THE SCIENCE OF SOLAR ENERGY

by Arnold Ringstad

The Science of RENEWABLE ENERGY

CONTENTS

IMPORTANT EVENTS IN THE DEVELOPMENT OF

SOLAR ENERGY

1958
The *Vanguard 1* satellite becomes the first space vehicle to use solar power.

1970s
Political conflicts over oil drive an interest in alternative energy sources, including solar power.

1950 | 1960 | 1970 | 1980 | 1990

1954
The modern history of photovoltaics begins as scientists demonstrate the first practical solar cell.

1987
The World Solar Challenge, a long-distance solar car race, begins in Australia.

1973
The University of Delaware builds Solar One, a home designed to demonstrate the potential of solar power.

1982
The 1-megawatt Arco Solar power plant in California opens.

1976
The first solar-powered calculator, the Sharp EL-8026, is released.

CHAPTER 1

HOW DOES SOLAR POWER WORK?

Solar energy is perhaps the most direct way by which people harness the power of sunlight. PV panels turn that light into electricity, and solar thermal systems make use of the Sun's heat. But these are not the only energy sources that originate with the Sun. In fact, nearly all of the energy we use ultimately comes from the Sun. The Sun's heat creates Earth's weather patterns, making the breezes that spin wind turbines. Its energy also drives the water cycle, creating the fast-flowing rivers that power hydroelectric plants. Even fossil fuels, formed when the remains of ancient plants were compressed over millions of years, received their original energy input from the Sun. In the process of **photosynthesis**, those ancient plants took in sunlight to keep themselves alive. When fossil fuels are burned today, that same energy is being released. So, studying the Sun

WORDS IN CONTEXT

photosynthesis
The process by which plants take in carbon dioxide, water, and sunlight and use them to produce oxygen and food.

is important to understanding not only solar power, but also nearly all human energy use.

Solar Science

The Sun is a star. It is one of hundreds of billions of stars in our galaxy. The Sun dominates its nearby area, known as the solar system. Eight planets—including Earth—and thousands of smaller objects, such as asteroids and comets, orbit the Sun. The Sun has a mass more than seven hundred times greater than that of all the planets combined.

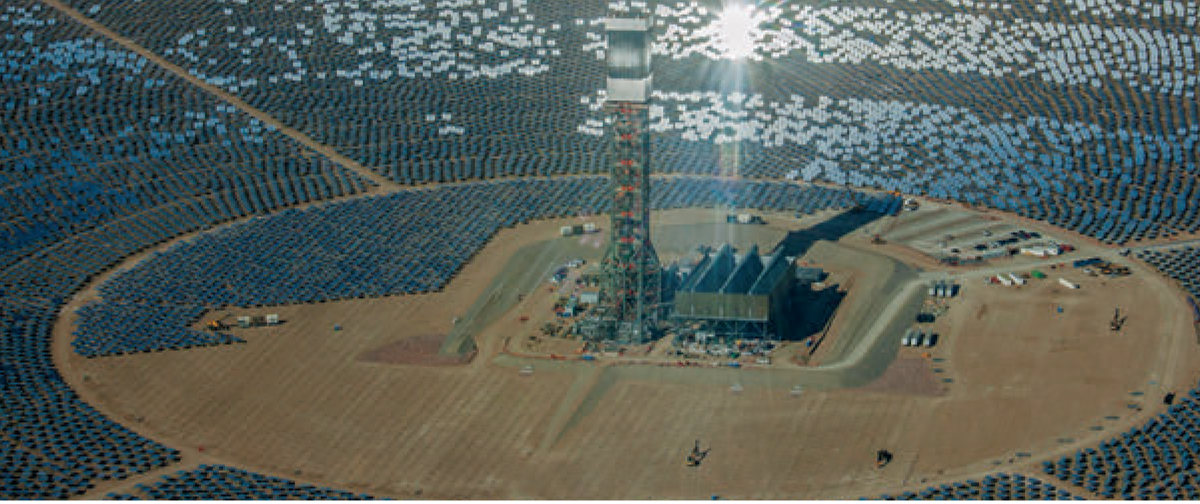
The Sun's enormous mass means that it has extremely strong gravity, and the force of this gravity pulls the Sun's mass inward. The result is a very hot, dense object. At the Sun's core, temperatures reach at least 27 million°F (15 million°C). These extreme conditions make it possible for a reaction called nuclear fusion to occur. In nuclear fusion, hydrogen atoms smash against each other, combining to form helium atoms. The new helium atom has a smaller mass than the individual hydrogen atoms did, and this extra mass is released as energy. The Sun is made up of about 90 percent hydrogen, providing enough fuel to power its fusion for billions of years into the future.

