

CHAPTER 5

PV Modules



A solar photovoltaic system has many components. Perhaps the most important component is the PV modules because they are the part of the system that produces the electricity that is supplied to a building or to the electric utility grid. It is very important for a PV system installer to understand how electricity is produced by a PV module and the differences among the various types of PV modules available in today's marketplace. This chapter takes a detailed look at the performance characteristics of PV modules, including how to analyze a module's I-V curve. The effects of temperature and shading on PV modules are also discussed.

Glossary of Terms

amorphous Having no definite form or distinct shape.

cell The basic unit of a PV module; modules are made up of several cells wired in a series or parallel configuration to deliver a desired voltage and current.

diode A semiconductor device that allows current to pass through in only one direction.

doping The process of adding impurities to silicon that results in changes to the silicon's electrical properties.

flat-plate The most common design of PV modules.

maximum power point (MPP) Indicates the maximum output of the module and is the result of the maximum voltage (V_{mp}) multiplied by the maximum current (I_{mp}).

multicrystalline silicon A module type where the solar cells are made of variously oriented individual crystals.

open circuit voltage (V_{oc}) The maximum voltage when no current is being drawn from the module.

photovoltaic effect The process of making electricity in a PV cell.

ribbon silicon A module type where the cells are made from continuous multicrystalline strips.

semiconductor A material that can be either an insulator or a conductor, depending in large part on the temperature of the material.

short circuit current (I_{sc}) The maximum current output of a module under conditions of a circuit with no resistance (short circuit).

Objectives

Upon completion of this chapter, the student should be able to

- Demonstrate an understanding of how electricity is produced by a photovoltaic cell.
- Demonstrate an understanding of what a PV module is made of.
- Demonstrate an understanding of the differences among single crystalline, multi-crystalline, and thin-film types of silicon PV modules.
- Recognize the differences among PV cells, modules, panels, and arrays.
- Analyze the I-V curve of a PV module.
- Demonstrate an understanding of the effects that temperature and shading have on the performance of a PV module.
- Demonstrate an understanding of the common testing standards for PV modules.

single-crystalline silicon A module type where the solar cells are made of a single crystal.

substrate material The lower layer of a PV module that completes the solar cell encapsulation and helps protect the solar cells and give the module strength.

superstrate A PV cell configuration in a module where glass is not only used as a supporting structure but also as a window for the illumination of the cells.

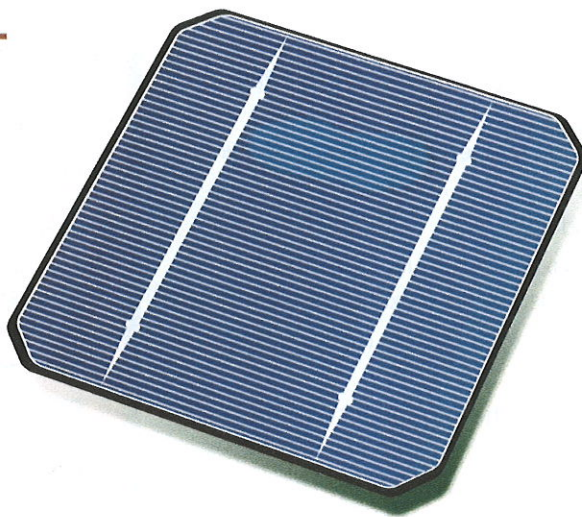
PV Modules

The primary component of a PV system is the solar **cell** (Figure 5-1). PV cells convert sunlight into direct current (DC) electricity. A typical PV solar cell is about 1/100 of an inch ($\frac{1}{4}$ mm) thick and 6 inches (153 mm) across. They produce about 1 watt of power in full sunlight at about $\frac{1}{2}$ volt DC. They have a very long lifespan and can produce electricity from the sun for 25 years or more.

