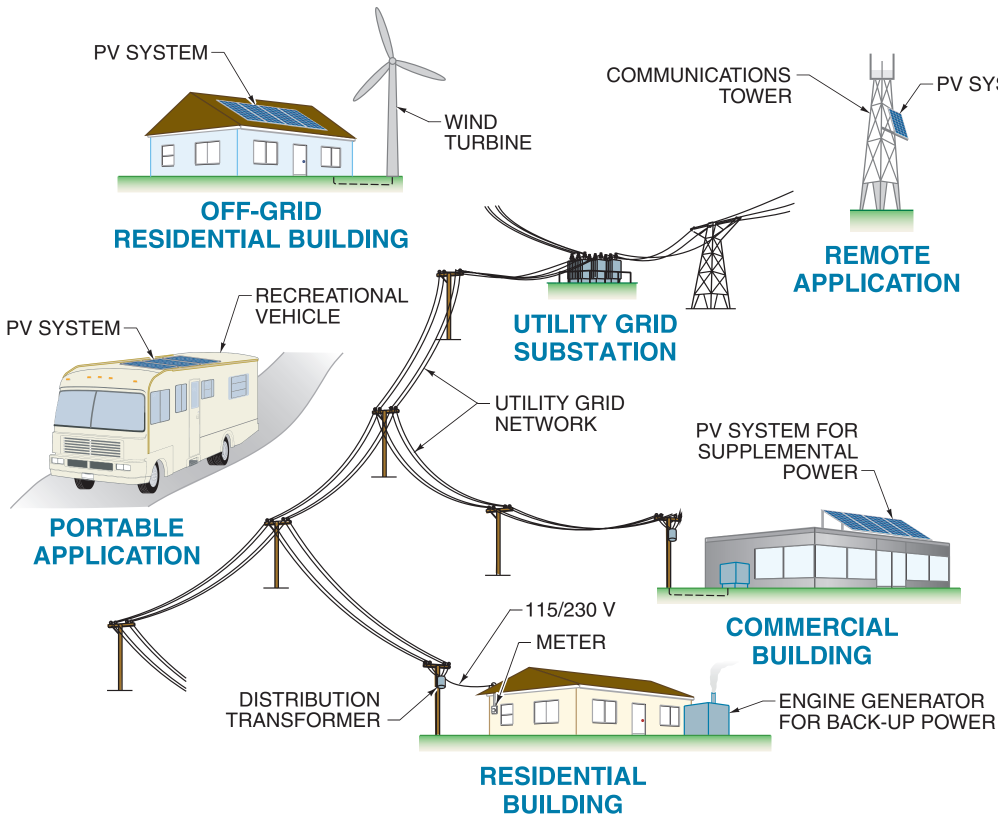


Figure 1-3. *Distributed generation systems produce electricity close to where it is used.*

Development

PV technology has been developing for more than 160 years, but has progressed exponentially in the last few decades. Photovoltaics has only recently become a practical technology for power generation.

Invention. Edmund Becquerel, a French physicist, is credited with discovering the photovoltaic effect in 1839. The nineteen-year-old scientist observed an increase in electron emissions between a pair of electrodes submerged in a conductive solution when the experiment was exposed to light. However, there was little practical application for electricity at the time, and the discovery went unutilized.

In 1873, British engineer Willoughby Smith observed the light sensitivity of selenium while testing materials for underwater telegraph cables. In the absence of light, selenium exhibited high resistance, but when exposed to light, selenium became highly conductive. The resistance was inversely proportional to the intensity of the light. **See Figure 1-4.** This observation of photoconductivity led to experimentation on how to use selenium to utilize solar energy.

DOE/NREL, Canyonlands Needles Outpost

Distributed generation systems provide electrical power in remote locations.

Power Generation

Direct energy conversion systems produce electrical power without any mechanical components. For example, fuel cells use electrochemical processes to convert hydrogen and oxygen into electrical energy, and photovoltaics use semiconductor properties to produce power from sunlight.

However, most power is generated by converting energy from one form to another until it ultimately becomes useful energy in the form of electricity. For example, coal-fired power plants change chemical energy (energy in the chemical bonds of coal) into heat energy by burning. The heat energy is applied to water, which becomes steam, another form of heat energy. The steam is routed to turbines where it moves the blades, which rotate a shaft, producing mechanical energy. The shaft drives a generator that uses the mechanical energy together with magnetic energy to produce electricity.

Steam is the most common method of converting heat energy into mechanical energy and ultimately electricity and is used in many types of power plants. Nuclear power plants convert atomic energy into heat energy, which creates electricity by way of steam. Other fossil-fuel-powered processes also use steam for energy conversion.

Energy sources that begin with mechanical energy, however, do not include steam or heat energy in the conversion cycle. In hydroelectric plants, water pressure and flow drives the turbine-generators. Turbine-generators can also be driven by wind or tidal power, or even the movement of fluids in solar thermal systems.

No energy conversion is 100% efficient. That is, there is always some energy that does not convert to a new form or is lost through byproducts or waste heat. The energy is not destroyed, but it escapes the system and does no useful work.

Selenium Photoconductive Cells

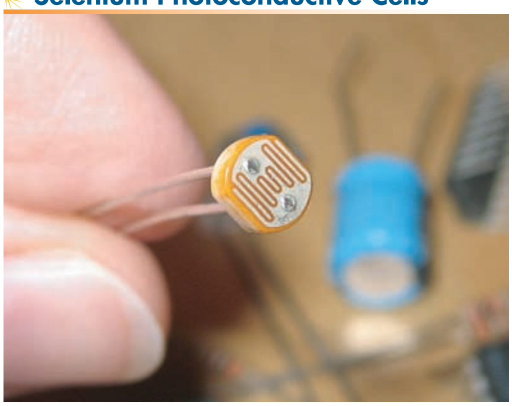


Figure 1-4. *Selenium photoconductive cells eventually found uses in light-sensing electronics, such as exposure timing circuits in cameras.*

The first true PV cells were developed by American inventor Charles Fritts in 1883. He covered a selenium wafer with transparent gold film, which produced a tiny current. However, its maximum efficiency never exceeded 1%, so it was considered impractical for power generation. Also, selenium is a relatively rare element, making the production of cells prohibitively expensive.

In 1954, Darryl Chapin and other researchers at Bell Laboratories were investigating the use of PV cells as a power source for remote telephone service stations, but their efforts to improve selenium cells were unsuccessful. At the same time and independently, fellow Bell researchers Calvin Fuller and Gordon Pearson were investigating silicon for use in transistors and rectifiers. They discovered that not only could adding certain impurities improve the desired electrical qualities for the transistors and rectifiers, but that this modified silicon rectifier produced an appreciable electric current when exposed to light. Fuller, Chapin, and Pearson subsequently collaborated and improved the silicon cell into the first useful PV cell. **See Figure 1-5.** The first cells had efficiencies of about 6%—unimpressive by today's standards, but a significant improvement over selenium. Bell called the invention a "solar battery" and conservatively envisioned its application as powering small or remote electrical systems.

