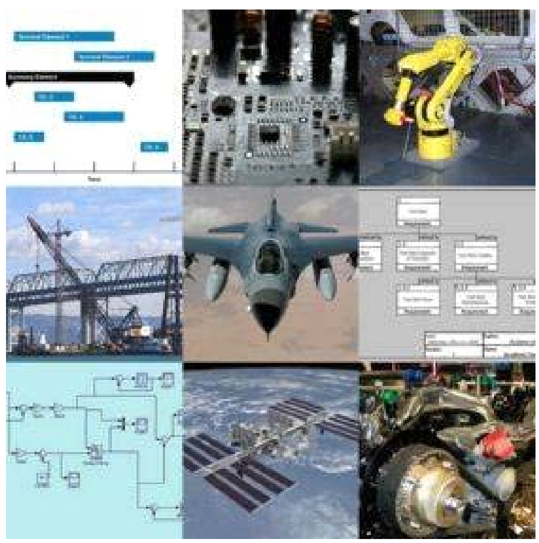
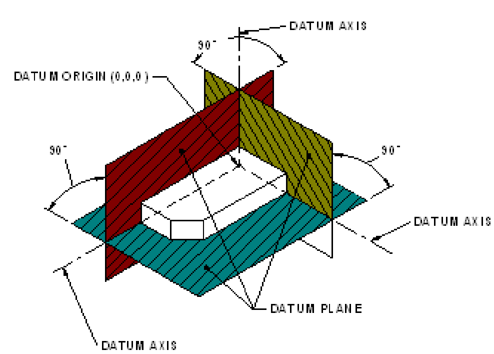
510 N. Crosslane Rd.
Monroe, Georgia 30656
(770) 266-6915 fax
(678) 643-1758

PDHStorm
Online Engineering & Technology Training

PDH & Professional Training





PDH Storm, by Engineers Edge, LLC

Acknowledgements

Authors: Gary Cook, Lynn Billman, and Rick Adcock

Typography, Design, and Artwork: Susan Sczepanski

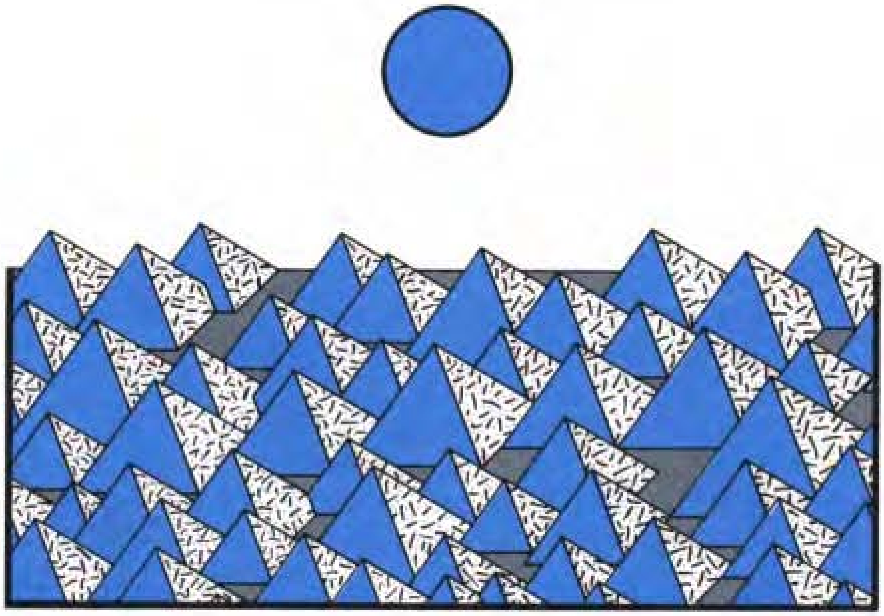
Cover Design: Susan Sczepanski and Ray David

Editing: Paula Pitchford, James Jones, and Barbara Glenn

Technical Advisors and Reviewers: Michael Thomas, Sandia National Laboratories and Ken Zweibel, Solar Energy Research Institute.

This publication was produced under the Solar Technical Information Program at the Solar Energy Research Institute (SERI) for the U.S. Department of Energy (DOE). We give special thanks to Vincent Rice and Robert Annan of the DOE for their support of the project and for their advice and review.

Photovoltaic
FUNDAMENTALS



Contents

Introduction

Photovoltaic (PV) systems convert sunlight into electricity. Once an exotic technology used almost exclusively on satellites in space, photovoltaics has come down to Earth to find rapidly expanding energy markets. Many thousands of PV systems have been installed around the globe. For certain applications, such as remote communications, PV systems provide the most cost-effective source of electric power possible.

Several important characteristics of PV systems make them a desirable source of power:

- They rely on sunlight.
- They generate electricity with little impact on the environment.
- They have no moving parts to wear out.
- They are modular, which means they can be matched to a need for power at any scale.
- They can be used as independent power sources, or in combination with other sources.
- They are reliable and long-lived.
- They use solid-state technology and are easily mass-produced and installed.

Photovoltaic devices can be made from many different materials in many different designs. The diversity of PV materials and their different characteristics and potentials demonstrate the richness of this growing technology.

