SOLAR ELECTRIC HANDBOOK

Photovoltaic Fundamentals and Applications

SOLAR ENERGY INTERNATIONAL
renewable energy education for a sustainable future

The Case for Renewable Energy

CHAPTER 1

SOLAR ENERGY INTERNATIONAL

In recent years, the topic of renewable energy and an overall "green" social conversation has captured the public consciousness of the United States and countries all over the world. Within this conversation, there are many different topics and rationales that are moving the application of renewable energy technologies from the category of alternative energy to mainstream adoption. This chapter provides an overview of the many arguments that make the case for renewable energy and explains the range of commercially available renewable energy technologies.

CHAPTER OBJECTIVES

- Explain the benefits all renewable energies share.
- List the various commercially available renewable energy technologies.
- Explain the purpose behind energy efficiency and conservation.
- Provide an overview of passive solar design, solar cooking, solar hot water systems, wind power, and micro-hydro technology.

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Domestic Energy Supply

Countries around the world are increasingly concerned with the stability, reliability, and economy of their energy supplies. For example, the United States imports much of its oil from other countries. In 2010, about 49% of the petroleum used in the U.S. came from outside U.S. borders.[1] This represents oil flowing into the U.S. at a rate of 11 million barrels per day. This amount also represents approximately hundreds of thousands of dollars per minute leaving the U.S. economy—to support the economies of Canada, Saudi Arabia, Venezuela, Nigeria, and other oil-producing nations.

Non-Renewable = Finite

The United States has worked very hard since the Industrial Revolution to build an extensive infrastructure for mining, drilling, transporting, refining, and distributing **fossil fuels**. All the while, the demand for energy has been increasing. For example, tens of millions of cars are built each year to run on fossil fuels, not to mention countless furnaces, water heaters, airplanes, and power plants.

Fossil Fuel

A non-renewable form of energy such as coal, petroleum, or natural gas that has high carbon content and is formed by the decomposition of organic matter

We get the vast majority of our energy from fossil fuels such as coal, oil, and natural gas, also known as hydrocarbons or non-renewable sources (see Figure 1.1). These fuels were created millions of years ago when plants and animals died, decayed, and

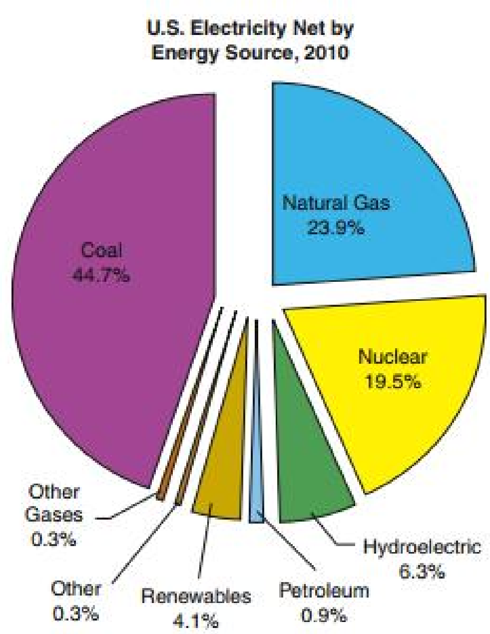

Figure 1.1: We get the vast majority of our energy from fossil fuels such as coal, oil, and natural gas.

[1] *Source:* U.S. Energy Information Administration, www.eia.gov/tools/faqs/faq.cfm?id=32&t=6

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were compressed under their own weight as they piled higher. An inconceivable amount of energy was captured and stored in this process, but the amount is finite and the supply dwindles every year.

Eventually the fossil fuel energy sources powering global demand will run out. Oil, for example, is approaching and may have passed its peak production level. This means we may have already reached the point in time when the maximum level of global oil extraction has been reached, with the rate of production dwindling as the years pass. As oil becomes more rare and more difficult to retrieve, it will also become more expensive.

Environmental Impacts

Extracting hydrocarbons from the earth and burning them creates the majority of the energy used to power everything from air conditioners to cars. The burning of hydrocarbons also creates carbon dioxide (CO_2) by freeing a carbon (C) atom that latches on to two oxygen (O) atoms during this process. Prior to the Industrial Revolution, there were less than 300 parts per million of CO_2 in the Earth's atmosphere. Today there are 387 parts per million—a 29% increase—and the concentration is continuing to rise. Not coincidentally, nine of the 10 warmest years in the modern meteorological record have occurred since the year 2000. In addition, the drilling, transportation, and burning of fossil fuels contributes numerous pollutants to our atmosphere beyond CO_2, including nitrogen dioxide, sulfur dioxide, and methane.