Growth. The space race in the 1950s and 1960s spurred the development of space technologies, including photovoltaics. PV cells were ideal power generators for satellites and spacecraft because of the complexity of supplying power by other means and the abundant solar resource available outside Earth's atmosphere. Cells were first developed for the Vanguard I satellite in 1958 and have been used on nearly every spacecraft and satellite since.

Invention of the PV Cell

Lucent Technologies Inc./Bell Labs

Figure 1-5. *The first practical photovoltaic cell was invented at Bell Laboratories in 1954.*

The first common Earth-based applications were in rural telephone systems and radio transmitters. **See Figure 1-6.** These systems brought communications to remote communities, especially in developing countries where the lack of electrical infrastructure made solar energy an ideal solution. Many applications of photovoltaics significantly improved life in developing countries, such as by providing power to pump water for sanitation and irrigation, filter water for drinking, light schools, and refrigerate medicines.

Further improvements in cell efficiency and refinements in cell manufacturing made PV technology a viable option for larger systems. Off-grid homeowners living in remote areas began incorporating PV systems into their homes as a way to enjoy the convenience of modern appliances while maintaining their secluded lifestyle. There were also consumers who saw merit beyond financial factors in "green" PV electricity. These markets were relatively small, but fostered steady growth in PV technology for many years.

Early PV Applications

Lucent Technologies Inc./Bell Labs

Figure 1-6. *Rural communications systems in the 1950s were the first terrestrial applications of PV technology.*

Energy Crises. Oil shortages in the 1970s increased interest in terrestrial PV applications. The U.S. government initiated terrestrial PV research and development projects and established what would become the National Renewable Energy Laboratory (NREL). Significant developments were made in PV technology, materials, inverters, and interactive systems, and federal legislation introduced tax credits to promote renewable energy production. Significant financial incentive programs are available to consumers in the United States, Europe, and Japan to encourage use of PV technology.

In 1960, solar cells were handmade and cost about $1000 per watt. Manufacturing improvements have reduced costs to less than $5 per watt, while production has grown exponentially. **See Figure 1-7.** Meanwhile, fossil fuel costs have increased as finite supplies have dwindled or become more difficult to reach. The increasing costs for conventional electricity have helped the PV industry grow.

See Figure 1-8. Today, PV technology is used in diverse applications including communications networks, grid-connected homes and commercial buildings, and rural and remote lighting and water pumping systems.

Germany is home to what is currently the largest PV installation in the world. The 10 MW Bavaria Solarpark consists of 57,600 PV modules on more than 62 acres of land.

PV APPLICATIONS

The earliest applications of PV systems were in situations where connections to the utility grid were unavailable or cost prohibitive. As PV efficiency has continued to improve and costs have fallen in recent years, more potential applications for PV technology have emerged. Greater demand and increasing production have accelerated the trend toward cost effectiveness in a wide range of applications.

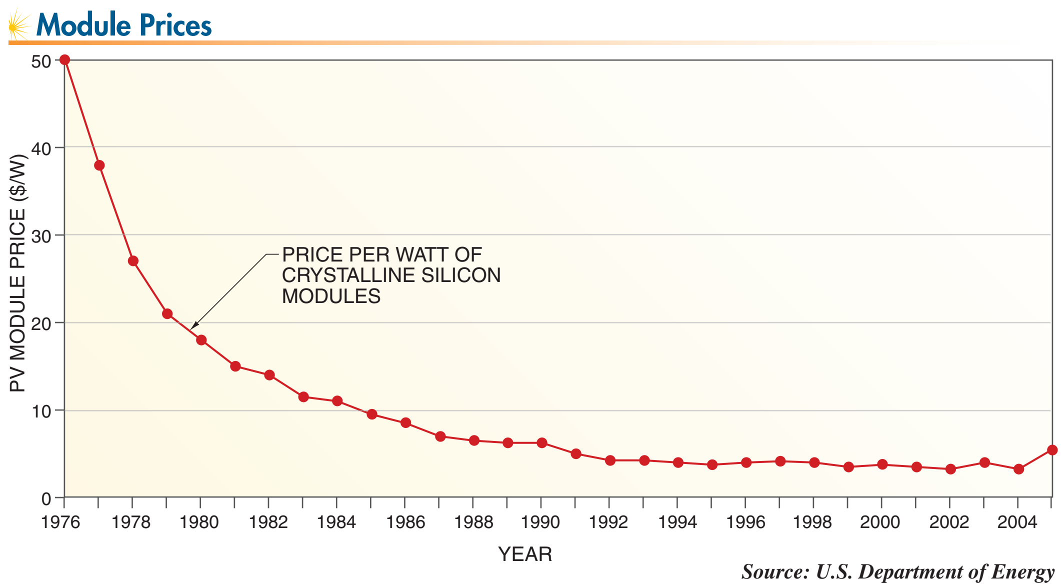


Figure 1-7. *Decades of development and manufacturing improvements have decreased the price per watt for PV systems.*

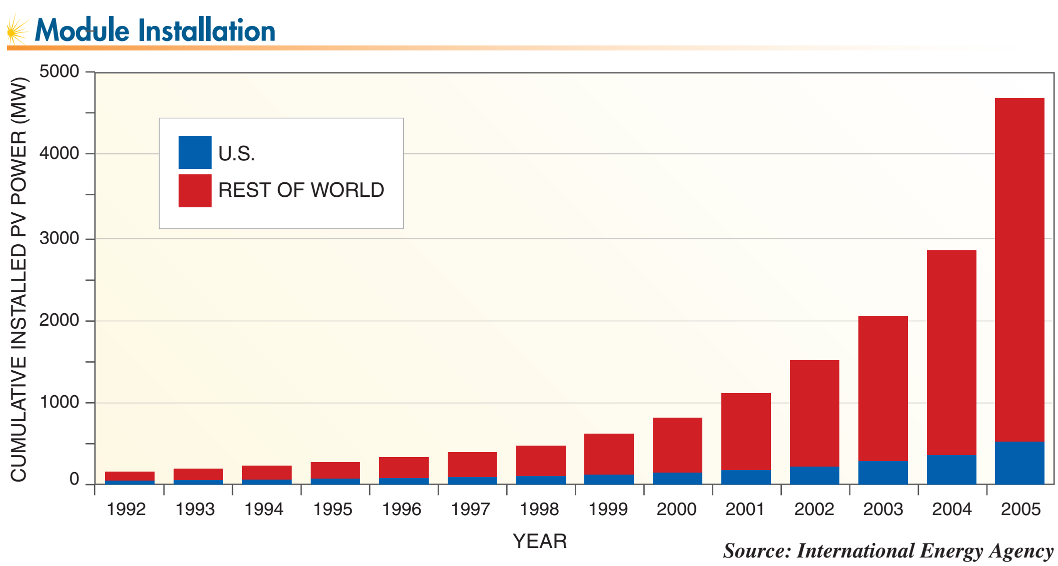


Figure 1-8. *Production and installation of PV systems is growing rapidly.*

Today, PV systems can be used in almost any application where electricity is needed and can support DC loads, AC loads, or both. PV systems may be as simple as a PV module directly connected to a load with no other components, or as complex as a utility-interconnected system with multiple power sources.

