Introduction

Photovoltaic (PV) systems are unique electrical generation systems that use semiconductor technology to make electricity directly from sunlight. Unlike solar water heating systems, which convert sunlight directly into heat, the purpose of PV systems is to generate electricity from sunlight. The first PV cells were developed by Charles Fritts in 1883. These primitive cells consisted of a selenium wafer covered by a thin layer of gold. Though interesting, the cells were quite expensive and did not produce enough electrical power for practical use. In 1954, Bell Laboratories developed a more powerful PV cell by integrating specific impurities into silicon-based semiconductors. The Bell engineers sought a cost-effective source of power for rural telephone systems and early PV modules were used for this purpose. The advent of space exploration in the late 1950s provided another practical use for solar PV cells. Sunlight is abundant in space and provides a never-ending source of energy. PV cells have been used as a source of electrical power for virtually all spacecraft since the Vanguard I satellite in 1958 (Figure 1).

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Figure 1
Photovoltaic cells provide power for satellites

The use of early PV cells was limited due to the high cost and relatively low power output. Applications focused on satellites, spacecraft and remote earth-based applications such as rural communications and off-grid cabins through the 1990s. However, in the

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late 1990s and after the turn of the century, the cost per watt began to decrease and the power output increased. This made widespread use a practical reality for the first time. The first utility-scale PV power plants were built by Atlantic Richfield oil company (ARCO) in California in response to the energy crises of the 1970s. The Lugo plant in Hesperia, California, produced 1 megawatt (MW), while the Carrizo Plain plant provided 5.2 MW of electricity from 1983 until it closed in 1994.

In the years that followed, continued advances in solar technology resulted in dramatic increases in the installation of distributed solar systems on individual homes and businesses and the construction of large-scale PV power plants. By December 2019, the completion of 1 million California residential PV systems was marked by a celebration in Fresno, California. Presently, there are another 1 million systems installed throughout the US, bringing the total to over 2 million. The majority of residential systems are located on rooftops with most of the rest ground mounted. Most residential PV systems produce power in the 4 to 8 kilowatt (kW) range. Large-scale ground-mounted systems, also known as "utility scale," provide power production ranging from hundreds of kilowatts (kW) to hundreds of megawatts (MW). Currently, the largest single current installation in the United States, Solar Star, produces 579 MW from 1.7 million PV modules located on a 3,200-acre site in the Southern California desert. Solar PV systems currently provide over 2 percent of the US

Figure 2

A large-scale PV system

electrical supply. However, for some states, that number is considerably higher. California derives 14 percent of its electrical supply from solar PV systems. Nationwide, a growth rate in excess of 20 percent per year has resulted in a total installed capacity in excess of 13,000 MW as of 2019 (Figure 2).

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The Photovoltaic Effect

Photovoltaic cells are created by infusing a semi-conductor material, usually silicon, with other elements. The process of infusion is known as "doping." The term "semi-conductor" applies to materials that are neither good insulators nor conductors of electricity. The quantity of valence or free electrons in the outer shell of the atom is the determining factor as to whether a material is an insulator (less free electrons), a conductor (more free electrons) or a semi-conductor (four electrons in the outer shell). Semi-conductor materials can be infused, or doped, with other elements so that the outer shell of the atom has less electrons creating P-type material. If infused so that there are more electrons in the outer shell, N-type material is created. Since electrons have a negative charge, a greater quantity of electrons is more negative (N for negative) than a lesser quantity of electrons (P for positive). Joining N-type material with P-type material creates the P-N junction, the basis for all digital electronic circuits. A semi-conductor device doped so that there is a single P-N junction is known as a "diode." Photovoltaic cells are diodes that emit excess electrons when photons strike the P-N junction. Photons are the basic unit of electro-magnetic radiation or light from the sun. The flow of electrons is, by definition, electrical current. The process that causes a diode to produce current when exposed to photons is known as the "photovoltaic effect" (Figure 3).

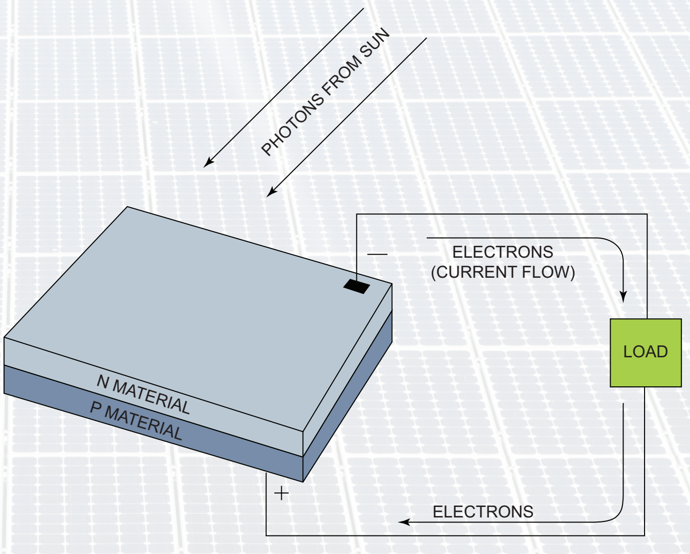

Figure 3
Photons from sunlight produce electrons from the solar cells

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