Humans contribute large quantities of greenhouse gases into the atmosphere where those gases trap heat from the sun—heat that would otherwise have bounced back into space. Human-induced changes to the atmosphere cause the planet to warm through this greenhouse effect, and overall air quality is also negatively affected. Although there is some debate about exactly how much climate change is human induced, the scientific community agrees that the burning of fossil fuels is increasing global temperatures.

THE PROBLEM OF NUCLEAR POWER

The case is frequently made for building new nuclear power plants, resting on the premise that nuclear generation emits virtually no carbon dioxide and that it provides national energy security through electricity that costs less than that from nearly any other source. However, while established nuclear plants may be cheaper to operate than other fossil-fueled plants, the cost of financing, building, and insuring *new* nuclear power plants proves nearly untenable. In addition, the uranium and plutonium used for nuclear fission are finite resources that must be mined and processed, and the radioactive byproducts of nuclear generation—such as spent fuel rods—are undoubtedly a dangerous and life-threatening pollution source that will linger for thousands of years. Combine these realities with the potential for accidents that threaten the safety and health of entire communities—such as in Three Mile Island, Chernobyl, and most recently Fukushima in Japan—and the reason why no new nuclear plant construction has begun since 1977 in the U.S. becomes vividly apparent.

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An Overview of Photovoltaics and the Solar Industry

CHAPTER 2

SOLAR ENERGY INTERNATIONAL

The photovoltaic effect—converting sunlight into electricity—is a phenomenon that was discovered many years ago, and has had many applications over its history. As the demand for energy has continued to grow, so too have the number and size of PV systems. Currently, due to a combination of policy initiatives, economic incentives, the need to increase the supply of electricity, and a growing desire for clean, renewable energy, the PV industry is growing faster than ever before.

CHAPTER OBJECTIVES

- Understand the basic history of PV technology development.
- Identify the drivers behind the growth of the PV industry worldwide and in the U.S.
- Describe the major components of PV policy needed for a sustainable grid-direct PV industry in the U.S.
- Describe the basic types of PV financial incentives used in the U.S.

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Photovoltaics or Solar Electricity

Solar electric systems, commonly called photovoltaic (PV) systems, transform light from the sun directly into electricity—without any moving parts. They are used in a wide range of locations, on any scale, and work reliably for decades.

PV technology is used practically throughout the world for both grid-connected and off-grid applications. Photovoltaic systems have many advantages over non-renewable energy technologies:

- The fuel for PV systems is free. Fuel is generally the largest operating cost of generators and other fossil-fuel powered sources of electricity. Freely available sunlight makes PV systems ideal for remote locations and for distributed generation in grid-connected applications.
- As an energy source, the sun shines everywhere. Although some locations receive more sun than others, properly designed photovoltaic systems can produce sufficient energy to meet a large portion of electricity demand nearly anywhere.
- PV modules are very durable, so long-term maintenance and repair costs are very low. Manufacturers typically warrant module output for 25 years.
- PV systems are modular, so the capacity can be increased as the need for energy increases. Systems can start small and grow as budget and growing demand allows.
- When used and maintained properly, PV systems can be more reliable than conventional fossil-fuel generators.
- PV energy generation is silent.
- PV systems do not produce hydrocarbons or combustion emissions while operating.

History of Photovoltaics

In 1839, French scientist Edmund Becquerel discovered the photovoltaic effect while experimenting with electrolytic cells exposed to light. In 1883, Charles Fritts described the first selenium-based solar electric cell, which produced electricity without consuming any fuel or generating waste heat. At this point PV was born, though it would be many years before it was very effective or practical. In the 1950s, scientists at Bell Laboratories began using silicon, the earth's second-most abundant element, to develop far more efficient, though still very expensive, photovoltaic cells. Early silicon cells were only used in exotic places where power was extremely valuable—such as spacecraft in orbit. The search for more efficient, less expensive solar cells continues, and they are now capable of reliably generating electricity at

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a steadily decreasing price. In 2010, the U.S. installed enough solar electricity (PV and CSP [concentrating solar power] combined) to generate 1,000,000,000 watts (1 gigawatt). This is enough electricity to power about 200,000 homes.