Space Applications

Space applications are extreme examples of off-grid remoteness, in that there is no possible way to connect satellites and spacecraft to a steady source of terrestrial electricity. The only options are to launch electricity, in the form of batteries, with the spacecraft, or to generate electricity in space. Fortunately, the available solar radiation outside Earth's atmosphere is even greater than on the ground.

Satellites were the first practical applications of PV technology and did much to increase the public's knowledge of PV systems. **See Figure 1-9.** However, space-bound PV systems are designed for high efficiency and low weight, with cost being less important. Since the priorities for space-bound PV systems are different from those for Earth-based PV systems, the technologies used for these different applications have diverged somewhat. Even so, the advanced technologies currently used in space applications, though currently cost prohibitive, may someday progress to become practical for terrestrial applications.

Space PV Applications

DOE/NREL, NASA/Smithsonian Institution/ Lockheed Corp.

Figure 1-9. *Nearly every satellite and spacecraft since 1958 has relied on a PV system for power generation.*

SolarWorld Industries America

Camels are used for transportation to remote areas of some countries. Portable PV systems are used to power small refrigeration units for medicines that must be kept cold during a journey.

Portable Applications

Portable PV systems power mobile loads such as vehicles, temporary signs and lighting, and handheld devices. **See Figure 1-10.** The primary advantage of PV systems in these applications is that the load is not permanently connected to a stationary power source and is free to move. Some portable applications require power when the sun is not available, requiring a battery as part of the PV system. Other portable applications, such as battery chargers for small electronics, are simpler systems that operate only under sunlight.

Most portable PV systems are relatively small and can power only modest loads. For ease of transportation, the systems should be relatively light. Portable systems also need to be repositioned each time they are relocated. They can usually be used while in motion, but if not constantly facing the sun, the power output will be reduced.

Vehicles. Recreational vehicles (RVs) and boats can benefit greatly from PV systems. If the vehicle has many loads, such as the appliances in an RV, the PV system is best suited to be a backup to a primary power source, typically an engine generator. A sailboat, however, may use a small, portable PV system as the primary method for charging the batteries for its relatively small number of loads, such as navigation lights and radios.

Portable PV Applications

DOE/NREL, Warren Gretz

SolarWorld Industries America

DOE/NREL, United Solar Ovonic

Figure 1-10. *Portable PV systems tend to be small and intended for specific loads.*

Temporary Signs and Lighting. Electronic construction signs cannot be connected to utility power, either because of remoteness or because of electrical construction hazards, and must be able to move between work areas at a construction site. Small PV systems with batteries can be added to the signs to power them continuously. Temporary lighting for short-term projects or nighttime construction work may be PV-powered because the short duration of the need may not warrant the time or expense of connecting to utility power.

Small Electronics. Small handheld PV systems can be used to directly power or charge small electronic devices such as cell phones, calculators, radios, GPS receivers, and lights, and are common accessories for campers, hikers, and military personnel. Manufacturers have developed these PV systems for ease of use, ruggedness, and portability, but power output is limited by their small size. These arrays are rigid or flexible panels that are unfolded and laid out on a sunny patch of ground. Small arrays have even been sewn into backpacks and jackets. The electronic device to be charged is connected to the PV system in the same way as the usual wall outlet charger.

Emergency Power. During natural disasters when the existing electrical infrastructure has been damaged and is off-line, portable PV power units can be brought in to supply critical services until the utility grid is repaired. Individual emergency PV systems can provide power for street and personal lighting, communications equipment, warning and message signs, water purification, refrigeration of medical supplies and food, or water pumping.

Remote Applications

Remote PV systems power loads that are permanently fixed but too distant to be connected to the utility power grid. A large number of applications require electricity in remote areas, making PV an ideal choice. **See Figure 1-11.**

Off-Grid Residences. The mainstream consumer PV market essentially began with off-grid residences, and this segment still composes a significant portion of the market. As systems have become more affordable, this application has become increasingly common among homeowners who demand value beyond environmental benefits from the systems. PV systems can be sized to power an entire home, but off-grid residences often include other sources of energy, such as wind turbines or engine generators, to supplement or back up the PV system.

Lighting. The availability of low-power DC lamps makes PV energy ideal for remote lighting applications. Lighting needs are clearly greatest at night, making power storage (in the form of batteries) a necessary part of these systems. PV systems can be used to light billboards, highways, information signs, parking lots, and marinas.

Remote Applications

DOE/NREL, Dave Parsons

OFF-GRID RESIDENCES

DOE/NREL, Minnesota Department of Commerce

REMOTE MONITORING

DOE/NREL, Jerry Anderson, Northwest Rural Public Power District

WATER PUMPING

Figure 1-11. *Remote areas where conventional utility-supplied power is out of reach are ideal for the application of PV technology.*

Communications. Radio, television, and telephone signals transmitted over long distances must be amplified by relay towers that are often located in areas inaccessible to utility power. The best sites for communications stations are at higher elevations, making it difficult to provide fuel and maintenance for generators. PV power is ideal for these stations. PV systems can also be used to power communication signals from emergency call boxes and electronic information signs.

Signage and Signals. Small PV systems can provide power for remote signage and signal devices, such as navigational beacons, sirens, highway warning signs, railroad signals, aircraft warning beacons, buoys, and lighthouses.

Remote Monitoring. Data monitoring for scientific research or other purposes is often required at sites far from conventional power sources. PV systems can be used as a power source for remote station monitoring and for transmitting meteorological, seismic, structural, or other data.

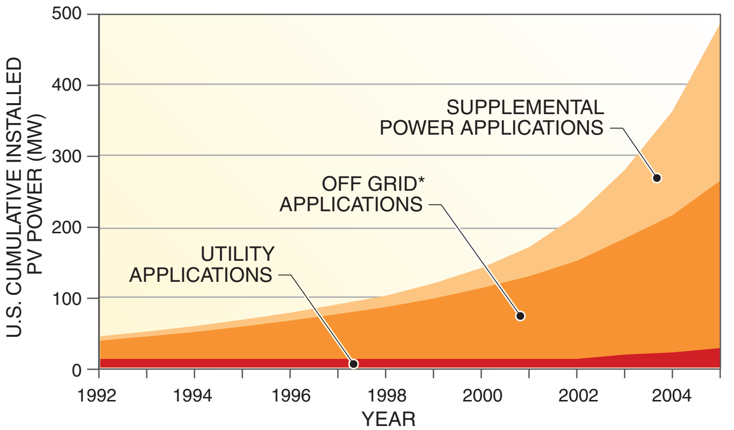
Water Pumping. Many water-pumping needs, such as livestock watering, are in remote areas of a farm or ranch and require the most water during the hottest days. These systems can be directly coupled, with the PV system running the pump during the sunniest times of day. PV-powered water pumping is also used to provide water for campgrounds, irrigation, and remote village water supplies.

