Solar Energy.

Authors: Plitnik, George R., B.A., B.S., M.A., Ph.D.

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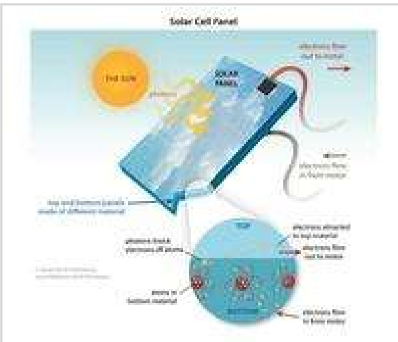
Summary

Solar energy is the energy from the sun that is captured and used to heat homes or provide electricity. The three main types of solar energy systems are passive, in which solar energy is stored without using any other energy source; active, in which electricity is used to capture the sun's energy; and photovoltaic, which directly converts sunlight into electricity. Although solar energy is free in that costs are not involved in generating it, it is not constant and must be captured and stored. Also, the systems used to capture solar power remain expensive.

Definition and Basic Principles

Solar energy is light from the sun that has been converted into heat energy or electricity. The three most common conversion methods are passive systems, which collect and store solar energy without the use of any other source of energy and using few or no moving parts; active systems, which collect and store energy by employing electric energy; and photovoltaic systems (PV), which convert sunlight into electricity. Both passive and active systems use glass to admit sunlight and prevent heat from escaping and mass to store the heat collected. The four types of passive systems are direct gain, indirect gain, attached gain, and thermosyphon. Active systems either collect sunlight directly on flat surfaces or use parabolic reflectors to achieve high temperatures by focusing the light. Either air or water may be used to transfer the heat from the collector to storage.



Solar Cell Panel: The solar cell panel collects energy from the sun and can provide electric energy. © EBSCO

PV systems use arrays of photocells to transform solar radiation directly into DC (direct current) electricity. The photocells, typically semiconducting silicon crystals, act as insulators until illuminated by radiant energy. The material then conducts electricity, effectively making each cell a small battery. By connecting photocells into large modular arrays, sufficient electric energy can be generated to power homes or, when sufficient modules are present, to produce electricity for a centralized power plant. Small PV systems may use battery storage or tie into the electric grid to allow energy to be withdrawn when needed or fed into the grid when not necessary.

Although solar energy is free energy in that there is no cost to generate it, it has several disadvantages. It is diffuse and intermittent, and it must be stored. Also, active collection devices are constructed of expensive nonrenewable resources such as aluminum and copper.

Background and History

Solar energy has always provided, directly or indirectly, virtually all of humanity's energy. Ancient Greek homes were oriented toward the south, and early Chinese architecture incorporated solar design to heat interior spaces. By the first century BCE, Rome had added clear glass windows to Greek solar designs to trap the heat, thus creating the first true passive solar design. The sun was also used to heat water entering the huge public baths indigenous to Roman society.

After the fall of Rome, solar architecture was forgotten until the sixteenth century, when greenhouses were used to grow exotic fruits and vegetables in northern Europe. By the eighteenth century, large glass windows enabled the construction of better greenhouses, which evolved in the nineteenth century into ostentatious conservatories for displaying exotic plants.

Active systems that focused sunlight to produce high temperatures were developed in the nineteenth century. Domestic hot water systems were first built and marketed in the early twentieth century. By mid-century, active systems using air to heat homes appeared, but their acceptance was limited because of their high costs.

Photovoltaics (PV) trace their origin to the late 1880s when Charles Fritts (1850–1903) developed a solar electric cell using germanium crystals, but commercial development stagnated until the 1950s when Bell Laboratories produced a viable but costly silicon-based system to power remote communication devices. The National Aeronautics and Space Administration (NASA), needing lightweight reliable energy sources for its nascent space program, adapted these PV systems for its first satellites, launched in the late 1950s.

In the 1970s, because of the oil embargoes and rise in fuel prices, solar energy began to capture the interest of the public. However, the decline in oil prices in the 1980s produced a drop in the interest in solar power. Since the mid-1990s, solar water heating systems have grown at an average annual rate of 20 percent, rendering solar water heating the most widely deployed solar technology of the early twenty-first century.