This booklet describes how PV devices and systems work. It also describes the specific materials and devices that are most widely used commercially as of 1990 and those that have the brightest prospects. Students, engineers, scientists, and others needing an introduction to basic PV technology, and manufacturers and consumers who want more information about PV systems should find this booklet helpful.

We begin with an overview and then explain the rudimentary physical process of the technology, the photovoltaic effect. Next, we consider how scientists and engineers have harnessed this process to generate electricity in silicon solar cells, thin-film devices, and high-efficiency cells. We then look at how these devices are incorporated into modules, arrays, and power-producing systems.

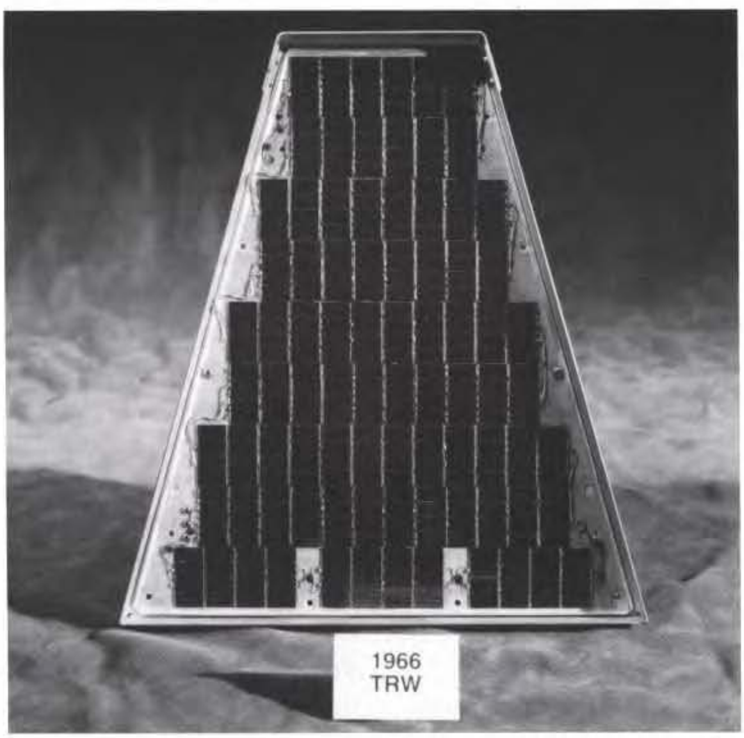
We have written and designed this book so that the reader may approach the subject on three different levels. First, for the person who is in a hurry or needs a very cursory overview, in the margins of each page we generalize the important points of that page. Second, for a somewhat deeper understanding, we have provided ample illustrations, photographs, and captions. And third, for a thorough introduction to the subject, the reader can resort to reading the text.

Chapter 1

An Overview of Progress

- The photovoltaic effect was discovered in 1839.
- Bell Laboratories scientists developed the first viable PV cells in 1954.

French physicist Edmond Becquerel first described the photovoltaic effect in 1839, but it remained a curiosity of science for the next three-quarters of a century. Becquerel found that certain materials would produce small amounts of electric current when exposed to light. The effect was first studied in solids, such as selenium, by Heinrich Hertz in the 1870s. Soon afterward, selenium photovoltaic (PV) cells were converting light to electricity at 1% to 2% efficiency. (The conversion efficiency of a PV cell is the proportion of sunlight energy that a cell converts to electrical energy.) Selenium was quickly adopted in the emerging field of photography for use in light-measuring devices.



This photovoltaic module was developed in 1966 by TRW for use on a space mission.

Major steps toward commercializing PV were taken in the 1940s and early 1950s when the Czochralski process for producing highly pure crystalline silicon was developed. In 1954, scientists at Bell Laboratories depended on the Czochralski process to develop the first crystalline silicon photovoltaic (or solar) cell, which had an efficiency of 4%.

Although a few attempts were made in the 1950s to use silicon cells in commercial products, it was the new space program that gave the technology its first major application. In 1958, the U.S. Vanguard space satellite carried a small array of PV cells to power its radio. The cells worked so well that PV technology has

Shortly after the development of silicon solar cells, ads like this touted photovoltaics as a new and promising source of electricity. But the development of affordable PV cells for use on Earth had to wait for the start of the federal/industry R&D program, some 20 years later. (Poster reproduction courtesy of Bell Laboratories and ARCO Solar News.)

been part of the space program ever since. Today, solar cells power virtually all satellites, including those used for communications, defense, and scientific research. The U.S. space shuttle fleet uses PV arrays to generate much of its electrical power.

The computer industry, especially transistor semiconductor technology, also contributed to the development of PV cells. Transistors and PV cells are made from similar materials and operate on the basis of similar physical mechanisms. Advances in transistor research have provided a steady flow of new information about PV cell technology. Today, however, this technology transfer process often works in reverse, as advances in PV research and development are sometimes adopted by the semiconductor industry.