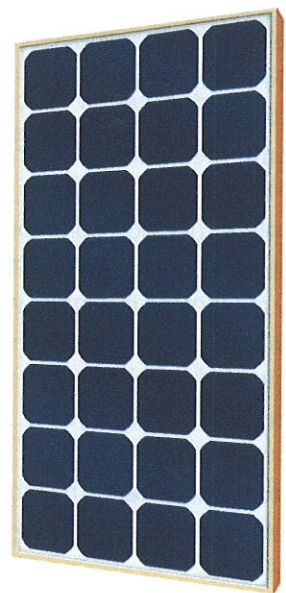
Photovoltaic modules (Figure 5-2) are assemblies of solar cells wired together to produce a desired voltage and current. The current output of a module depends on the surface area of the solar cells in the modules. The most common PV module design is a **flat-plate** module. In the flat-plate design the cells are covered with an antireflective coating to enhance sunlight absorption. PV cells are encapsulated within the module framework to protect them from the weather. They are laminated between a clear outer superstrate and an encapsulating inner substrate. The term **superstrate** refers to a PV cell configuration in a module where glass is not only used as a supporting structure but also as a window for the illumination of the cells. As part of the solar cell encapsulation, the glass is above the solar cell and becomes the outer layer, or “super”-strate. A **substrate material**, or lower layer,

FIGURE 5-1

A photovoltaic solar cell, the primary component of a PV system.



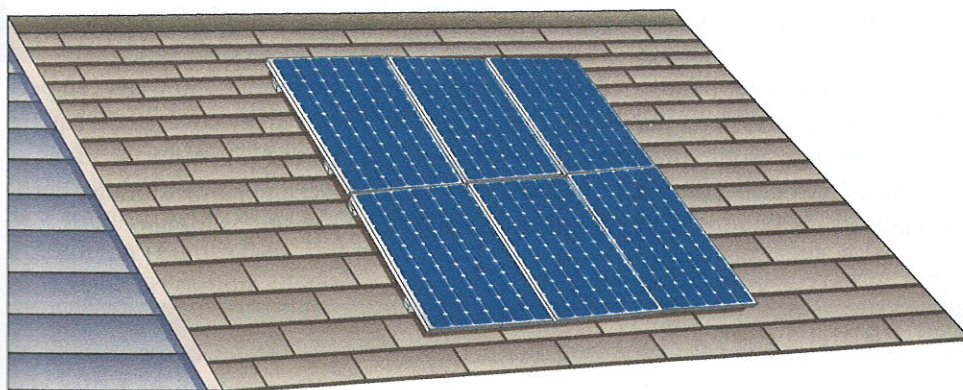
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FIGURE 5-2

A flat-plate PV module. This module consists of several PV cells wired in series to produce a desired voltage and current.

**FIGURE 5-3**

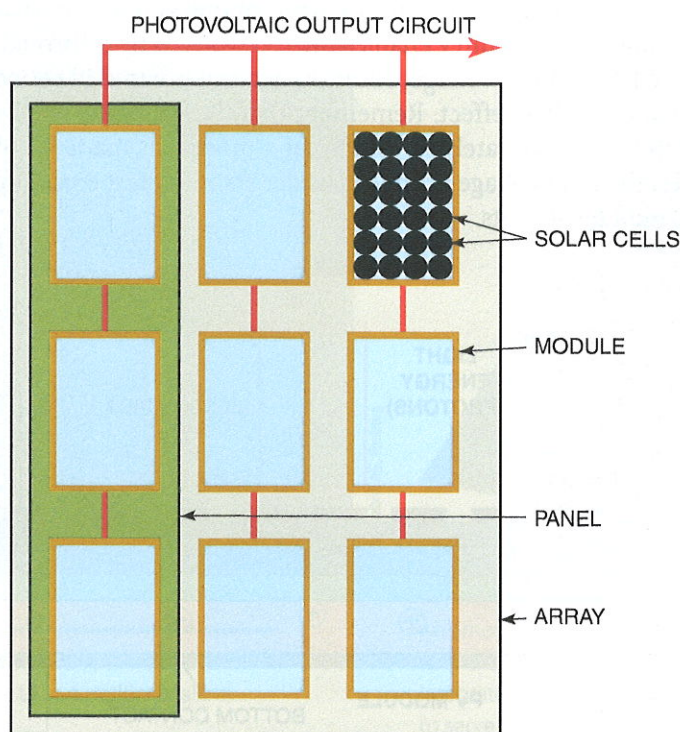
An array is a group of modules wired together to get a desired voltage and current.

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completes the solar cell encapsulation and helps protect the solar cells and give the module strength. Modules used in today's PV systems typically are rated from 100 to 300 watts. Modules with higher wattage ratings are physically larger. Higher rated modules are desirable because the cost per watt is lower. The terms *panel* and *module* are used interchangeably, but according to the *National Electrical Code*®, a panel is technically a group of modules wired together to get a desired voltage.