How Solar Cells Work

A **solar cell** (see Figure 2.1) produces electricity whenever sunlight hits it, in a process as reliable and predictable as the sun rising and setting each day. When photons of sunlight strike the surface of a solar cell, the energy they carry is imparted to electrons in the cell, knocking them free. The electrons want to return to their source—meaning back to the cell—and the path that allows them to do this is a wire grid on the surface of the cell connected to further electrical wiring; this flow of captured electrons is electricity. However, unlike most electricity generators, no fuel (except sunshine) is used in the PV process. Regardless of the physics and chemistry behind solar electricity (discussed further in Unit 3), the most important concepts to understand are that the photovoltaic process is dependable and increasingly affordable.

Solar Cell

The smallest discreet component of a PV module that, when exposed to sunlight, generates electricity

A Note about the Terms "Solar" and "Grid-Direct"

In general, solar electricity receives the most media coverage and is a very visible renewable energy technology. As a result, it is common to read or hear the word

Figure 2.1: PV modules made of numerous solar cells are used in a wide range of applications; grid-direct PV systems are the fastest growing market segment.

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Basics of Electricity

CHAPTER 3

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This chapter focuses on the fundamentals of electricity, an important base of knowledge that will be built upon throughout the book. This chapter also covers the International System of Units (SI) prefixes commonly used to further quantify electrical terminology, such as kilo-, milli-, and mega-.

Becoming familiar with basic electrical terms and units and how they are interrelated, and being able to use the calculations in this chapter, are not only critical to understanding and designing PV systems, but also are applicable to other types of electrical systems.

CHAPTER OBJECTIVES

- Define the two types of electrical current (ac and dc) and explain their differences.
- Explain the relationships between volts, amps, amp-hours, watts, watt-hours, and kilowatt-hours.
- Perform basic power and energy calculations.

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Electrical Energy Sources

Photovoltaic (PV) Module

A module consisting of PV cells wired together to produce a desired voltage and current (electricity) when exposed to sunlight

Battery

A chemical energy storage device for dc electricity

Electricity is a secondary power source, meaning that it is produced from other, primary power sources. There are several primary sources from which electricity is produced and different means for storing it, including:

- Solar modules—also called **photovoltaic (PV) modules**—create electricity from light by a process known as the photovoltaic effect.
- **Batteries** store electricity in chemical form. Energy is released or absorbed through chemical reactions.
- Electromagnetic induction produces electricity by the rotation of a coil through a magnetic field. The energy for this rotation can come from fossil fuel-powered generators, steam-driven power plants, or from renewable sources such as spinning hydro turbines and wind turbines.

Electrical Terminology

Regardless of how it is generated, the terms used to describe and quantify electricity are the same.

Voltage

Voltage

The unit of electromotive force, or electrical pressure, denoted either by the scientific symbol E or the electrical symbol V

The first term to review is **voltage**. The scientific symbol for voltage is E, but it often is written as its electrical symbol, V, because it is measured in volts. Voltage can be thought of as "electrical pressure"; it is the unit of electromotive force.

It is common to use a water pressure analogy to illustrate electricity and distinguish between electrical terms: Imagine two large water tanks connected together at the bottom by a pipe, but with a closed valve between them; one tank is nearly full, and the other is nearly empty (see Figure 3.1). The full tank has the potential for water

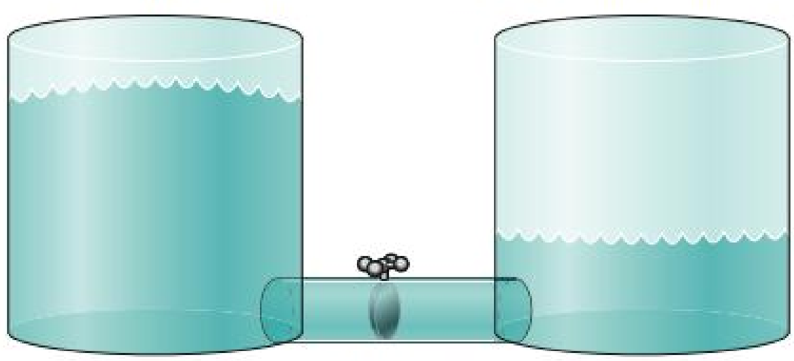

Figure 3.1: Voltage—or potential between two points—can be visualized with a water pressure analogy.