How It Works

Although less than half of the solar radiation that reaches the Earth is available for human use (some is absorbed by the atmosphere, land, and oceans, and some is radiated back to space), this amount is prodigious enough to provide for all human energy needs if it could be efficiently captured. Because solar radiation is dilute and noncontinuous, large collector areas are necessary, and storage devices must be integrated. Photovoltaic systems convert radiation directly into electricity, and solar thermal units collect energy for interior spaces or water heating. Passive systems convert sunlight directly into interior space heating, and active heating systems require electricity to power pumps or fans. Active systems may be subdivided into those that use flat-panel stationary collectors and those that focus incoming solar rays to achieve temperatures high enough to create steam.

Photovoltaic. Photovoltaic cells transform solar radiation directly into electricity. The cells consist of two types of silicon crystals in which bound electrons are energized into a conducting state when irradiated by light. The freed electrons cross the junction between the two crystals more easily in one direction than the other, thus creating negative and positive surfaces, the basis of a battery. This photobattery provides direct current (DC) electricity. The brighter the irradiating light, the greater the current. By connecting large arrays of such cells, a solar module, which typically can provide 170 watts per square meter of surface area at 14 percent efficiency, is created.

Solar panels that are used to power homes and businesses are typically made from modules holding about forty cells. A typical house requires an array of ten to twenty solar panels to provide sufficient power. The panels are mounted at a fixed angle facing south, or they can be mounted on a tracking device that follows the sun, allowing them to maximize solar energy capture. For large electric facility or industrial applications, hundreds of solar arrays are interconnected to form a large utility-scale photovoltaic system.

Passive Solar Heating. Passive solar heating systems use south-facing glass windows to collect solar energy and a room's interior mass to store energy and regulate temperature swings. The three main types of passive systems are direct, indirect, and attached gain. Direct-gain systems incorporate ample interior mass for storage, and indirect-gain systems require a massive wall positioned directly behind the south-facing glass. Attached-gain systems consist of a greenhouse, accessible to the house, attached to an exterior southern wall. When the greenhouse is warm, the doors can be opened to heat the house. A fourth system, the thermo-siphon, uses flat-plate collectors to heat water and a storage tank located above the collector top. Heated water rises by natural convection into the storage tank, creating a siphon effect that keeps the fluid circulating. Because no electricity is used, this constitutes a passive system.

A well-designed passive system, in addition to double-paned south-facing glass and interior mass, includes movable insulation to cover the windows at night, overhangs above the windows to keep out the summer sun, and sufficient house insulation to minimize heat loss.

In direct-gain systems, the thermal mass, incorporated into a floor or wall, is typically brick, tile, or concrete. The mass must be sized to the total area of south-facing glass—the greater the area of glass, the greater the mass required to prevent overheating the room. Indirect gain systems use a massive wall of brick or barrels of water located in proximity to the south-facing glass. The outside-facing surface of the mass is painted black to effectuate solar gain stored in the mass. The heat is released through vents into the interior living space by natural convection; at night, the vents are closed, preventing convective heat loss, while the mass radiates heat into the interior space.

Attached gain, or greenhouse, systems are usually entirely glass with concrete or soil serving as the mass. When properly designed, an attached greenhouse can be used to provide food as well as heat during the winter. A different application of passive solar is the thermal chimney ventilation system, consisting of an interior vertical shaft vented to the exterior. When the chimney warms, the enclosed air is heated, causing an updraft that draws air through the building.

Active Solar Heating. Active solar heating systems transfer a sun-heated fluid (air or water) from an exterior south-facing collector to the point of use or to a storage facility. In air systems, the storage facility is a bed of rocks, and in water systems, tanks of water.

In addition to the collector and storage feature, active systems include a pump or fan to circulate the fluid and a differential thermostat that regulates fluid flow to those times when the collector is at least 10 degrees Fahrenheit hotter than the storage facility. Active systems may be used to heat interior space or to produce domestic hot water. The circulating fluid for domestic hot-water systems is always water, and the storage unit is a water tank. Space heating units may circulate either air or water, but air systems are more common.

Solar flat-plate collectors consist of a rectangular box containing a black metallic plate covered by nonreflecting tempered glass. In water systems, tubes to conduct water are soldered to the plate, and in air systems, small channels direct the air. When the sun strikes the black surface, light is changed into heat, which is transferred to the fluid moving across the heated surface. For maximum efficiency, collectors should be oriented directly south and set at an angle (from horizontal) equal to the local latitude (for domestic hot-water systems) or latitude plus 10 degrees (for space heating systems).