Despite these advances, photovoltaics in 1970 was still too expensive for most terrestrial uses. In the mid-1970s, rising energy costs, sparked by a world oil crisis, renewed interest in making PV technology more affordable. Since then, the federal government, industry, and research organizations have invested hundreds of millions of dollars in research, development, and production. Often, industry and the federal government work together, sharing the cost of PV research and development (R&D).

Much of this effort has gone into the development of crystalline silicon, the material Bell's scientists used to make the first

Photovoltaic cells were first used in space to power a 5-mW backup transmitter on the Vanguard 1 in 1958. Today, solar cells power most satellites; even the U.S. shuttle fleet uses PV to generate much of its electrical power. (Rendition courtesy of Lockheed.)

- **In the 1950s, the space program ushered in PV's first application. Solar cells power virtually all of today's satellites.**
- **Despite advances, in the early 1970s PV was still too expensive for terrestrial use.**
- **The energy crises of the 1970s sparked a major effort by the government and industry to make PV more affordable.**

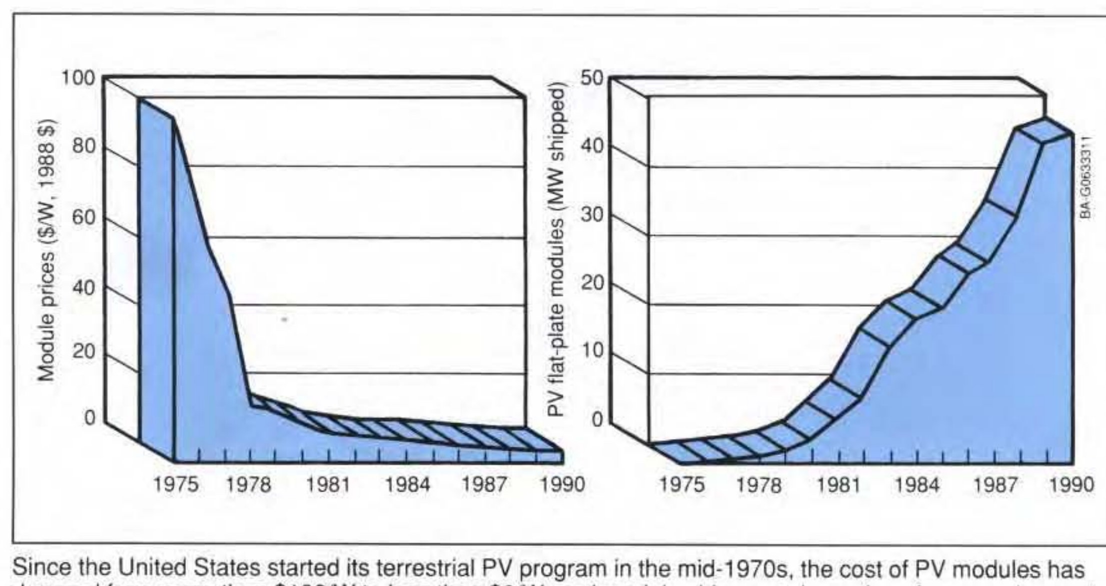
- **Today's PV systems are efficient and reliable; they generate electricity for as little as 25¢/kWh.**
- **Technical advances have helped the annual PV market grow from a few thousand watts in the 1970s to nearly 47 million watts today.**

practical cells. As a result, crystalline silicon devices have become more and more efficient, reliable, and durable. Industry and government have also explored a number of other promising materials, such as noncrystalline (amorphous) silicon, polycrystalline cadmium telluride and copper indium diselenide, and other single-crystal materials like gallium arsenide.

Today's commercial PV systems can convert from 5% to 15% of sunlight into electricity. They are highly reliable, and they last 20 years or longer. The cost of PV-generated electricity has dropped 15- to 20-fold, and PV modules now cost around $6 per watt (W) and produce electricity for as little as 25¢ to 30¢ per kilowatt-hour (kWh).

A Growing Market

Price reductions have helped to spur a growing market for photovoltaics. Shipments of PV modules have risen steadily over the last few years. In the last three years, worldwide module shipments have grown by 60% to nearly 47 million watts (MW). Revenues for the PV industry could be greater than $800 million in 1991. Japan, European nations, China, India, and other countries have either established new PV programs or expanded existing ones. The number of organizations involved in



Since the United States started its terrestrial PV program in the mid-1970s, the cost of PV modules has dropped from more than $100/W to less than $6/W, and module shipments have risen from nearly zero to approximately 47 MW.

Photovoltaic cells power millions of small consumer products such as calculators, radios, watches, car window defrosters, and — as shown here — walk lights.

Mid-size PV systems (from a few watts to a few thousand watts) provide power for remote applications all over the world, including water pumping, refrigeration, highway lighting, and village power. Above, photovoltaics power a water-level-monitoring station on the Laramie River in Central Wyoming.

manufacturing and R&D grew from less than a dozen in the early 1970s to more than 200 in 1990.

The market is active in three principal areas: consumer products, stand-alone systems, and utility applications. Millions of small PV systems (producing from a few milliwatts, or a few thousandths of a watt, to a few watts) currently power watches, calculators, radios, portable TVs, walk lights, and a variety of other consumer goods. These systems are typically made with thin-film amorphous silicon material.