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to flow from it into the less-full tank, which will occur when the valve is opened between the two. Once the tank volumes level out, there will no longer be any difference between the two and thus no potential for flow. The water level difference between the two tanks—and thus the potential for flow—equates to voltage.

In order to have electron movement (and thus electricity), there also needs to be a difference in "pressure," shown in Figure 3.2 as the five-volt difference between the PV array and the storage battery. This is often referred to as a **voltage potential**. In order for the PV array to "push" electrons into the battery, it must have a higher voltage than the battery.

Voltage Potential

The difference in electrical "pressure" between two given points

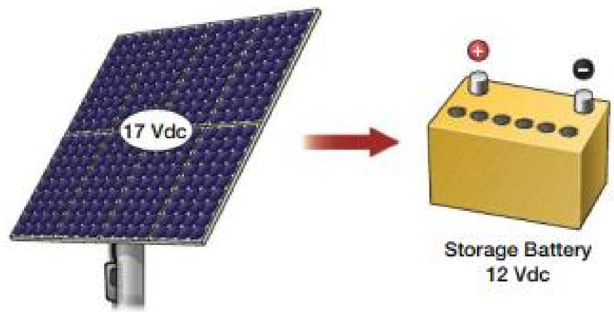

Figure 3.2: Voltage potential is a difference in electrical "pressure"—the higher voltage of the PV array allows it to charge the battery.

Current or Amperage

The next term to become familiar with is **current**. The scientific symbol for current is I, for the "intensity" of the current, but it can also be expressed by its electrical symbol, A, because it is measured in amperes, which is often shortened to "amps."

Current

The rate of the flow of electrons through a conductor, also called amperage and denoted by the scientific symbol I or the electrical symbol A

Current can be thought of as the rate of the flow of the electrons through a wire. Continuing the water analogy, current is how fast the water is flowing, and would be measured in gallons per minute.

The coulomb (kū lŏm) is a unit equal to 6.24×10^{18} (6.24 billion billion) electrons. That's a lot of electrons! When one coulomb passes a point in one second, one amp of current has flowed. In other words, 1 amp = 1 coulomb per second. The coulomb is not a unit that is mentioned very frequently, but current, measured in amps, is a critical part of system design.

Resistance

The next term is **resistance**, which is the opposition of a material to the flow of an electrical current, much like the way friction reduces the flow of water through a pipe. Electrical resistance is measured in ohms and written either as the Greek letter Omega (Ω) or R.

Resistance

The opposition to electrical current flow based on material type, diameter, length, and ambient temperature; measured in ohms and written either as Ω (the Greek letter Omega) or R

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Components

CHAPTER

4

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In this chapter, the focus is on the different types of PV systems and the ways they are configured. Depending on whether a PV system is being used to power a boat, a grid-connected home, or a remote telecommunications site, some system configurations will be better suited than others. And in fact, some won't work at all for certain applications. The different system types covered are PV direct, stand-alone, grid-direct, and grid-tied with battery back-up.

It is important to be able to accurately catalog and describe all the necessary components in each type of system and to be able to diagram a basic schematic showing the interaction among components and the direction of energy flow.

CHAPTER OBJECTIVES

- List the features and applications and identify a schematic of the following PV system configurations:
  - PV direct
  - Stand-alone
  - Grid-direct
  - Grid-tied with battery back-up
- Identify and describe the basic functions of the different components that make up these systems.

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Photovoltaic Modules

Photovoltaic (PV) Module

A module consisting of PV cells wired together to produce a desired voltage and current (electricity) when exposed to sunlight

Photovoltaic (PV) modules generate dc electricity from sunlight and are one of the common components in all of the system types in this chapter (see Figure 4.1 and Chapter 5). Once a group of modules is wired together, mounted on a structure, and connected to other components, they are referred to as an array.

Loads

Electrical Load

Any device that uses ac or dc electricity to operate, such as computers, dishwashers, and refrigerators

Any equipment that uses electricity to function—from a light bulb to a freezer to an arc welder—is called an **electrical load**. Loads are the other common component in all of the system types in this chapter. Most electrical loads are designed to run on either ac or dc electricity, not both. For example, the compact fluorescent lamps

Figure 4.1: PV modules generate dc electricity from sunlight.