Some of the energy released by the fusion process comes in the form of photons, or individual units of light. They travel outward from the Sun's core, but the extreme density within the Sun means that the photons can travel only a few millimeters before colliding with an atom. When this happens, they may be absorbed and emitted again. This occurs repeatedly, with the photons taking what scientists call a

While solar water heaters come in sizes both large and small, concentrating solar power installations have generally been built only at power-plant scale. These large power stations are significantly more complex than solar water heaters. CSP engineers must design and arrange a series of mirrors or lenses, select materials that can handle extreme temperatures, and find a way to efficiently turn that heat into electricity. CSP plants typically have a generating capacity of 100 megawatts or more.

The Ivanpah Solar Plant in California is an example of one of these CSP installations. It is located at Ivanpah Lake, a dry lakebed in the Mojave Desert near the Nevada border. The Ivanpah plant uses a power tower system. In this CSP plant design, a central tower has a solar receiver and boiler at its top. It is surrounded by concentric circles of mirrors on the ground that all reflect light onto this receiver. The mirrors, known as heliostats, are mounted on devices that tilt them so that they can track the Sun as it moves through the sky. The extreme intensity of the light at the receiver heats it up to very high temperatures, which the boiler uses to create superheated steam. This steam is then piped down the tower to a turbine, where it generates electricity.

The Ivanpah plant has three separate towers. Each is 459 feet (140 m) tall, and each is surrounded by its own set of heliostat mirrors. In all, the Ivanpah plant has approximately 300,000 of these heliostats. The entire installation covers some 3,500 acres (1,400 ha). Together, the three towers generate about 377 megawatts of electricity.

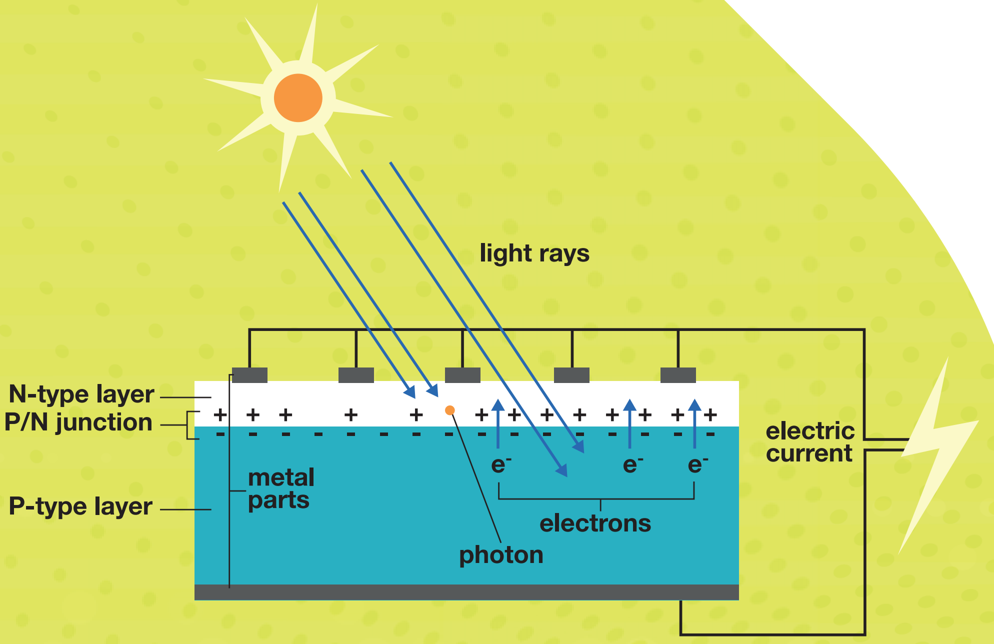


Thousands of heliostat mirrors reflect light onto a central tower in California's Ivanpah Solar Plant. This solar plant was completed and connected to the electrical grid in 2013.

The project's developer, BrightSource, says that this is "enough to serve more than 140,000 homes in California during the peak hours of the day."[9]

Photovoltaic Cells: Using the Sun's Light

Photovoltaic cells offer another way to turn the Sun's energy into electricity. Rather than using sunlight's heat, photovoltaics use the sunlight itself. The modern history of this technology dates back to 1954. In that year, scientists with New Jersey's Bell Labs demonstrated the first practical solar cell. It was similar in appearance to modern solar cells, but it was primitive by today's standards. This experimental silicon device was used to power a small radio transmitter. The *New York Times* reported that the silicon solar cell "may mark the beginning of a new era."[10] Over the next few decades, PV cells remained much too expensive for ordinary consumers, but they found widespread use in satellites.



Inside a Photovoltaic Cell

PV cells have improved a great deal over the past few decades, but the basic scientific principles behind them remain the same. A solar cell contains two layers of **semiconducting materials**, most commonly silicon. One layer, called the N-type layer, contains extra **electrons**. The other layer, called the P-type layer, contains extra empty spaces where electrons can go. The place where the layers meet is known as the P/N junction.