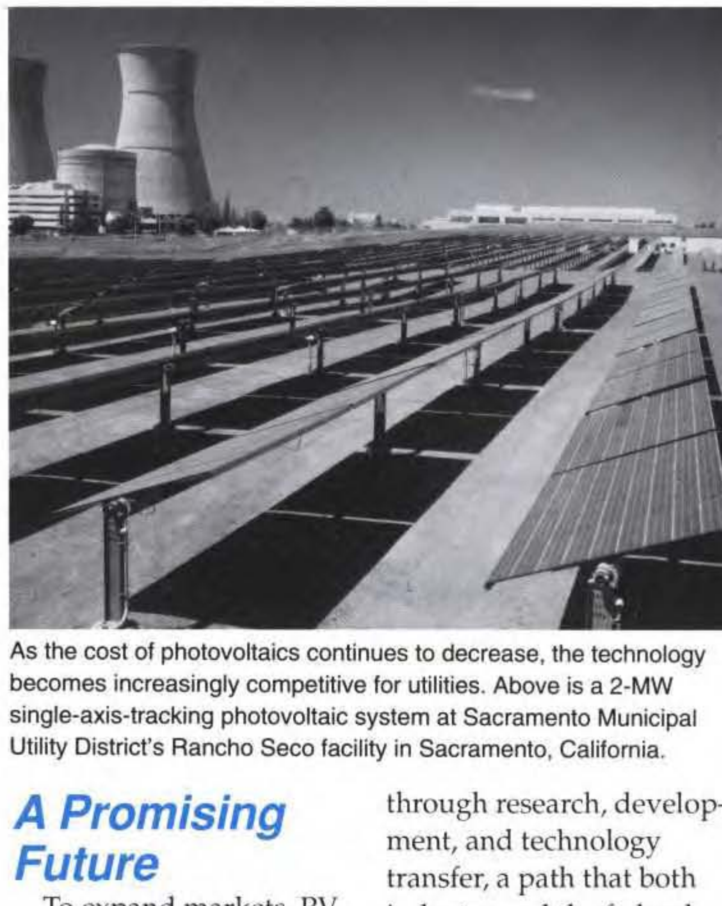
The largest of the photovoltaic markets is for mid-size, stand-alone systems, producing from a few watts of power to a few thousand watts. These are most often used to provide electricity in remote locations not served by a utility grid. Stand-alone PV systems are used in automated applications such as highway lighting, navigational buoys,

- **Millions of consumer products, such as calculators and portable TVs, are powered by small PV systems.**
- **Mid-size, stand-alone PV systems are effective power sources, especially for remote applications.**

- Tens of thousands of homes and cabins worldwide rely on PV systems for most or all of their electrical needs.
- Electric utilities are experimenting with large PV generating stations.
- As the cost of photovoltaics continues to decrease, through the avenues of R&D and mass production, the technology will become increasingly competitive for large-scale production of electricity for utilities.

lighthouses, microwave repeater stations, and weather stations. These stand-alone PV systems have proven to be reliable, maintenance-free, and cost-effective power sources. Also, tens of thousands of homes and cabins worldwide now rely on PV systems for most or all of their electrical needs. Solar electricity provides power for water pumps, for refrigerators that store vaccines and drugs, and for communications. PV systems have enormous potential to furnish electricity to towns and villages throughout the world that are not now connected to a utility grid.

PV is generally not yet competitive with most conventional sources for utility-size applications. However, several large PV systems (producing from a hundred thousand to several million watts) do provide supplemental power to electric utilities in the United States and a few other countries.



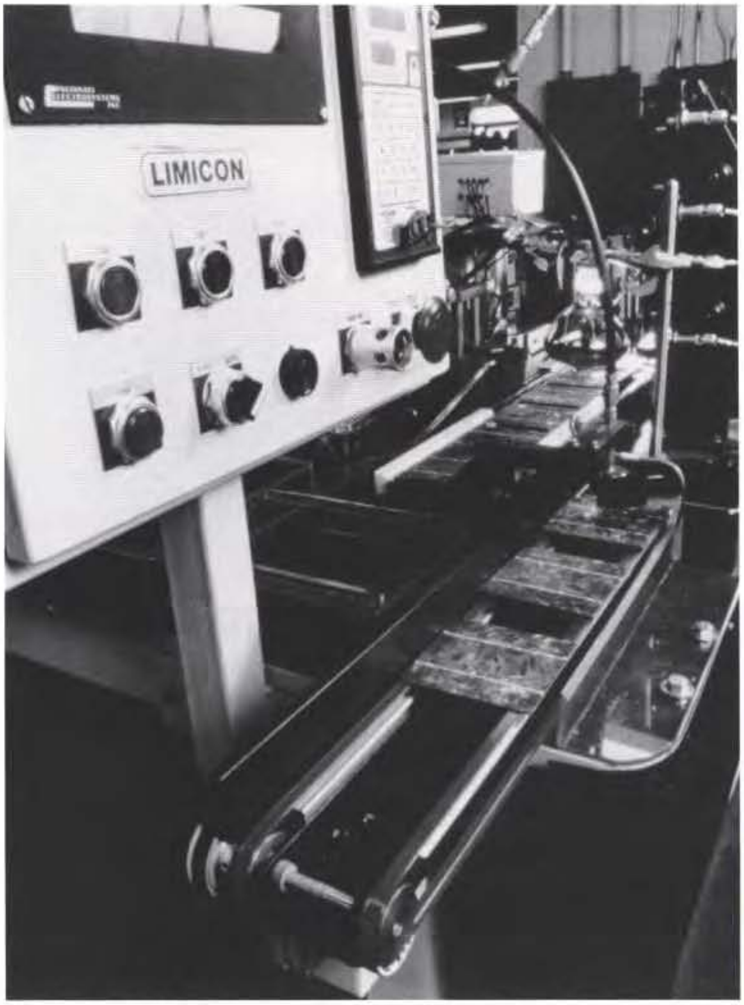
As the cost of photovoltaics continues to decrease, the technology becomes increasingly competitive for utilities. Above is a 2-MW single-axis-tracking photovoltaic system at Sacramento Municipal Utility District's Rancho Seco facility in Sacramento, California.