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found in a conventional hardware store only run on ac power. However, there are also versions of compact fluorescents that only operate on dc power.

Because the world is dominated by ac electricity distribution, ac loads are most common. DC appliances are considered to be specialty items and can be difficult, and in some cases impossible, to find. Good places to look for dc devices are solar product distributors and RV or marine stores. Selection is typically limited, but everything from televisions to ceiling fans and electric hot water elements are available.

PV Direct

The most basic PV configuration is a **PV direct system** (see Figure 4.2). Two examples of common PV direct systems are solar attic fans (see Figure 4.3) and solar water pumping projects that use cisterns or storage tanks (see Figure 4.4).

PV Direct System

The simplest type of PV system, consisting of only a PV module and a dc load

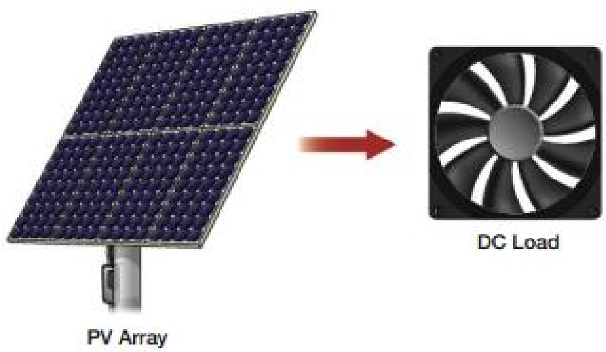

Figure 4.2: The most basic PV system configuration is PV direct.

Figure 4.3: The PV module provides power for the attic fan; when there is lots of sun—and presumably lots of heat in the attic—the PV module directly runs the fan.

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Photovoltaic (PV) Modules

CHAPTER 5

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There are many different types and technologies of PV modules, but they all have the same goal—to efficiently and reliably produce electricity from sunlight. This chapter describes the photovoltaic effect, the different types of PV cell technologies, and PV terminology; it also investigates the effects of temperature and sunlight intensity on PV performance and examines manufacturers' specifications and marketing claims.

CHAPTER OBJECTIVES

- Describe how a PV cell produces electricity from sunlight.
- Identify the differences among various PV cell technologies.
- Predict the effects of temperature and irradiance on voltage and current values.
- Decipher important data from module specification sheets.

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Terminology

Photovoltaic (PV) Cell

The smallest module component capable of producing electricity from the sun; produces one-half a volt, with the amount of current depending on the surface area

PV Module

A group of cells wired together, encapsulated, and sometimes framed

PV Panel

Although often used interchangeably with the term PV module, actually a collection of modules that form a single, field-installable unit

PV Array

A group of PV modules or panels wired together and mounted to a surface

Semiconductor

A material that can conduct electrical current to a degree between that of an insulator and a conductor

P-N Junction

The area of a PV cell where the positive and negative layers come together and an electric field is created with a 0.5 volt dc potential difference between the two layers of silicon cells

Solar electric module terminology starts with the **photovoltaic (PV) cell**, the smallest component capable of producing electricity from the sun (see Figure 5.1).

PV cells are wired together, laminated between glass and a backing material, and typically framed with aluminum to form a **PV module**. Technically, a group of modules wired together is called a **PV panel**, but in the field the terms panel and module are often used interchangeably. Finally, the PV panels, however many there may be, wired together form a **PV array**.

How a PV Cell Works

A silicon PV cell is a **semiconductor** with two main layers, as shown in Figure 5.2: the positive, or "P", layer, and the negative, or "N", layer. The positive layer is doped, or chemically treated, with boron to give it a positive charge, and the negative layer is doped with phosphorus to give it a negative charge.

The area where the positive layer and the negative layer come together is called the **P-N junction**, and an electric field is created with a 0.5 volt dc potential between the two layers. The P-N junction also acts as a barrier: It permits electrons to travel through the cell from the P layer to the N layer, but not in the other direction.