Supplemental Power Applications

Systems that are connected to the utility grid and use PV energy as a supplemental source of power offer the greatest flexibility in possible system configurations. **See Figure 1-12.** This is because the size and type of system are not defined by the electricity demand. Being connected to the utility allows the consumer to choose how much supplemental power to derive from alternative sources such as PV systems. The supplemental power offsets a portion of the power needed from the utility, resulting in lower electricity bills.

A PV system may or may not save money in the short-term when competing against inexpensive utility power. However, since installing a PV system for supplemental power is a choice rather than a necessity, owners typically value the advantages of their system beyond purely financial factors. Since supplemental systems are the fastest-growing segment of the PV system market, the additional advantages are clearly very important.

PV System Applications



Source: International Energy Agency

* includes portable and remote applications

Figure 1-12. *Supplemental power systems, most often for single-family homes, are the fastest-growing type of PV system installation.*

PV systems can be used to provide supplemental power to any utility-connected building or structure, including residences, commercial buildings, factories, and institutions. These applications are all similar, except that the systems vary in size. Array mounting systems may also vary because of the differences in construction methods and design of these types of buildings.

Utility-Scale Applications

Utility-scale PV power plants consisting of thousands of modules are not yet common, but are currently being researched as a viable renewable energy option for large-scale electricity generation. **See Figure 1-13.** Initial costs are high and power output varies with the weather, reducing reliability. However, PV systems produce power during daylight hours, when electricity demand is greatest, increasing their value to the utility.

PV technology, as opposed to conventional nuclear, coal-fired, or gas-fired power plants, can provide additional advantages for utility-scale power generation. Utilities can build PV power plants more quickly than conventional power plants because a PV system is simpler and its components are easier to install than those used in other power-generating technologies. The only moving parts of a PV system are in the tracking system, if one is used. PV power plants can be located closer to populated areas than can conventional power plants because they do not involve hazardous materials or cause air, water, or noise pollution. Also unlike conventional power plants, PV power plants can be easily expanded incrementally as demand increases. However, PV power plants require a large area wherever they are located.

Utility-Scale Applications

DOE/NREL, Warren Gretz

Figure 1-13. *PV technology can be used for large-scale power production, but this application is not yet common.*

Unfortunately, PV electricity still costs considerably more in the United States than electricity generated by conventional plants, and the additional cost must be offset by government subsidies or passed on to the consumer. Yet as the technology continues to improve and fossil fuel costs rise, PV power becomes increasingly cost-effective.

PV INDUSTRY

A diversity of knowledge, skills, and abilities are required to design, install, and commission PV systems. The process involves a number of qualified individuals and organizations, each with an important role in ensuring the safe, reliable, and long-term performance of the PV power system.

Like most industries, the PV industry has several levels of business. **See Figure 1-14.** These levels can include a variety of enterprises: large and small, domestic and foreign, and public and private.

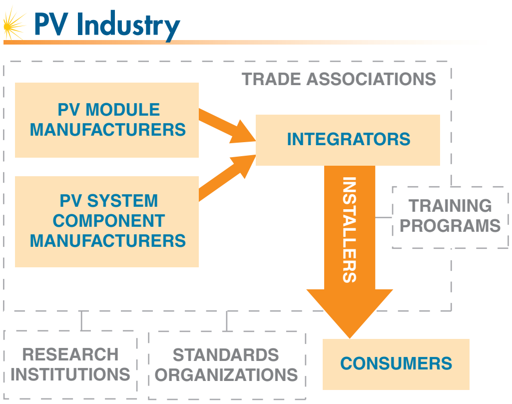
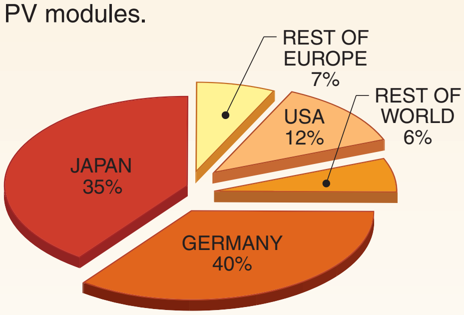


Figure 1-14. *The PV industry is composed of several levels of businesses and organizations.*

World PV Industry

In 1996, the U.S. had 31% of the world's installed PV capacity, the largest share held by any country. By 2005, PV installations in the United States had grown to more than six times the 1996 level, but accounted for only 12% of the world's installed PV capacity. Some other countries have been installing PV systems at a much faster rate than the United States. Currently, the global PV industry is dominated by Japan and Germany. These countries produce and install most of the world's PV modules.



Source: International Energy Agency

TOTAL INSTALLED PV POWER (2005)

The strong growth overseas is driven by progressive incentive policies and high utility rates. Germany currently consumes about half of the worldwide production of solar modules, mostly for utility-connected residences and commercial buildings.

Manufacturers

There are more than 70 PV cell and module manufacturers in the world, representing hundreds of individual manufacturing sites. The equipment needed to fabricate and assemble the PV modules is adapted from the semiconductor electronics industry and specialized for PV manufacturing. Additional manufacturers support the PV industry by supplying the other major components and equipment, such as inverters and mounting systems. These products are used in various types of renewable energy systems.

Electrical equipment manufacturers design, develop, and fabricate the balance-of-system (BOS) components. *Balance-of-system (BOS) components* are the electrical and structural components, aside from the major components, that are required to complete a PV system. BOS components include the conductors, connectors, switchgear, fuses, and hardware that connect, support, or interface between the primary devices such as the array, inverter, and battery system. Electrical BOS components are also common outside the PV industry, as they are used in nearly every electrical system.

Integrators

PV manufacturers do not typically sell directly to consumers wishing to install a PV system. PV system components also are not commonly purchased through distributors or retailers that stock other electrical equipment or building hardware. In between PV manufacturers and consumers are integrators. An *integrator* is a business that designs, builds, and installs complete PV systems for particular applications by matching components from various manufacturers. Integrators typically develop relationships with a small group of manufacturers, who may then offer preferred pricing and referrals to the integrator.

There are more than 170 integrators in the United States alone. Integrators work with homeowners, businesses, organizations, and utilities to design, mount, monitor, and maintain PV systems. They also work with builders and architects to create aesthetically-pleasing buildings using PV systems that meet local codes, standards, and regulations.

Silicon

Silicon is the primary raw material for producing PV cells. Silicon makes up one-quarter of Earth's crust and is found in many minerals, including sand, amethyst, granite, quartz, flint, opal, asbestos, and clay. Even so, silicon is difficult to process into a usable form because it is always combined with other elements.

PV cells use many of the same processing and manufacturing techniques as other semiconductor devices, such as computer chips, so the silicon processing and supply chain is well established. However, the two industries compete for the same supply of processed silicon and the combined demand can exceed the supply. After many decades of progressively lower PV module prices per watt, increasing demand has put pressure on the refined silicon supply. The high demand and limited supply has stabilized or even slightly reversed the price trend. For continued growth in both industries, the silicon supply chain will need to respond with significant capacity increases.