A Promising Future

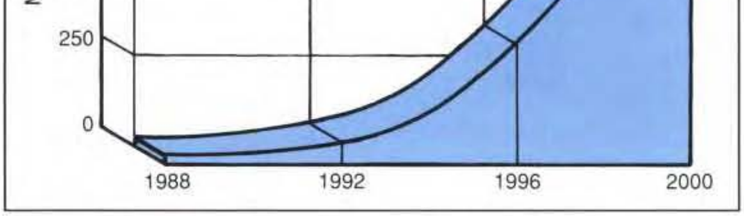
To expand markets, PV costs need to be reduced further. There are two basic ways to reduce these costs. The first is through mass production, an avenue that the PV industry will follow as it continues to mature and grow. The second is through research, development, and technology transfer, a path that both industry and the federal government are pursuing.

The federal government's R&D program is managed by the Department of Energy (DOE). The goals of the program are twofold. In the short term, through the mid-1990s, the objective is to reduce the cost of PV electricity to about 12¢/kWh, which is the retail cost of electricity in many parts of the United States. The objective for the longer term, past the turn of the century, is to cut the cost of PV electricity in half again to about 6¢/kWh, which would make PV costs as low as those of most conventional sources of generated electricity.

Achieving these goals should help spur the market growth for photovoltaics in all applications, from remote stand-alone systems to utility power plants. Photovoltaic systems are already supplying a growing portion of America's demand for electricity. Photovoltaic systems are also increasingly becoming an option for the developing world, as the demand for electricity grows to serve the needs of burgeoning national economies and a human population that will double in the next century.



Mass production and advances in PV technology are crucial for PV systems to become competitive with conventional methods of generating electricity for utilities.



The world market for photovoltaic systems could increase dramatically by the end of this century.

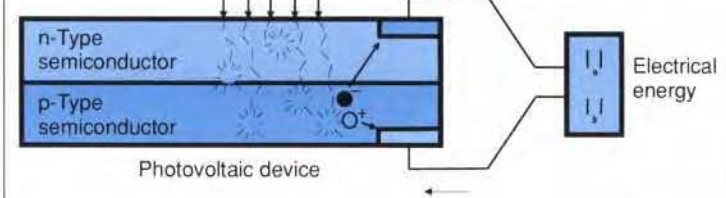
- **The federal government aims to cut the cost of PV electricity to about 6¢/kWh.**
- **The PV market could grow dramatically by the turn of the century, supplying the world with as much as one billion watts of new electrical power per year.**

Chapter 2

The Photovoltaic Effect

- **In the PV effect, sunlight energy generates free electrons in a semiconductor device to produce electricity.**
- **The sun supplies all the energy that drives natural global systems and cycles.**
- **Each wavelength in the solar spectrum corresponds to a frequency and an energy; the shorter the wavelength, the higher the frequency and the greater the energy.**

The photovoltaic effect is the basic physical process through which a PV cell converts sunlight into electricity. Sunlight is composed of photons—packets of solar energy. These photons contain different amounts of energy that correspond to the different wavelengths of the solar spectrum. When photons strike a PV cell, they may be reflected or absorbed, or they may pass right through. The absorbed photons generate electricity. The energy of a photon is transferred to an electron in an atom of the semiconductor device. With its newfound energy, the electron is able to escape from its normal position associated with a single atom in the semiconductor to become part of the current in an electrical circuit. Special electrical properties of the PV cell—a built-in electric field—provide the voltage needed to drive the current through an external load.