An array (Figure 5-3) is a group of modules wired together to get a desired voltage and current. The array is the part of a PV system that is usually visible because of where it is located. It is made up of several PV modules and takes up a large area. The array can be roof mounted, ground mounted, pole mounted, or even integrated into a building's structure. As a general rule, the larger the array, the larger the amount of electrical power that the PV system can produce. On the other hand, the larger the array, the more money the PV system will cost. Figure 5-4 shows the location of a solar cell, module, panel, and array in a solar photovoltaic system.

A module is not very efficient when it comes to converting sunlight to electricity. Many modules convert only about 10 to 15 percent of the available solar

**FIGURE 5-4**

The location of a solar cell, module, panel, and array in a solar photovoltaic system.

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radiation to electrical energy. For example, if an array consisted of modules with 15 percent efficiency and it was mounted where it would receive 1000 watts per square meter of solar irradiance, the array would produce about 150 watts (15 percent \times 1000 watts) per square meter of array area. If this array covered 50 square meters, the array would produce about 7500 watts of power ($150 \text{ W/m}^2 \times 50 \text{ m}^2 = 7500 \text{ watts}$). Module efficiency has continued to improve, and some modules commercially available today have efficiency ratings of 19 percent or higher.

The Photovoltaic Effect

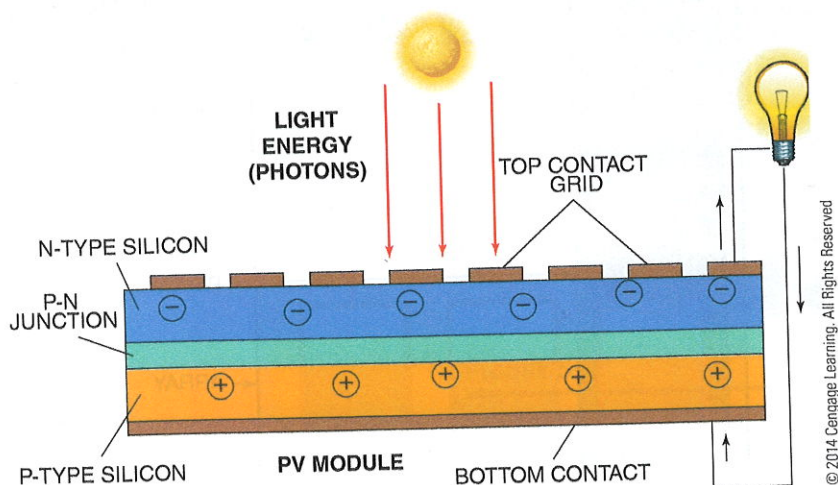
The voltage production in a PV cell is called the **photovoltaic effect**. To understand the photovoltaic effect, you must first understand a little about how silicon based PV cells are made.

The manufacturing process of a single crystalline cell starts with silicon being purified and grown into a crystalline structure. Silicon in its pure form is called a **semiconductor**. A semiconductor is a material that can be either an insulator or a conductor, depending in large part on the temperature of the material. Colder temperatures cause semiconductors to act more as an insulator, and warmer temperatures cause semiconductors to be more like a conductor. Impurities are added to the silicon through a process called **doping**, which changes the silicon's electrical properties.

The silicon is grown into a cylindrical shape and then sliced into very thin wafers that are doped with either boron or phosphorous. Boron, which has an electron deficiency, creates a positively charged material (P-type). Phosphorous, which has an excess of electrons, creates a negatively charged material (N-type). The region in the cell created by the positive and negative layers is called the P-N junction. A voltage in the PV cell is produced when sunlight causes the loosely held electrons to move from the silicon layer. These electrons are attracted to the positively charged boron layer. An electrical force is developed at the P-N junction, and electrons begin to flow through metal contacts built into the cell. The contacts in a cell are connected from the front of one cell to the back of another cell in the module. This circuitry enables the electrons to flow through P-N junctions of each cell, building a voltage, because each cell is wired in series. Figure 5-5 illustrates the photovoltaic effect. Remember that the voltage at the P-N junction of each PV cell is approximately $\frac{1}{2}$ volt. So, if a module is made up of 72 cells all wired in series, the total voltage produced under standard test conditions (STC) by the module would be 36 volts.