Sharp Electronics Corp.

Quartz mining is a significant source of silicon for the PV industry.

Installers

Installers may be directly employed by an integrator, or by an electrical contractor who specializes in PV installations. Safe and quality PV system installations are essential for the success and acceptance of this emerging technology. Installers, both the contractors and the individual electricians, have important roles in ensuring quality PV installations. **See Figure 1-15.** Installers should exhibit quality electrical craftsmanship and, because of the unique aspects of the equipment and interfacing of PV technology, they should be qualified specifically for installing PV systems. All PV system installers should meet the following criteria:

- Complies with applicable building and electrical codes and standards
- Applies for permits and approvals from local building and utility authorities as required
- Knows his or her capabilities and limitations, and seeks outside expertise as required
- Selects and sizes systems and equipment to meet performance expectations
- Recommends well-engineered, quality components
- Ensures equipment is properly labeled and safety hazards are identified
- Locates and orients array to maximize performance and accessibility
- Mounts array with strong, weather-sealed attachments
- Uses accepted utility-interconnection practices and obtains utility approvals as required
- Completes work in a timely manner while practicing safe and orderly work habits
- Employs safe and accepted methods in the installation and use of PV equipment
- Completes inspections, commissioning, and acceptance tests
- Provides owner/operator with appropriate documentation, instructions, and training
- Provides follow-up service for completed work as required

An experienced installer also has considerable design knowledge and familiarity with many types of PV systems and components and can diagnose and troubleshoot even complex systems effectively. Installers are perhaps the most visible members of the PV industry to the consumers, making it vital that installers be professional and qualified individuals.

Skilled Installers

DOE/NREL, Craig Miller Productions

Figure 1-15. *Skilled and well-trained installers are needed to ensure quality PV system installations.*

Consumers

The consumer, or end user, is the owner of the building or structure powered by the PV system. Consumers include homeowners, developers, and businesses. In some cases, integrators and installers work with agents of the consumer, such as architects, engineers, general contractors, or managers. Consumers drive the growth of the PV industry but may or may not be knowledgeable about PV systems, including the types of features that are available, the advantages and disadvantages of PV power, or how to finance a system. Therefore, much of the marketing effort by the PV industry is aimed toward educating potential consumers about various PV options and incentives.

Organizations

Numerous not-for-profit organizations work to promote and further the PV industry, including organizations involved in research, marketing, installer training, and standards development. These organizations also aim to make systems safer for the installer and the owner/operator.

Research Institutions. In the United States alone, more than 70 universities and three national laboratories are working to further develop the PV industry. Research is also under way in Europe, Japan, and other parts of the world. Research institutions are the underlying force to improve existing PV manufacturing techniques and develop the next generation of technologies. These institutions also educate and train the leaders and high-tech workforce of the future PV industry.

Trade Associations. Businesses within an industry, even competitors, often join together to form trade organizations in order to support each other and promote the industry to the consumer, in an effort to increase the market for all involved. Manufacturers, integrators, and other groups in the PV industry have formed alliances including the Solar Energy Industries Association (SEIA) and Solar Electric Power Association (SEPA). These organizations host trade shows and conferences to facilitate industry contacts and educate the public. Not all businesses belong to trade associations, but most find them to be mutually beneficial alliances.

Installer Training. Training programs on the installation and operation of PV systems are organized by manufacturers, schools, or trade unions. These programs promote quality installations but can vary widely in length and scope, which can make it difficult for consumers to choose a skilled integrator or installer for a desired system. The North American Board of Certified Energy Practitioners (NABCEP) is an organization seeking to standardize installer qualifications.

DOE/NREL, Ajeet Rohatgi

Universities and research institutions are investigating ways to improve the efficiency of PV technologies.

Case Study

IBEW-NECA Technical Institute (Chicago)

Location: Alsip, IL (41.7°N, 87.8°W)
Type of System: Utility-interactive
Peak Array Power: 1.1 kW DC
Date of Installation: Winter 2004-2005 (original installation)
Installers: Apprentices and journeymen
Purpose: Training

The IBEW-NECA Technical Institute (IN-TECH) uses a mixture of permanent and temporary PV systems to train apprentices and journeymen, each with its own strengths. The two permanent installations include a rooftop rack array and an awning-type array cantilevered off a wall. These systems feed into the building's electrical system and serve as ongoing monitoring and maintenance learning tools for commercial-type PV systems. Two temporary systems are based on residential-type sloped single roofs and provide hands-on installation experience. One of the temporary roof systems is unique for two reasons.

First, the system is indoors. The training center is located in a former high school, with a gymnasium that provides a large area to accommodate a section of a residential roof. The roof is sloped about 35°. Although it is only a few feet off the ground, the students work as if it were an actual roof and follow all applicable safety rules, including the use of fall protection harnesses.

IBEW-NECA Technical Institute
Students receive training on every part of installing a PV system, including connecting to utility power.

The system provides a complete training exercise, including routing electrical conduit and connecting the system to the utility. At the back of the roof is a framed wall that supports an electrical panel, inverter, and electric meter. The meter is pre-wired into the building's electrical system with a standard electrical service entrance, as if the PV system was on a detached building with a typical utility connection.

The first part of the training exercise includes configuring the mounting system, attaching the PV modules, wiring the modules together into an array, bending conduit and routing wires from the roof to the electrical panels, connecting the inverter and other components, and testing the system. A row of 12 HID lights mounted to the ceiling and aimed toward the roof simulates sunlight so that the system can be tested under typical outdoor conditions. Loads can be powered from the system for demonstration.

IBEW-NECA Technical Institute
The finished PV system can be tested for performance and used for troubleshooting exercises.

For the second part of the exercise, the instructors test the students' troubleshooting and problem-solving skills. The instructors intentionally create a small problem with the system, such as by disconnecting a conductor or changing the settings on the inverter, and challenge the students to find the problem. The students use test instruments and their knowledge of the system and its operation to determine the cause of the problem and provide the remedy.

The other unique aspect of this system is that the PV installations are infinitely repeatable. After one class has completed training, the system is disassembled for the next class. The modules, mounting system, conductors, conduit, and connectors are completely removed. Only the roof attachment points, empty electrical enclosures, and service entrance remain, and the training exercise begins again for a new class.

NABCEP is composed of representatives from throughout the renewable energy industry and works with the renewable energy and energy efficiency industries and professionals to develop and implement quality credentialing and certification programs for practitioners. NABCEP certification for PV installers, including contractors, supervisors, and journeymen, requires both experience and education, ensuring that certified professionals meet minimum levels of expertise in PV systems and installation. Certification is awarded upon successful completion of an exam.

Standards. Many organizations that develop standards and safety guidelines for the electrical industry are also involved, directly or indirectly, in the PV industry. Several standards organizations publish standards and guidelines related to photovoltaics, including the Institute for Electrical and Electronics Engineers (IEEE), ASTM International, and the International Electrotechnical Commission (IEC). These documents cover standard terminology, module test procedures and conditions, solar radiation measurement, electrical connections, performance, power conditioning, and many other topics.