When a photon hits the solar cell, it may knock one of the electrons free. Both the electron and the empty space, or hole, it left behind can then move around the cell. The electron is drawn to the N-type layer, and the hole is drawn to the P-type layer. The moving electrons create an electric current. Metal parts conduct this electricity, carrying it away for use or storage before returning the electrons to the cell.

In the 1970s, political conflicts over oil, one of the world's leading fossil fuels, led to renewed investment in other energy sources, including solar power. PV technology improved over time, dropping in price and converting more of the Sun's energy into useful electricity. Solar cells appeared in small devices, such as watches and calculators. They also appeared in larger sizes as panels on the roofs of homes and businesses. Eventually, they were collected in power plants as huge solar arrays. According to the nonprofit environmental organization the Earth Policy Institute, "The price of solar photovoltaic panels has declined . . . from $74 a watt in 1972 to less than 70 cents a watt in 2014."[11]

WORDS IN CONTEXT

semiconducting materials
Materials whose ability to conduct electricity increases as temperature increases.

electrons
Particles with a negative charge that are found in atoms and carry electricity.

Energy, Bandgaps, and Efficiency

Each photon that strikes a solar cell has a particular amount of energy, measured in units called electron volts (eV). The energy varies based on where the photon falls on the electromagnetic spectrum. For example, the energy of photons in the visible light range of the spectrum ranges from 1.65 eV to 3.1 eV. Some kinds of photons, such as those that make up radio waves, have less energy. Others, such as those that make up X-rays, have more energy. About 50 percent of the energy in sunlight is made up of visible light. An additional 40 percent consists of lower-energy photons, and the final 10 percent consists of higher-energy photons.

Inside a solar cell, the amount of energy needed to knock an electron loose is known as the bandgap. The value of the bandgap varies based on the materials used to construct the cell. In the case of silicon solar cells, the bandgap is 1.1 eV. When a photon with lower energy than the bandgap strikes the cell, it is unable to knock

Multijunction Solar Cells

Though traditional silicon solar cells theoretically top out at an efficiency of about 33 percent, there is a way to get efficiency even higher: multijunction cells. Traditional cells have one silicon P/N junction that can be used to generate electricity. In multijunction cells, several layers of different materials meet at multiple junctions. The top layer has a high bandgap, capturing high-energy photons and letting lower-energy ones pass through. The next layer down has a lower bandgap, and a third layer has a still lower bandgap. This design, with multiple bandgaps and multiple junctions, allows the cell to turn more of the sunlight's energy into electricity. Scientists have demonstrated efficiencies as high as 45 percent with this technology.

Rather than using silicon, multijunction solar cells are made out of different semiconductor materials, such as gallium indium phosphate and gallium arsenide. Complex manufacturing methods are needed to assemble multijunction cells. These materials and production techniques make multijunction cells much too expensive for everyday use. They have mostly been reserved for use in satellites and other spacecraft. In these applications, generating the most electricity possible for a given weight of solar cells is important, and high cost is usually not a barrier. However, researchers are investigating ways to drive down costs and make multijunction cells more widely accessible.

an electron loose. Instead, it simply warms the solar panel slightly. When a photon with higher energy than the bandgap hits the cell, it successfully knocks an electron loose. However, the photon's additional energy beyond the bandgap is not captured. Because their energy is greater than 1.1 eV, the photons in visible light, with energies ranging from 1.65 eV to 3.1 eV, can always knock an electron loose in a silicon solar cell. But this also means that any extra energy beyond the bandgap is wasted.

This wasted energy reduces the solar cell's efficiency. The DOE defines this efficiency as "the percentage of the solar energy shining on a PV device that is converted into usable electricity."[12] Of all the solar energy hitting a typical silicon PV panel, about 18 percent is lost because it has less energy than the bandgap. Another 49 percent is lost as excess energy in photons with a greater energy than the bandgap. That leaves 33 percent. In theory, this is the maximum efficiency of a silicon solar cell.

In addition to the bandgap issue, other factors can reduce the efficiency of solar cells. One is a process called recombination, which comes in two types: direct and indirect. In direct recombination, a freed electron and a hole run into each other before flowing through the cell as electrical current, combining and emitting a photon rather than generating electricity. In indirect recombination, electrons or holes run into an impurity or defect in the solar cell material and release their energy as heat. Another factor affecting efficiency is temperature. High temperatures can change the properties of the silicon, reducing

INTRODUCTION: POWERED BY SUNLIGHT

1. "California Clean Energy Tour Solar Star Projects," *California Energy Commission*, n.d. www.energy.ca.gov.

2. Quoted in Eric Wesoff, "Solar Star, Largest PV Power Plant in the World, Now Operational," *Greentech Media*, June 26, 2015. www.greentechmedia.com.