FIGURE 5-5

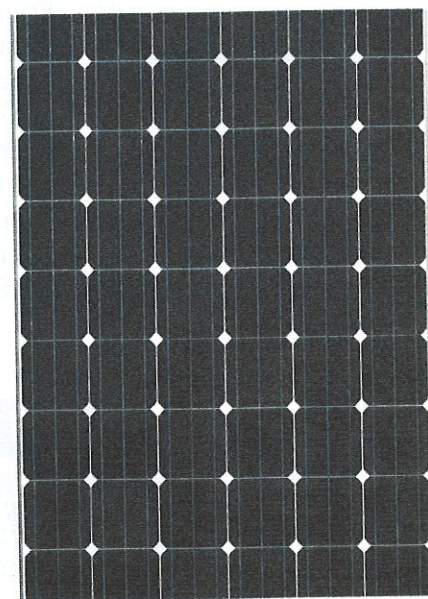
An illustration of the photovoltaic effect.



PV Module Types

Modules can have different cell material, glazing material, and electrical connections. The type of module typically used today is determined primarily by the composition of the silicon crystalline structure. If it is grown as a single crystal, it is called **single-crystalline silicon** or monocrystalline silicon (Figure 5-6). If it is cast into an ingot of multiple crystals, it is called polycrystalline silicon or **multicrystalline silicon** (Figure 5-7). If it is drawn out and allowed to cool and then solidify as a continuous multicrystalline strip, it is called **ribbon silicon**. If it is deposited as a thin film, it is called **amorphous silicon** or just thin-film (Figure 5-8). Amorphous means that there is no definite shape that the module comes in. Thin-film modules are available in a variety of shapes and styles. Single-crystalline cells are a little more efficient than polycrystalline cells. Amorphous silicon is less expensive to manufacture but is only about half as efficient as single-crystalline cells.

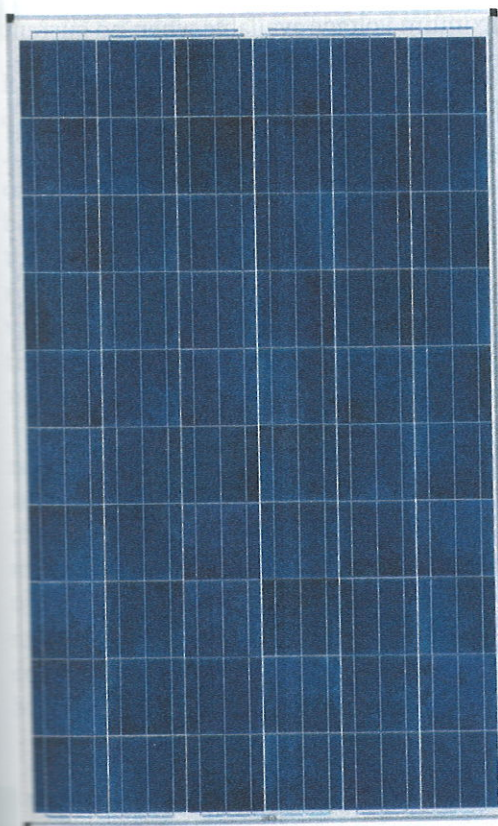
Concentrator modules incorporate small solar cells surrounded by some type of reflective material that concentrates sunlight onto the cells. They are more efficient than regular modules but are not typically used in residential or commercial PV systems.



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FIGURE 5-6

A single-crystalline silicon PV module. It can also be referred to as a monocrystalline silicon module.



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FIGURE 5-7

A polycrystalline silicon PV module. It can also be referred to as a multicrystalline silicon module.

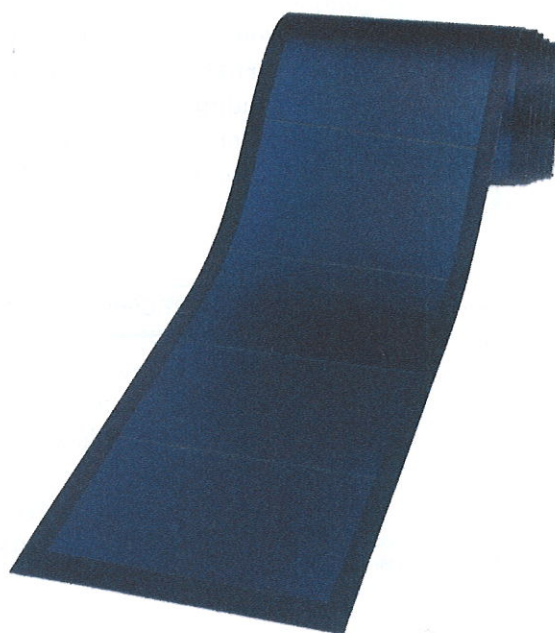


Photo Courtesy of Inovateus Solar

FIGURE 5-8

An amorphous silicon PV module. It can also be referred to as a thin-film module. The module shown is a Building Integrated Photovoltaic (BIPV) module and is designed to serve a dual purpose of roofing and power generation.