Both space heating and domestic hot-water systems use water mixed with propylene glycol antifreeze as the circulating fluid, propelled by a pump. Heat from the fluid is transferred to the hot-water storage tank through a heat exchanger, to be used for domestic hot water or as preheated fluid for hydronic baseboard heating systems.

When air is used as the working fluid, excess heat is stored either in smooth rocks or in a phase-change material. Rock storage consists of a 280-cubic-foot bin of 1-inch-diameter smooth rocks weighing 7 tons. When the collector is warmer than the house, a fan pumps the air directly from the collectors into the house. When heat is not required, air is directed through the rock bin, transferring the heat into the rocks. At night, air from the house can be circulated through the rocks to reclaim the stored heat.

Focusing Collectors. Concentrated sunlight is realized in one of two ways: troughs of parabolic mirrors that focus sunlight to an oil-filled tube positioned along the focal line, or huge assemblies of mirrors that reflect sunlight from a large area to a small central receiver. Either method may be used in a solar thermal power plant, where the concentrated radiation is used to produce high-temperature steam that drives a turbine to create electricity. A solar furnace is a type of focusing collector employing parabolic curved mirrors to concentrate sunlight to a focal point to generate extremely high temperatures.

Applications and Products

Photovoltaic Systems. Because PV cell arrays are expensive, the cost of the electricity produced in photovoltaic systems has traditionally exceeded the cost of fossil fuel electricity. Since the mid 1970s, however, the cost has consistently decreased so that by 2014, the cost per kilowatt of photovoltaic electricity was comparable to fossil fuel costs. Low market penetration, new technology, and insufficient economies of scale have inhibited even lower costs for PV systems, and prices have continued to drop as research raises the conversion efficiency of PV cells. By 2020, the cost of energy for PV solar was 82 percent less than the 2010 cost. As one of the most rapidly growing alternate energy sources with production doubling every two years since about the 1980s, it is projected that solar installations will continue to increase and the cumulative world capacity will continue to rise. In 2019 the global solar capacity had risen to 580 gigawatts.

Although individual household PV modules are more expensive per kilowatt than large centralized PV power plants, individual units become cost competitive when distribution costs are eliminated. Between 2010 and 2019, solar module costs fell dramatically by 90 percent—a trend projected to continue, particularly in regions with ample sunlight, expensive fossil fuel electricity, and government incentives.

Traditionally solar cells have been made from pure crystalline silicon doped with boron or phosphorus. The manufacturing process is not inexpensive, and the conversion efficiency rarely exceeds 15 percent. Research on using amorphous silicon has led to less expensive PV cells but these cells have considerably lower efficiencies of less than 6 percent. Nevertheless, PV laminates composed of thin nonreflective layers of amorphous silicon photocells coated on flexible plastic have been made into roofing material. With such panels, a dual function is served: Roofs are weather-protected with material that generates electricity whenever the sun shines. Because PV modules have no moving parts and low maintenance, these systems are projected to last at least thirty years, the typical lifetime of quality roofing shingles. If the excess energy is stored in rechargeable batteries, it would be possible for homeowners to eliminate their reliance on the grid. Alternately, if the PV system is integrated with the grid, the need for a large bank of storage batteries is eliminated. Excess electricity is sent back into the grid for credit, and the grid provides for nighttime or cloudy weather requirements.

Worldwide, the trend through the 2000s has been toward ever larger scale centralized PV power stations, as typified by the large-scale, 550-megawatt solar park in Charanka, India, which was the first of its kind in the country, completed in 2012 and later expanded. The 550-megawatt facility in San Luis Obispo, California, called the Topaz Solar Farm, was completed in 2014. The following year, Solar Star in Rosamond, California, was complete and was at the time the world's largest solar farm with 1.7 million solar panels.

Since batteries are not practical as a backup supply in large-scale applications, storage is achieved using excess energy to pump water from a lower elevation reservoir to a higher one; the energy is reclaimed by releasing the water through a hydroelectric generator. By judiciously pairing PV systems with wind energy and biogas generators, a twenty-four-hour supply of renewable electricity can be virtually guaranteed. Such a system has been successfully pilot tested by the Institute for Solar Energy Supply Technology at the University of Kassel, Germany.