3. "The Future of Solar Energy," *Massachusetts Institute of Technology*, 2015. www.energy.mit.edu.

4. "New Energy Outlook 2017," *Bloomberg New Energy Finance*, 2017. www.about.bnef.com.

5. Quoted in John Fialka, "Are We Entering the Photovoltaic Energy Era?" *Scientific American*, December 15, 2016. www.scientificamerican.com.

CHAPTER 1: HOW DOES SOLAR POWER WORK?

6. Quoted in Lee Phillips, "The Future of Solar Energy Is Bright," *Ars Technica*, February 16, 2017. www.arstechnica.com.

7. "Solar Water Heaters," *US Department of Energy*, n.d. www.energy.gov.

8. Quoted in "World's Tallest Tower Goes Solar, Saving 3,200 kwh/Day," *Go Green*, n.d. www.go-green.ae.

9. "Ivanpah," *BrightSource Limitless*, n.d. www.brightsourceenergy.com.

10. Quoted in "April 25, 1954: Bell Labs Demonstrates the First Practical Silicon Solar Cell," *American Physical Society*, n.d. www.aps.org.

11. "Seven Surprising Realities behind the Great Transition to Renewable Energy," *Earth Policy Institute*, May 13, 2015. www.earth-policy.org.

12. "Solar Performance and Efficiency," *US Department of Energy*, August 20, 2013. www.energy.gov.

13. Karl W. Böer, "Solar Heating and Cooling of Buildings—Results and Implications of the Delaware Experiment," *National Science Foundation*, November 18–20, 1973. www.babel.hathitrust.org.

14. "Harnessing Solar Energy at Home," *US Department of Energy*, October 1, 2014. www.energy.gov.

15. Quoted in David Reid, "Kamuthi: The World's Largest Solar Power Project," *BBC*, May 24, 2017. www.bbc.com.

CHAPTER 3: HOW CAN VEHICLES USE SOLAR ENERGY?

26. "Juno Overview," *National Aeronautics and Space Administration*, August 3, 2017. www.nasa.gov.

27. Quoted in "NASA's Juno Spacecraft Breaks Solar Power Distance Record," *NASA Jet Propulsion Laboratory*, January 13, 2016. www.jpl.nasa.gov.

28. Quoted in Michael Coggan, "Dutch Team Nuon Celebrate Victory in World Solar Challenge Race from Darwin to Adelaide," *ABC News*, October 22, 2015. www.abc.net.au.

29. "History," *Bridgestone World Solar Challenge*, n.d. www.worldsolarchallenge.org.

30. Quoted in Ronan Glon, "Why You Can't Order a Toyota Prius with a Roof-Mounted Solar Panel," *Digital Trends*, June 17, 2016. www.digitaltrends.com.

31. "NASA Armstrong Fact Sheet: Helios Prototype," *National Aeronautics and Space Administration*, February 28, 2014. www.nasa.gov.

32. Quoted in Damian Carrington, "Solar Plane Makes History after Completing Round-the-World Trip," *Guardian*, July 25, 2016. www.theguardian.com.

33. Quoted in Carrington, "Solar Plane Makes History after Completing Round-the-World Trip."

34. Quoted in Damon McMillan, "Did a Solar-Powered Autonomous Boat Just Cross the Pacific Ocean?" *Maker Media*, August 22, 2016. www.makezine.com.

35. Quoted in Christopher Mims, "World's Mightiest Solar Boat Unveiled," *Scientific American*, March 1, 2010. www.scientificamerican.com.

FOR FURTHER RESEARCH

BOOKS

John Allen, *Careers in Environmental and Energy Technology*. San Diego, CA: ReferencePoint, 2017.

Lester R. Brown, *The Great Transition: Shifting from Fossil Fuels to Solar and Wind Energy*. New York: W.W. Norton & Company, 2015.

Matt Doeden, *Green Energy: Crucial Gains or Economic Strains?* Minneapolis, MN: Twenty-First Century Books, 2010.

Stuart A. Kallen, *Cutting Edge Energy Technology*. San Diego, CA: ReferencePoint, 2017.

Andrea Nakaya, *What Is the Future of Solar Power?* San Diego, CA: ReferencePoint, 2012.

Christine Zuchora-Walske, *Solar Energy*. Minneapolis, MN: Abdo Publishing, 2013.

WEBSITES

Bureau of Labor Statistics: Careers in Solar Power

https://www.bls.gov/green/solar_power

On the website of the Bureau of Labor Statistics, the government agency that studies the nation's workforce, learn more about solar energy and the many careers that support this rapidly growing field.

Department of Energy: Solar

https://energy.gov/science-innovation/energy-sources/renewable-energy/solar

The website of the Department of Energy, the US agency that promotes innovative energy policies, features information about all kinds of renewable energy sources, including solar power.

INDEX