Other Solar Cell Types

Even though silicon cells are still the most common type of solar cell, other types are available, including copper indium gallium selenium (CIGS) and cadmium telluride (CdTe). Gallium arsenide (GaAs) cells are very efficient but are cost prohibitive to produce. However, because of their high efficiency, they are used extensively in satellite and other outer-space applications.

Another type of solar cell called a photoelectrochemical cell actually uses a chemical process to produce electricity from sunlight. Although not currently being used in residential and commercial PV systems, it is expected that this cell type will find its way into the marketplace in the future.

PV Module Performance Characteristics

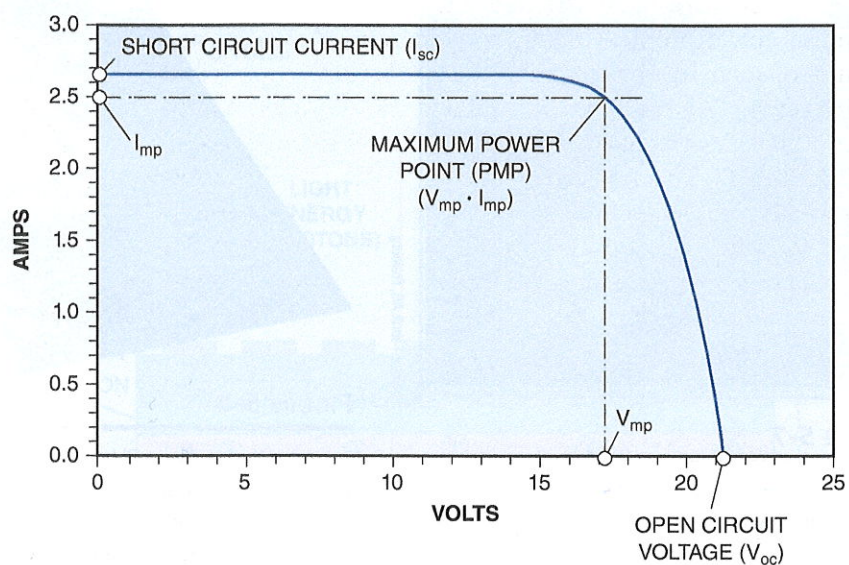
Output characteristics for a PV module can be found in an *I-V curve* (Figure 5-9). An I-V curve is simply a representation of all of the different voltage and current values for a specific module in standard operating conditions. These values are usually based on standard operating conditions of a solar irradiance of 1000 watts per square meter and cell temperature of 77°F (25°C). The information from a module's I-V curve is used to rate module performance and to help determine the size of the PV system array.

Open circuit voltage (V_{oc}) is the maximum voltage available when no current is being drawn from the module. It is used to determine the maximum circuit voltage for both a module and an array. You can verify the open circuit voltage by allowing sunlight to shine on a module or array and then measure the voltage across the output terminals with a voltmeter (Figure 5-10). Remember that the voltage is DC, so set your meter accordingly.

The **short circuit current (I_{sc})** is the maximum current output of a module under conditions with no resistance (a short circuit). At this point on the I-V curve, the voltage is 0 and the power output is also 0. The short circuit current is important for an installer to know because it is used to determine maximum

FIGURE 5-9

An I-V curve for a common PV module size.



available circuit currents in the PV system and is used to size overcurrent protection devices and system conductors. You can verify the short circuit current by using an ammeter to take the measurement. If the I_{sc} is 10 amps or less, most multimeters set to measure amperage can be connected directly across the module leads (Figure 5-11). It is safe to use a multimeter to measure amperage directly inline with a module because the short circuit currents are low. If the I_{sc} is greater than 10 amps, you'll need to use a clamp-on ammeter attachment with a multimeter, or a separate clamp-on ammeter. Remember that the current being measured is DC so the meters will need to be set accordingly. Most clamp-on ammeters can only be used on alternating current (AC) circuits.