The National Electrical Code® (NEC®), developed by the National Fire Protection Association (NFPA), is a set of rules on safe practices for the installation of electrical equipment. The NEC® applies to jurisdictions (municipalities, counties, or states) that have adopted it as their governing electrical code, which includes most of the United States and some other countries. The code applies to all electrical systems, including both utility-connected and stand-alone PV systems. Article 690 of the NEC® specifically addresses the design and installation of PV systems and equipment. Article 690 includes definitions, requirements for sizing conductors and circuit protection, disconnecting means, wiring methods, grounding, marking, and connections to other systems.

Product listing organizations test products for safety and conformity to standard requirements. Products that pass are certified, or "listed," as being quality products that match the manufacturer's specifications and fulfill the requirements for safety. These products may then bear the listing organization's mark, which is considered a symbol of quality. Underwriters Laboratories Inc.® (UL®) is the most prominent listing organization and publishes safety and quality standards against which products are tested. **See Figure 1-16.**

Product Listing Organizations

Figure 1-16. *The official mark of a listing organization signifies that a product meets the organization's standards for safety and quality.*

Fossil fuels include oil, coal, and natural gas. Fossil fuels are so-named because they are the result of the decay of organic matter from millions of years ago. The burning of fossil fuels produces carbon dioxide and other toxic substances that contribute to pollution and global warming. Supplies of fossil fuels are limited, and it is becoming increasingly difficult to find and exploit new reserves.

Utilities

Utilities have a unique place in the PV industry. They are the primary producers of the conventionally generated electricity that PV-generated electricity aims to replace, so they compete with PV installations. Utilities operate large, expensive power plants designed for specific generating processes, such as nuclear reactions or burning coal, so they are typically slow to change. However, progressive utilities are also potential PV system owners, as they adopt PV and other renewable energy sources for future growth and eventual phase-out of existing power plants. Either way, utilities are a major part of the PV industry.

Government Policies

To establish an energy portfolio that is sustainable for future growth, state and federal governments, and governments of other countries, have enacted various energy polices. This will become increasingly important as more countries develop and industrialize. Energy demand is expected to continue growing exponentially and new technologies must be available to help meet the demand. **See Figure 1-17.** These policies are primarily aimed at reducing dependency on fossil fuel energy, mandating efficient energy use, and encouraging the development of renewable energy resources. The primary ways in which federal, state, and local governments encourage renewable energy, including photovoltaics, is through incentives and quotas.

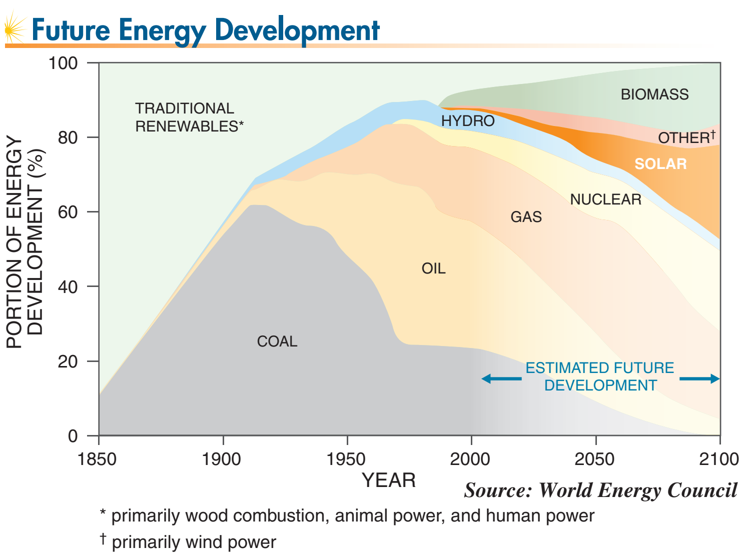


Figure 1-17. *Renewable energy is expected to compose an increasingly larger portion of energy production.*

Incentives. Incentive programs include grants, rebates, renewable energy credits, low-interest or no-interest loans, sales and property tax exemptions, income tax credits or deductions for individuals and corporations, and cash payments based on energy production. Federal programs are available throughout the United States, while state programs vary widely. Even some utilities offer incentive programs in their areas. Online databases of various incentive programs help consumers research available programs for their area.

Quotas. The quota mechanism is a state policy and is typically called a renewables portfolio standard (RPS). An RPS places an obligation on either the state's utilities or the consumers to source a specified fraction of their electricity from renewable energy sources by a certain deadline. For example, California has committed to producing 20% of its electricity needs with renewable energy by 2010. **See Figure 1-18.** Utilities that fail to meet their obligation are required to pay a penalty fee for each unit of electricity short of the goal. This quota mechanism creates or expands the market for renewable energy systems, which drives competition and is expected to lower costs to the consumer.

SOLAR ENERGY TECHNOLOGIES

Photovoltaics is only one of many technologies for utilizing solar energy. Many other methods can make use of solar energy to produce heat, electricity, light, and even cooling. Some techniques have been used by humans since ancient times. For instance, the sun baked bricks into strong building materials, and dried foods for preservation. Wind, a product of solar energy, moved people across oceans. The modern world has built on these technologies to utilize this abundant resource in more efficient and direct ways.

SMA Technologie AG

Combinations of energy sources, such as photovoltaics and wind turbines, provide a balanced supply of energy.

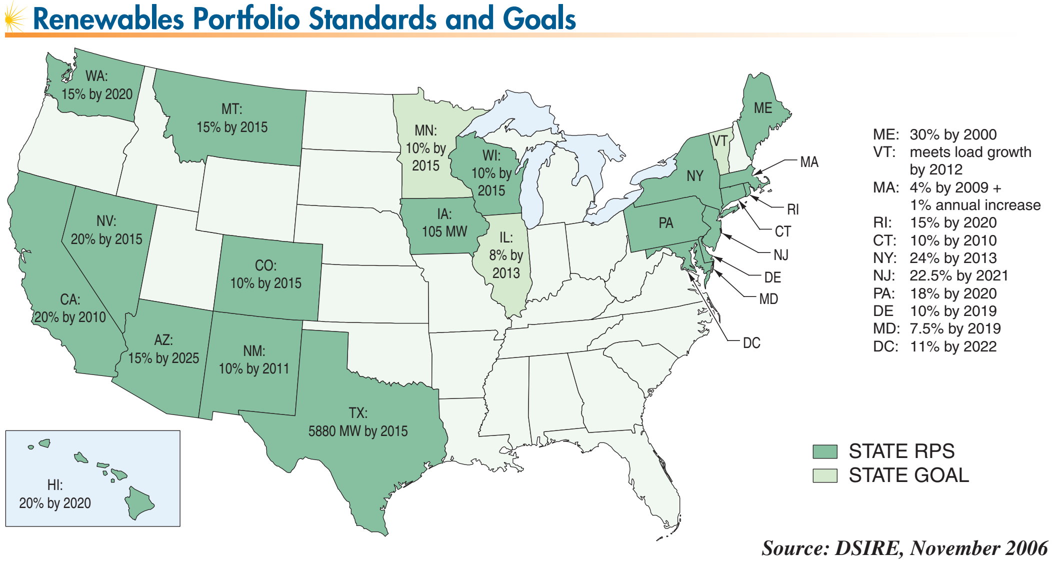


Figure 1-18. *Renewables portfolio standards and goals vary by state.*

Collectors

Most solar energy technologies involve special equipment that is added to or incorporated into a structure to collect, convert, and distribute the energy gained from the sun. A *solar energy collector* is a device designed to absorb solar radiation and convert it to another form, usually heat or electricity. Collectors are also sometimes called receivers. Solar collectors are classified into flat-plate and concentrating collectors according to their ability to utilize the different types of solar radiation.