Passive Solar Heating. Daylighting systems collect and disperse sunlight into interior spaces using skylights, clerestory windows, and light tubes. Physiological and psychological benefits accrue when natural lighting replaces artificial, and the necessity of summer air-conditioning to eliminate waste heat from incandescent bulbs is reduced. Properly implemented systems can reduce lighting related energy consumption by 25 percent.

Integrated passive systems that combine solar heating, ventilation, and lighting, tailored to the local climate, create well-lit spaces maintaining a comfortable temperature with minimal use of fossil fuel energy. For agriculture, greenhouses have been superseded by less expensive tunnels of polyvinyl covering rows of crops to support winter growth.

Another application, still in the experimental stage, is the solar pond, a pool of saturated saltwater at least six feet deep that collects and stores solar energy. The concentration of salt increases with depth, preventing convection currents and allowing the temperature to increase with depth. An experimental pond near the Dead Sea was able to achieve temperatures approaching 200 degrees Fahrenheit at its bottom layer. When used to drive a heat engine to produce electricity, the overall efficiency was 2 percent.

Solar cookers use solar radiation for cooking, drying, and pasteurization. The simplest solar cooker consists of an insulated container with a transparent cover that can achieve temperatures as high as 300 degrees Fahrenheit. More elaborate cookers, using focusing mirrors, can achieve temperatures of 600 degrees Fahrenheit in direct sunlight.

Active Solar Heating. Solar thermal technologies can be used for water heating, space heating, air-conditioning, and process heating. The most common types of solar water heaters are glazed flat-plate collectors, evacuated tube collectors to achieve higher temperatures, and unglazed flat-plate collectors used to heat swimming pools. By 2018, the global capacity of these systems totaled 482 gigawatts, with China being the greatest consumer by far, installing a total of over 330 gigawatts of solar water heating. Over 90 percent of homes in Israel and Cyprus use solar domestic hot-water systems, while in the United States and Australia, the main application is as heaters for swimming pools.

Solar distillation, operating by passive, active, or hybrid modes, is used to make saltwater or brackish water potable. Water for household use or storage may be easily disinfected by exposing water-filled bottles to sunlight for several hours. More than 2 million people in developing countries disinfect their daily drinking water by this method. In small-scale sewage treatment plants, solar radiation is an effective means of treating wastewater in stabilization ponds without employing chemicals or using electricity.

Phase-change materials, such as Glauber's salt (sodium sulfate decahydrate), store energy by transforming from solid to liquid at a temperature of about 85 degrees Fahrenheit. Heat from the sun is absorbed by melting the salt; when the temperature drops below the melting point, the salt resolidifies, releasing the stored heat.

Concentrating Collectors. Hybrid solar lighting systems use sun-tracking focusing mirrors and optical fiber transmission to provide interior lighting. Typically half of the incident sunlight can be transmitted to rooms, where it replaces or supplements conventional lighting.

The Solar Kitchen, located in Auroville, India, uses a stationary spherical reflector to focus light to a linear receiver, perpendicular to the sphere's interior surface, where steam, used for kitchen process heat, is produced.

A solar concentrating device developed by Wolfgang Scheffler in 1986 produces temperatures between 850 and 1,200 degrees Fahrenheit at a fixed focal point by means of flexible parabolic dishes that track the sun's diurnal motion and adjust curvature seasonally. By 2008, more than 2,000 large Scheffler cookers had been built, most used for cooking meals. The world's largest system, in Rajasthan, India, can cook up to 35,000 meals daily.

Another application, developed by Sandia National Laboratories, combines high temperatures from focusing collectors with a catalyst to decompose carbon dioxide into oxygen and carbon monoxide. The carbon monoxide can then be reacted with hydrogen to produce hydrocarbon fuels.

In the United States, the first commercial concentrating system, Solar Total Energy Project (STEP), was developed in Shenandoah, Georgia. This system was developed as part of the National Solar Thermal Energy Program that was instituted in the 1970 during the oil crisis, and STEP was jointly financed by Georgia Power and the US Department of Energy. In Southern California, a system of parabolic trough collectors heats oil in tubes along the focal line. The heated oil is used to produce steam to power a generator.