Maximum power point (MPP) (P_{mp}) (P_{max}) indicates the maximum output of the PV module and is the result of the maximum voltage (V_{mp}) multiplied by the maximum current (I_{mp}). Maximum power is sometimes referred to as peak power or peak watts. V_{mp} is the operating voltage when the module's power output is at maximum. I_{mp} is the operating current when the module's power output is at maximum. For example, if a module's V_{mp} is 25 volts and I_{mp} is 6 amps, the P_{mp} would be 150 watts.

PV Module Operating Point

It is the electrical load, or the battery bank if used, that actually determines the operating point of a module on an I-V curve. As seen on an I-V curve, the short circuit current (I_{sc}) is based on 0 ohms load resistance, and the open circuit voltage (V_{oc}) is based on an infinite amount of load resistance. Any point along the module's I-V curve has a specific load resistance that corresponds to a specific operating voltage and operating current. The value of the load resistance increases as you follow the I-V curve from the left to the right. Use Ohm's law to find the resistance needed to operate a PV module at any point on the I-V curve.

Solar cells work most efficiently when operating at their maximum power points. Changing temperatures and varying amounts of solar irradiance mean the maximum power point changes often. As a result, most installers choose to use equipment in their PV systems that provides maximum power point tracking (MPPT). This feature will maximize PV module performance and is included in most grid-tie inverters and a few charge controllers used in stand-alone systems. Equipment that has MPPT will be discussed in greater detail later on in this textbook.

PV Module Efficiency

The efficiency of a PV module is based upon how well the incoming solar power is converted to usable electrical power. You might remember that to find the percent efficiency of an electrical machine like a motor, you divide the output power by the

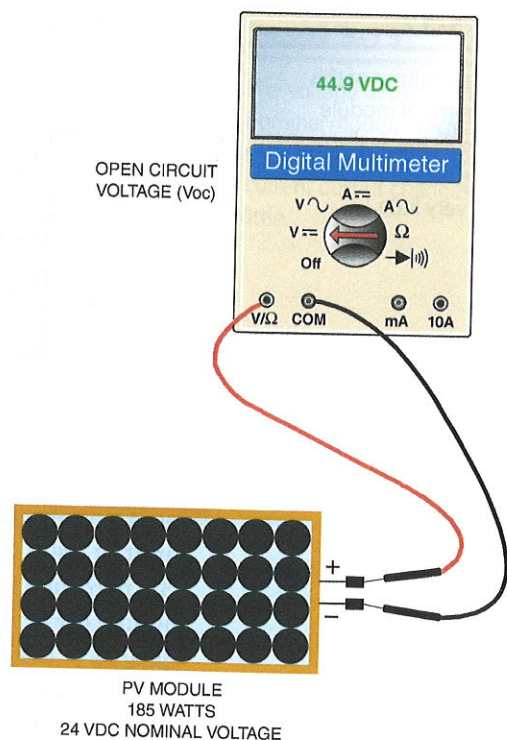


FIGURE 5-10

Measuring the open circuit voltage (V_{oc}) of a PV module.

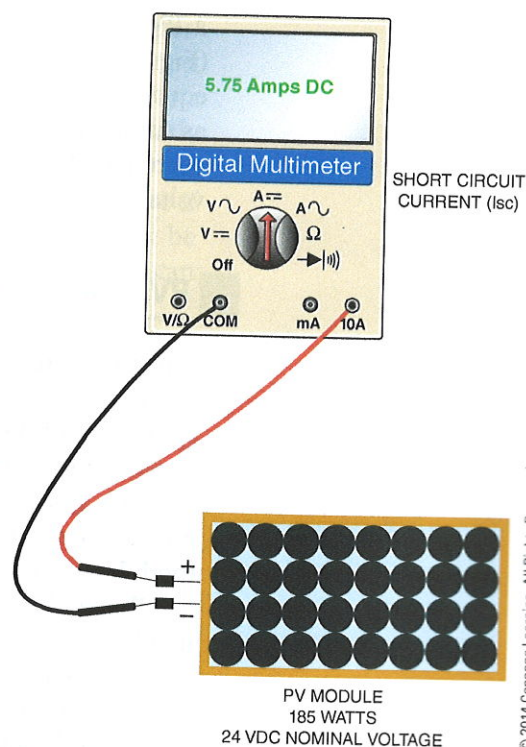
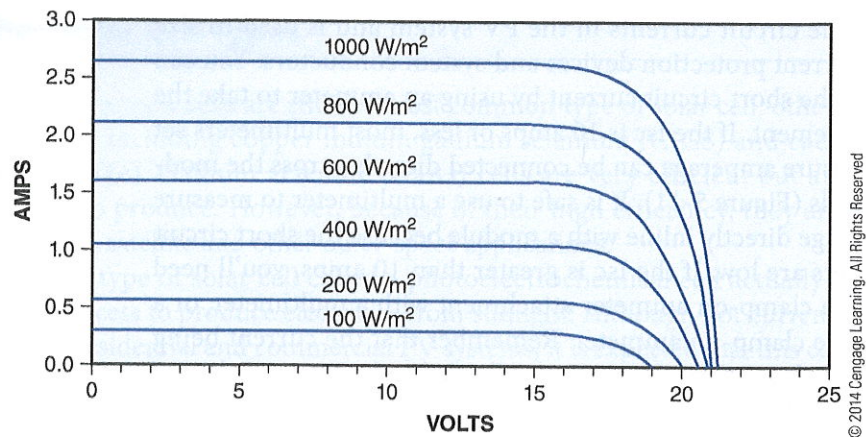