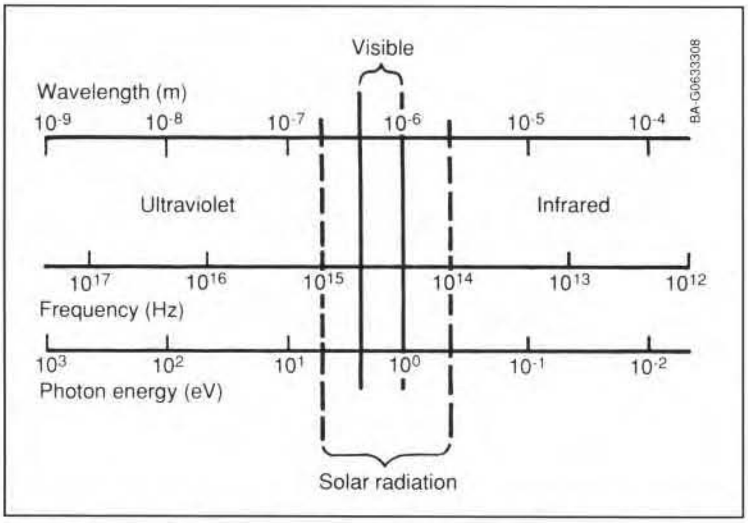


In the typical PV cell, photon energy frees electrical charge carriers, which become part of the current in an electrical circuit. A built-in electrical field provides the voltage needed to drive the current through an external load.

Energy from the Sun

The sun's energy is vital to life on Earth. It determines the Earth's surface temperature, and supplies virtually all the energy that drives natural global systems and cycles. Although some other stars are enormous sources of energy in the form of x-rays and radio signals, our sun releases 95% of its energy as visible light. Visible light represents only a fraction of the total radiation spectrum; infrared and ultraviolet rays are also significant parts of the solar spectrum.

Each portion of the solar spectrum is associated with a different level of energy. Within the visible portion of the spectrum, red is at the low-energy end and violet is at the high-energy end (having half again as much energy as red light). In the invisible portions of the spectrum, photons in the ultraviolet region,



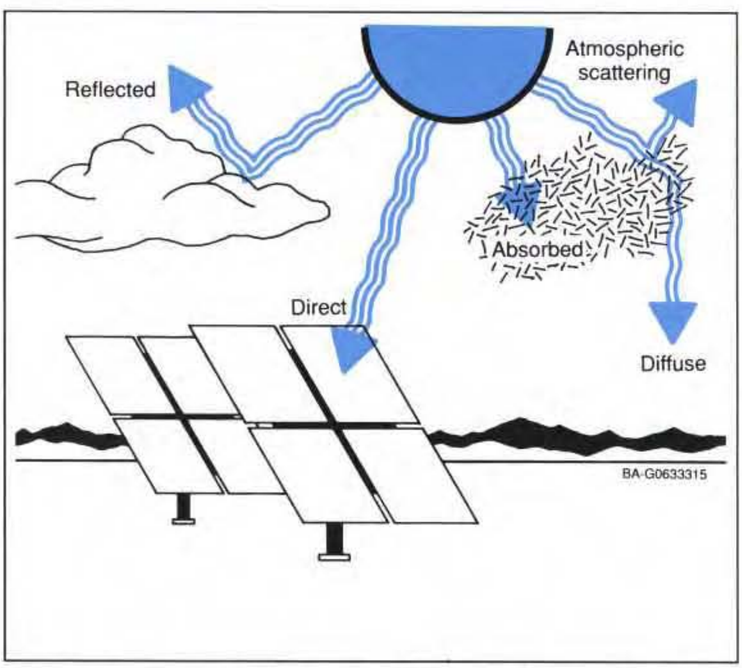
The sun emits virtually all of its radiation energy in a spectrum of wavelengths that range from about $2x10^{-7}$ to $4x10^{-6}$ m. The great majority of this energy is in the visible region. Each wavelength corresponds to a frequency and an energy; the shorter the wavelength, the higher the frequency and the greater the energy (expressed in eV, or electron volts; an eV is the energy an electron acquires when it passes through a potential of 1 V in a vacuum).

which cause the skin to tan, have more energy than those in the visible region. Photons in the infrared region, which we feel as heat, have less energy than the photons in the visible region.

The movement of light from one location to another can best be described as though it were a wave, and different types of radiation are characterized by their individual wavelengths. These wavelengths—the distance from the peak of one wave to the peak of the next—indicate radiation with different amounts of energy; the longer the wavelength, the less the energy. Red light, for example, has a longer wavelength and thus has less energy than violet light.

Each second, the sun releases an enormous amount of radiant energy into the solar system. The Earth receives a tiny fraction of this energy; still, an average of 1367 W reaches each square meter (m^2) of the outer edge of the Earth's atmosphere. The atmosphere absorbs and reflects some of this radiation, including most x-rays and ultraviolet rays. Yet, the amount of sunshine energy that hits the surface of the Earth every minute is greater than the total amount of energy that the world's human population consumes in a year.