Flat-Plate Collectors. A *flat-plate collector* is a solar energy collector that absorbs solar energy on a flat surface without concentrating it, and can utilize solar radiation directly from the sun as well as radiation that is reflected or scattered by clouds and other surfaces. Flat-plate collectors may be installed in a fixed orientation or on a sun-tracking mount. Nearly all commercial and residential solar energy installations use flat-plate collectors. **See Figure 1-19.**

Concentrating Collectors. A *concentrating collector* is a solar energy collector that enhances solar energy by focusing it on a smaller area through reflective surfaces or lenses. The high-intensity sunlight is focused onto high-efficiency solar cells or working fluids that transfer thermal energy. Since concentrating collectors utilize only radiation directly from the sun, they must continually track the sun. Concentrating collectors have increased efficiency and reduced size because of the ability to channel more solar radiation onto the desired surface. **See Figure 1-20.**

Renewable energy is a class of energy resources that are replaced rapidly by natural processes. These resources include solar, wind, water, tidal, geothermal, and biomass energy.

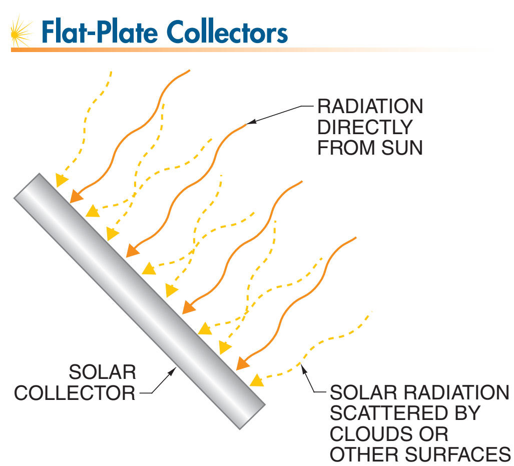


Figure 1-19. *A flat-plate collector can utilize any solar radiation, direct or reflected, that strikes its surface.*

Concentrating Collectors

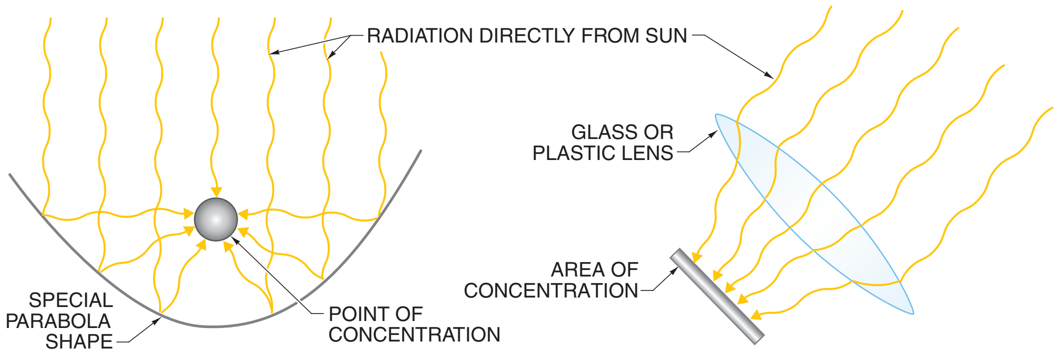


Figure 1-20. *Concentrating collectors focus a large area of direct solar radiation onto a relatively small area.*

Solar Architectural Design

Many of today's buildings and homes are built with energy conservation and natural resources in mind. Passive solar design techniques incorporated into architecture decrease the amount of energy needed for lighting, heating, cooling, and other loads. The most influential design option is to thoroughly insulate and seal the building envelope. This involves thicker walls, more insulation, sealing joints and transitions, double-pane windows, and other features. Walls and roofs made with stone, concrete, or similar materials draw in and hold heat. These measures can significantly reduce the heating and cooling loads necessary to condition the indoor spaces since less energy can escape through the building envelope to the outside environment.

Positioning windows to face south allows maximum sunlight and heat into the building. **See Figure 1-21.** If too much sun during the summer is an issue, deciduous trees can be planted to shade windows in warm weather, reducing cooling loads, but allowing sun through in cool weather when the leaves fall. Awnings can also be used to create shade in the summer and allow exposure to sun in the winter.

Solar Thermal Energy

Solar thermal energy systems convert solar radiation into heat energy. Most systems use working fluids that are heated by the sun in solar collectors. Either flat-plate or concentrating collectors can be used. The heat in the fluid is then distributed to a reservoir to store the heat energy, or to other parts of the system to utilize the heat energy.

Solar Architectural Design

DOE/NREL, Warren Gretz

Figure 1-21. *Solar architectural design uses building materials or design techniques to provide light and comfortable temperatures inside a building.*

Solar Thermal Heating. Solar thermal heating collectors are dark-colored containers for the working fluid that convert absorbed solar radiation into heat and transfer the heat to the working fluid. **See Figure 1-22.** The fluid is usually an antifreeze and water solution, but it may be plain water if there is no danger of freezing. If used for space heating, the fluid could even be air. The fluid may be heated in batches, in which case the collector also stores the fluid until it is needed. Alternatively, the heated fluid may be pumped through the collectors and stored in a separate reservoir.

Solar Thermal Energy Collectors

DOE/NREL, Alan Ford

Figure 1-22. *Solar thermal energy is a relatively simple way to provide domestic hot water or heating.*

Solar thermal heating systems can be scaled for many different applications, but are primarily used in residences to heat water and living spaces. The working fluid may be used to directly warm the home through radiant floor heating, or the heat may be transferred to water or air through heat exchangers. Solar thermal energy can even be utilized in the winter in northern climates, though a supplemental heat source may be needed to fully heat the fluid on cold days.

Solar thermal heating systems can be classified as passive or active. In passive systems, the working fluid circulates through the solar collectors and the rest of the system by convection without the use of mechanical equipment. In active systems, fans and pumps are used to circulate the fluid.

Solar Thermal Cooling. Solar thermal cooling uses the heat energy to power a refrigeration cycle. The heat energy is used to compress a gas, which, when expanded in another part of the system, cools a set of coils. Air blown over the coils cools and is used to air-condition the building. This process requires an extremely hot working fluid, so it is not yet an efficient process except in the sunniest climates, but improvements continue.