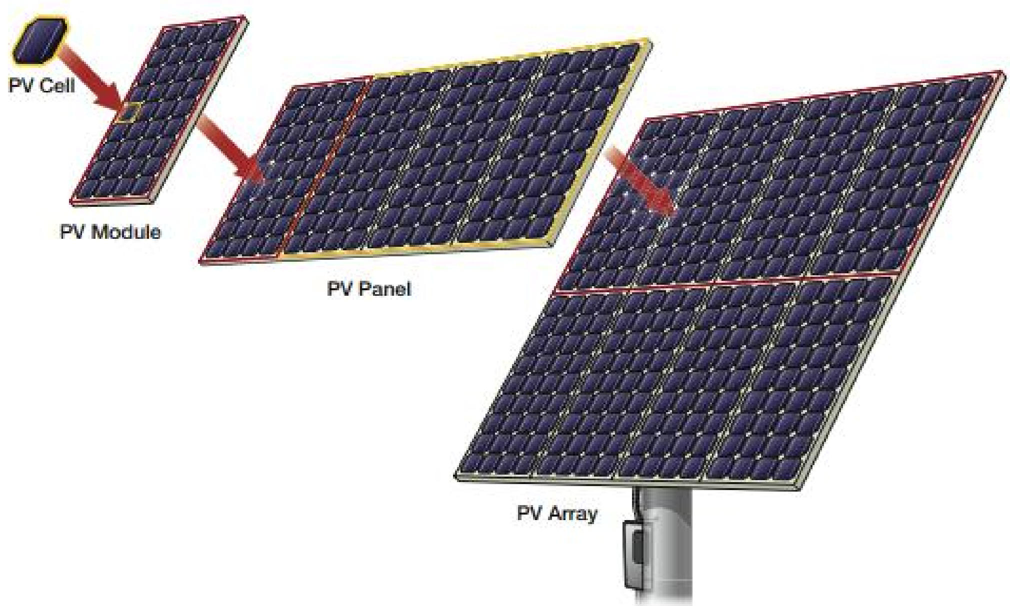

Figure 5.1: From smallest to largest, PV technology starts with the cell, continues to the module, then the panel, and finally the array.

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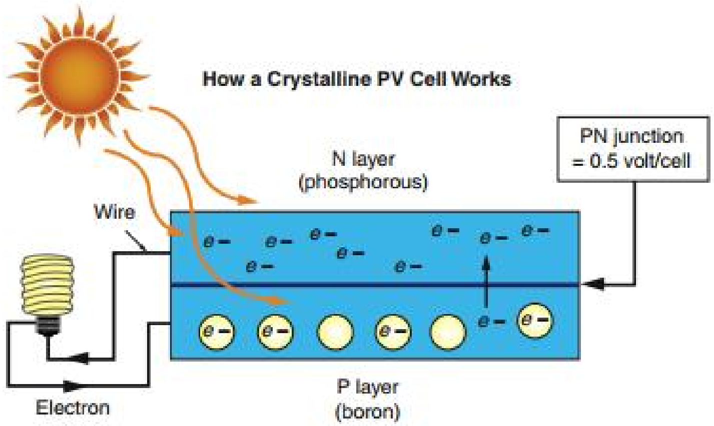

Figure 5.2: In this sideview of a silicon PV cell, electrons from the negative layer of the cell flow through the load and return to the positive side.

A conducting wire grid is placed on the top and bottom of the cell. When photons of sunlight strike the PV cell surface, their energy bumps electrons in the N layer silicon into the conduction band of the crystalline semiconductor cell structure. The wire grid on the cell provides a low-resistance path for the electrons to flow to the P layer, but first they are routed through an electrical load, represented by the light bulb in Figure 5.2.

Because the voltage of an individual crystalline PV cell is only ≈ 0.5 Vdc, a PV module consists of numerous cells, wired together in series. The connection between the P layer of one cell and the N layer of an adjacent cell increases the overall voltage, which is additive in series. When 36 cells are wired in series, the expected voltage of the module would be around 18 volts. Unlike voltage, the current of the cell is dependent on the surface area, meaning the larger the cell, the more current it can produce. In general, the current of each cell will be the same as the current of the module (though in some cases it may only be half of the module current).

THE NATIONAL RENEWABLE ENERGY LABORATORY (NREL)

The National Renewable Energy Laboratory (NREL) is the only federal laboratory dedicated to the research, development, commercialization, and deployment of renewable energy and energy efficiency technologies. It is a government-owned, contractor-operated facility, funded through the U.S. Department of Energy (DOE).

NREL's research and development programs range from understanding renewable resources for energy, to the conversion of these resources to renewable electricity and fuels, and ultimately to the use of renewable electricity and fuels. NREL's research and development capabilities include everything from

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