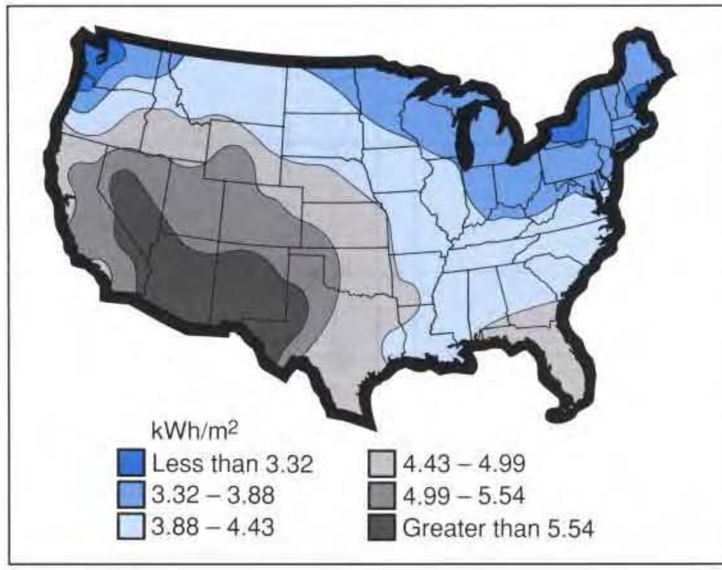
When sunlight reaches Earth, it is distributed unevenly in different regions. Not surprisingly, the areas



The Earth's atmosphere and cloud cover absorb, reflect, and scatter some of the solar radiation entering the atmosphere. Nonetheless, enormous amounts of direct and diffuse sunshine energy reach the Earth's surface and can be used to produce photovoltaic electricity.

- **An average of 1367 W of solar energy strikes each square meter of the Earth's outer atmosphere.**
- **Although the atmosphere absorbs and reflects this radiation, a vast amount still reaches the Earth's surface.**
- **The amount of sunlight striking the Earth varies by region, season, time of day, climate, and measure of air pollution.**

Although the quantity of solar radiation striking the Earth varies by region, season, time of day, climate, and air pollution, the yearly amount of energy striking almost any part of the Earth is vast. Shown is the yearly average radiation on a horizontal surface across the continental United States. Units are in kWh/m2.



- **The amount of electricity produced by a PV device depends on the incident sunlight and the device efficiency.**
- **Knowing how the PV effect works in crystalline silicon helps us understand how it works in all devices.**
- **All matter is composed of atoms.**
- **Positive protons and neutral neutrons comprise the nucleus of the atom.**

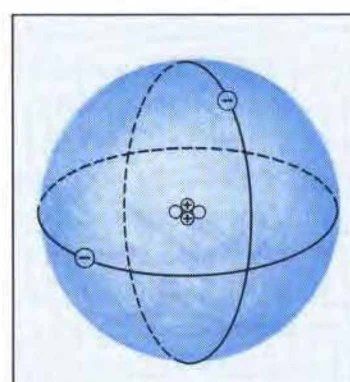
near the equator receive more solar radiation than anywhere else on Earth. Sunlight varies with the seasons, as the rotational axis of the Earth shifts to lengthen and shorten days as the seasons change. The amount of solar energy falling per square meter on Yuma, Arizona, in June, for example, is typically about nine times greater than that falling on Caribou, Maine, in December. The quantity of sunlight reaching any region is also affected by the time of day, the climate (especially the cloud cover, which scatters the sun's rays), and the air pollution in that region. These climatic factors all affect the amount of solar energy that is available to PV systems.

The amount of energy produced by a PV device depends not only on available solar energy but on how well the device, or solar cell, converts sunlight to useful electrical energy. This is called the device or solar cell efficiency. It is defined as the amount of electricity produced divided by the sunlight energy striking the PV device. Scientists have concentrated their R&D efforts over the last several years on improving the efficiency of solar cells to make them more competitive with conventional power-generation technologies.

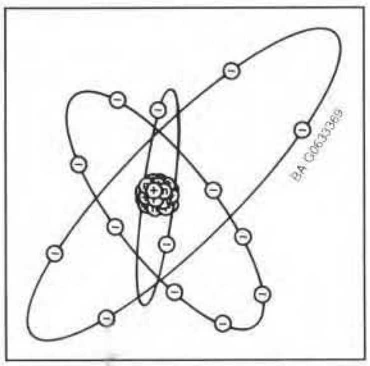
An Atomic Description of Silicon

We use crystalline silicon to explain the photovoltaic effect for several reasons. First, crystalline silicon was the semiconductor material used in the earliest successful PV device. Second, crystalline silicon is still the most widely used PV material. And third, although other PV materials and designs exploit the PV effect in slightly different ways, knowing how the effect works in crystalline silicon gives us a basic understanding of how it works in all devices.

All matter is composed of atoms. Atoms, in turn, are composed of positively charged protons, negatively charged electrons, and neutral neutrons. The protons and neutrons, which are of approximately equal size, comprise the close-packed central nucleus of the atom, where almost all of the mass of



All matter is composed of atoms. Positive protons and neutral neutrons, making up the bulk of the weight of an atom, are tightly packed in the nucleus. Negative electrons revolve around the nucleus at different distances, depending on their energy level.