Central receivers, or power towers, use an extended assembly of moveable sun-tracking mirrors to reflect sunlight to a small region on top of a tower, where temperatures between 1,000 and 2,700 degrees Fahrenheit provide the motive power to produce electricity. The first large-scale demonstration facility, constructed in southern California in 1982, was a 10-megawatt plant, later increased to 200 megawatts, at a cost competitive with fossil fuel plants. Shortly after this plant proved its feasibility, additional commercial units in the 30- to 50-megawatt range were constructed in the southwestern United States, Spain, Italy, Egypt, and Morocco. By the end of 2013, several new large thermal solar generating stations became operational in the United States, which more than doubled the generating capacity. Abengoa's Solana plant, which was constructed in Arizona, produces 250 megawatts of energy, and Bright Source in California's Mohave Desert produces over 390 megawatts. More large-scale additions were completed in 2015 and 2016, and in 2014, Iraq successfully experimented with several versions of small-scale power towers with the goal of collecting and redirecting solar energy to produce steam for power generators. Thermal storage is provided by molten nitrate salts pumped from a cold reservoir to a hot reservoir by excess solar energy. The stored energy is used to produce superheated steam for the electric generation system when the tanks are emptied. The high-temperature storage increases the efficiency of electrical conversion, making these systems competitive with coal-burning plants.

The world's largest solar furnace, constructed in 1970 in the French Pyrenees mountains, where annual sunlight exceeds three hundred days, consists of an array of 63 flat moveable mirrors that reflect sunlight into a huge curved mirror. The mirror, covering one entire side of a multistoried building, consists of 9,600 curved glass reflectors totaling an area of 20,000 square feet. This mirror focuses the light onto an area of about 1 square foot, where the 1,000 kilowatts of power delivered creates a temperature in excess of 5,400 degrees Fahrenheit. Furnaces of this type are primarily used for research in the high-temperature properties of metal oxides or in exposing materials to intense thermal shock.

Careers and Course Work

By the middle of the twenty-first century, solar power is likely to be the dominant global energy resource; consequently, numerous new career opportunities await those with technological interests and skills. One of the fastest-growing jobs in the country, in fact, is solar PV installers; according to the US Bureau of Labor Statistics, employment of PV installers was expected to grow by more than 50 percent between 2019 and 2029. If a student finds that their college or university does not offer an undergraduate major in solar energy, those wanting to enter the field can major or minor in electrical engineering, mechanical engineering, or physics. To obtain a job as a PV installer, a course in photovoltaic systems at a technical school or community college, or other experience in the construction industry, may be all that is necessary.

The Research Laboratory of the University of Central Florida (Cocoa), in addition to researching PV materials, conducts solar thermal systems testing. Other US research programs are found at Georgia Institute of Technology, North Carolina State University, and the Universities of Wisconsin, Texas, Delaware, Oregon, and Arizona.

Social Context and Future Prospects

Every day, the Earth receives ten thousand times more energy from the sun than humans consume from fossil fuels. As fossil fuels are depleted and the pollution produced by them becomes increasingly problematic, sustainable alternate energies, with the sun as a major provider, will become the planet's viable energy future. The increased use of solar energy will require two economic shifts, supply and demand. First, the pressure to shift to clean, renewable energy supplies is mandated by the increased costs to society of continued reliance on polluting nonrenewable fuels. Second, a move away from large centralized power plants to increased reliance on smaller locally generated energy providers is anticipated. Several indirect benefits of the world's transition to a solar economy include the creation of wealth in underdeveloped countries rich in solar resources, improved homeland security through reductions in energy imports, reduced pollution and lessened effects on the global climate, and the ready availability of potable water through desalination plants.

During the first decades of the twenty-first century, it became apparent that several crises were converging. As the world's population increases, obtaining the basic necessities of life, such as food and water, becomes progressively more problematic for underdeveloped nations. At the same time, the global demand for energy is accelerating as fossil fuel resources are being depleted and global warming threatens ultimately to render Earth uninhabitable. Arguably, the best course for humanity is to convert to sustainable food production and energy use. Solar energy, in all its myriad forms, is uniquely positioned to accomplish this transition, if people have the fortitude to endure temporary deprivation so as to ultimately abide harmoniously with the natural environment.

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