Solar Thermal Electricity. Solar thermal energy can also be used to produce electricity, though the processes use working fluids in different ways. The most common types of systems rely on concentrating solar power.

Concentrating solar power (CSP) is a technology that uses mirrors and lenses to reflect and concentrate solar radiation from a large area onto a small area. The energy is then used to heat working fluids or materials that will be used to produce electricity. These systems are complex to build, so they are only feasible for utility-scale power plants. The three main styles of CSP plants include trough collectors, dish collectors, and power towers. **See Figure 1-23.**

DOE/NREL, Warren Gretz

Large reflecting units for concentrating solar systems are often composed of many small mirrors, which allows for easy replacement of broken parts.

Parabolic trough collector systems are the most common and cost efficient. A curved trough focuses sunlight on an absorber tube. The trough is rotated throughout the day to maximize the received solar energy. The absorber tube is filled with fluid, typically oil, which becomes very hot. The oil is then passed through a heat exchanger that transfers heat to water, which boils and produces steam. The steam is used to drive steam turbines that produce electricity.

A dish collector is a large, reflective, parabolic dish that focuses light from a large area onto a single point above the dish. At that point, the intense sunlight heats a working fluid. The resulting heat energy is then converted into electricity in the same way as in trough collector systems.

Power tower systems use a large number of mirrors to concentrate sunlight on a target at the top of a tower. The target, or receiver, is filled with fluid to absorb the resulting intense heat. The fluid is commonly molten salts, which have the ability to hold large amounts of heat. The heat energy can then be transferred to water to produce steam that drives steam turbines. Power tower designs have also been used to directly heat water into steam, eliminating the molten sodium step, but this system cannot produce electricity after sunset. The salts, however, hold heat for hours and can continue to produce steam at night.

Solar Cooking. Solar cookers use energy from the sun to heat food or beverages. The container of food or liquids essentially becomes the solar thermal collector. Solar cookers are made with reflectors that direct and concentrate light into the inside of a dish- or box-shaped cooker. The cooking vessel is dark in color to absorb the maximum amount of heat. Food to be cooked is placed inside the solar cooker, just as if it were an ordinary oven.

Solar Chemical Energy

Utilizing solar energy directly through chemical processes is a less-developed technology, but is of great interest as a future energy source. Scientists expect to be able to harness solar energy in chemical reactions in a manner similar to how plants use solar energy through photosynthesis. The energy might then be released through reverse reactions.

Concentrating Solar Power

DOE/NREL, Dave Parsons

TROUGH COLLECTOR

DOE/NREL, Warren Gretz

DISH COLLECTOR

DOE/NREL, Sandia National Laboratories

POWER TOWER

Figure 1-23. *The intense solar radiation needed to produce electricity from thermal energy requires solar concentrating systems.*

However, an indirect use of solar chemical energy is through biofuels. Plants grow and produce chemicals by utilizing solar energy. Many of the oils found in plant seeds are chemically similar to petroleum and can be similarly refined into fuels. For example, biodiesel is a fuel that can be made from sources such as soybeans, waste vegetable oil, or even animal fats, and is compatible with any existing diesel engine. Biodiesel also burns cleaner than petroleum-based diesel. Similarly, ethanol fuel can be produced from corn and burned in modified gasoline engines.

Solar Lighting

Solar lighting includes equipment and techniques to direct natural lighting into a home or building. Increasing the amount of natural light indoors is more environmentally sound and easier than using grid electricity. Some of the methods could be considered one aspect of solar architectural design, such as window placement, but solar lighting can also include special materials or components to bring additional light indoors. For example, fiber-optic light pipes can bring sunlight into almost any indoor space and from any direction.

Summary

- Photovoltaics (PV) is a solar energy technology that uses the unique properties of semiconductors to directly convert solar radiation into electricity.
- Many advantages and benefits add value to PV systems beyond the potential economic savings.
- Photovoltaics is an environmentally friendly technology that causes no noise or pollution.
- Currently, the most significant disadvantage of PV systems is the high initial cost compared to prices for competing power-generating technologies.
- The photovoltaic effect was discovered long before it was used for the generation of electricity.
- Improvements in cell efficiencies and manufacturing methods are reducing the cost of PV systems.
- Higher costs for conventional electricity-generating technologies help make PV and other renewable energy systems more cost-effective.
- Space applications were the first practical use of PV technology.
- PV systems are particularly well-suited for portable and remote applications.
- Supplemental power systems are the fastest-growing application of PV systems.
- Utility-scale PV power plants are not yet common, but are being studied for future widespread use.
- There are many levels of business and organizations that support the PV industry.
- Skilled installers are critical for quality installations and good public perception of the PV industry.
- Government renewable energy policies support further development and growth of the U.S. PV industry.
- Flat-plate collectors absorb solar energy from many directions on a flat surface without concentrating it.
- Concentrating collectors focus solar radiation from a large area onto a small area that contains special PV cells or heat-absorbing materials.
- Integrating solar energy design techniques into architecture is an example of a passive solar energy technology.
- Solar thermal energy is an efficient use of solar radiation that can be utilized in many ways.
- Solar thermal energy can be converted into electricity, though only on a large scale that is impractical for residential and commercial applications.
- Sunlight can be used for natural lighting in almost any indoor space by using fiber optics.

Definitions

- ***Photovoltaics*** is a solar energy technology that uses unique properties of semiconductors to directly convert solar radiation into electricity.
- A ***photovoltaic (PV) system*** is an electrical system consisting of an array of one or more PV modules, conductors, electrical components, and one or more loads.
- A ***load*** is a device that consumes electricity.
- A ***utility*** is a company that produces and/or distributes electricity to consumers in a certain region or state.
- The ***grid*** is the utility's network of conductors, substations, and equipment that distributes electricity from its central generation point to the consumer.
- ***Distributed generation*** is a system in which many smaller power-generating systems create electrical power near the point of consumption.
- ***Balance-of-system (BOS) components*** are the electrical and structural components, aside from the major components, that are required to complete a PV system.
- An ***integrator*** is a business that designs, builds, and installs complete PV systems for particular applications by matching components from various manufacturers.
- A ***solar energy collector*** is a device designed to absorb solar radiation and convert it to another form, usually heat or electricity.
- A ***flat-plate collector*** is a solar energy collector that absorbs solar energy on a flat surface without concentrating it, and can utilize solar radiation directly from the sun as well as radiation that is reflected or scattered by clouds and other surfaces.
- A ***concentrating collector*** is a solar energy collector that enhances solar energy by focusing it on a smaller area through reflective surfaces or lenses.
- ***Concentrating solar power (CSP)*** is a technology that uses mirrors and lenses to reflect and concentrate solar radiation from a large area onto a small area.

Review Questions

1. Compare the advantages and disadvantages of installing a PV system.
2. Compare the design priorities of PV systems for space, portable, and supplemental-power applications.
3. What are some advantages to using PV technology to build utility-scale power plants?
4. How is installer training vital to the continued growth of the PV industry?
5. Why are concentrating collectors more efficient than flat-plate collectors?
6. Explain the two main technologies that can convert solar radiation into electricity.