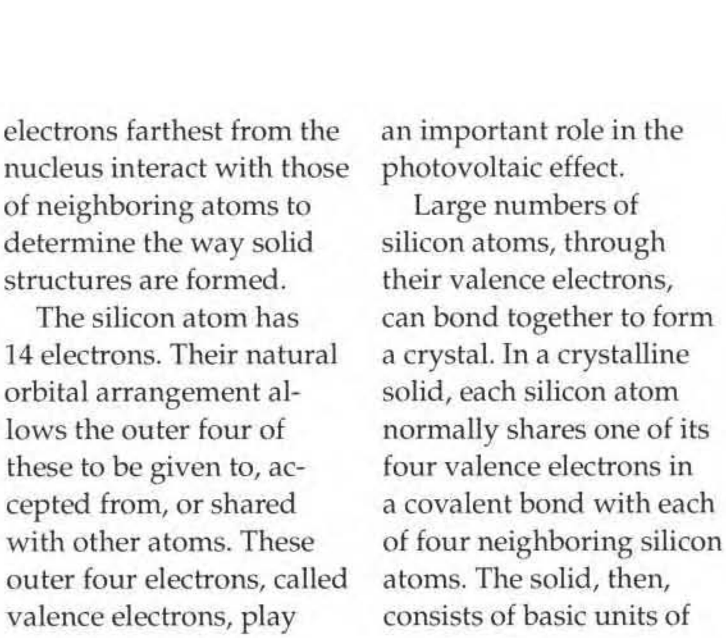
As depicted in this simplified diagram, silicon has 14 electrons. The four electrons that orbit the nucleus in the outermost, or valence, energy level are given to, accepted from, or shared with other atoms.

the atom is located. The much lighter electrons orbit the nucleus at very high velocities. Although the atom is built from oppositely charged particles, its overall charge is neutral because it contains an equal number of positive protons and negative electrons.

The electrons orbit the nucleus at different distances, depending on their energy level; an electron of lesser energy orbits close to the nucleus, while one of greater energy orbits farther away. The electrons farthest from the nucleus interact with those of neighboring atoms to determine the way solid structures are formed.

The silicon atom has 14 electrons. Their natural orbital arrangement allows the outer four of these to be given to, accepted from, or shared with other atoms. These outer four electrons, called valence electrons, play an important role in the photovoltaic effect.

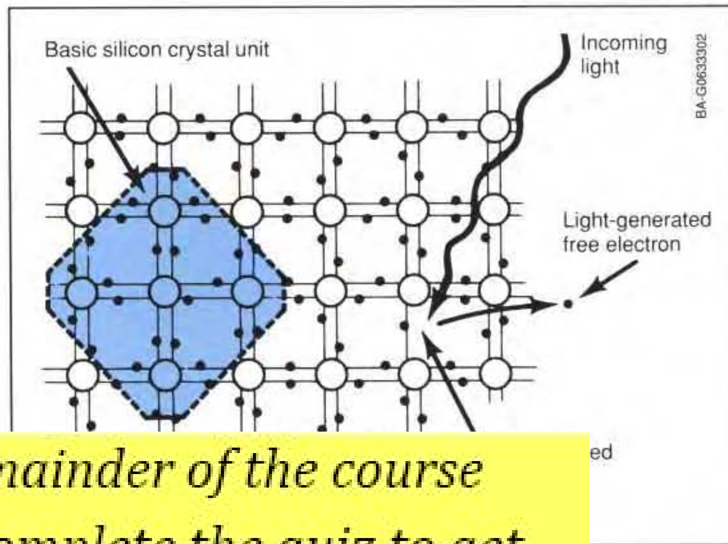
Large numbers of silicon atoms, through their valence electrons, can bond together to form a crystal. In a crystalline solid, each silicon atom normally shares one of its four valence electrons in a covalent bond with each of four neighboring silicon atoms. The solid, then, consists of basic units of



In the basic unit of a crystalline silicon solid, a silicon atom shares each of its four valence electrons with each of four neighboring atoms.

- **Negative electrons orbit the nucleus at different distances, depending on their energy level.**
- **Outermost, or valence, electrons determine the way solid structures are formed.**
- **Four of silicon's 14 electrons are valence electrons.**
- **In a crystalline solid, a silicon atom shares each of its four valence electrons with each of four other silicon atoms.**

Light of sufficient energy can dislodge a negative electron from its bond in the crystal, creating a positive hole (a bond missing an electron). These negative and positive charges, which move freely for a time about the crystal lattice, are the constituents of electricity.



- Light of sufficient energy can dislodge an electron from its bond in the crystal, creating a hole.
- These negative and positive charges (free electrons and holes) are the constituents of electricity.
- PV cells contain an electric field that forces free negative and positive charges in opposite directions, driving an electric current.
- To form the electric field, the silicon crystal is doped (by introducing elements of another element) to alter the crystal's electrical properties.

To view the remainder of the course material and complete the quiz to get PDH credit and certificate, you must purchase the course.

First, close this window and click "Create an Account" or "Login" located on the ***right side of the webpage*** *then select the link at the bottom of the webpage:*

"Send payment via Paypal or Credit Card"

ilicon PV
ommon
lightly
cture of
al. This
vn as
duces an
element
ant") into
al to alter
perties.
either
ence
posed to

atoms,
valence
sed for
silicon (so
of the
negative
rons). A
m occupies
in the
at was
rly by the
eplaced.
nce
ver the

tice. The electron is now a part of the conduction band, so called because these free electrons are the means by which the crystal conducts electricity.

riers (through an external circuit) is what defines electricity.

There are several ways to form the electric field

bonding responsibilities of the four silicon valence electrons that they replaced. But the fifth valence electron remains free, without bonding