FIGURE 5-11

Measuring the short circuit current of a PV module with a multimeter.

FIGURE 5-12

The current output of this 12 VDC nominal module decreases as the available solar irradiance decreases. Voltage changes very little.



input power and then multiply by 100. For example, if a 1HP electric motor has an input of 1800 watts and an output of 1500 watts, the motor's efficiency would be 83.3 percent: $(1500 \text{ watts} / 1800 \text{ watts}) \times 100 = 83.3 \text{ percent}$). The efficiency of a PV module (or array) is found in much the same way. Solar irradiance is multiplied by the area of the module (or array) to get the solar power in watts. It is then divided into the maximum power output of the module (or array). For example, a PV module that has 1.5 square meters of area and a maximum power output of 170 watts is exposed to a solar irradiance of 1000 watts per square meter. The module's percent efficiency is 11.3 percent: $(170 \text{ watts} / 1.5 \text{ m}^2 \times 1000 \text{ W/m}^2) \times 100 = 11.3 \text{ percent}$.

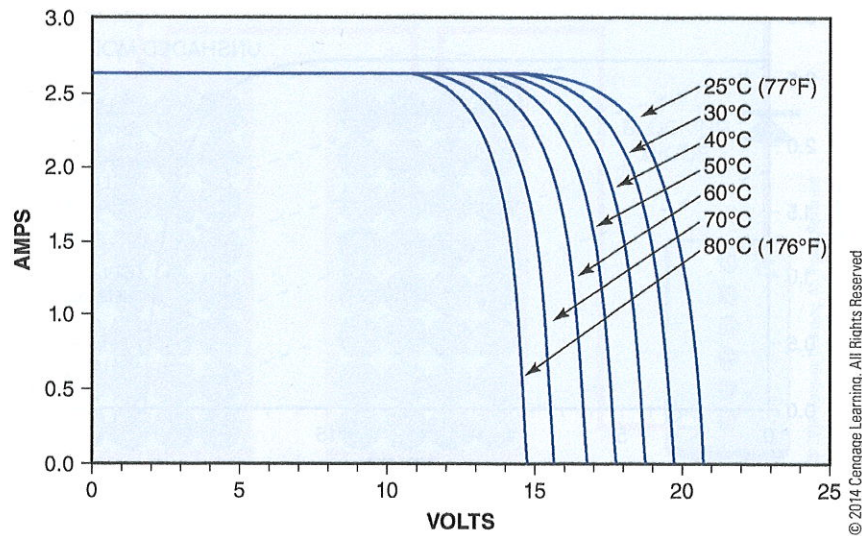
Effect of Sunlight Intensity

A PV module's current output is proportional to the intensity of the solar radiation (Figure 5-12). More intense light equals greater module output. Less intense light equals a smaller module output. The I-V curve shape remains basically the same as sunlight intensity drops, but it does move downward, indicating both a lower current and power output. However, even as the current and total power drops, the voltage is not changed very much.

PV Module Cell Temperature

When the temperature of a module's cells warm up to above the standard operating temperature of 77°F (25°C), the module operates less efficiently and the voltage decreases (Figure 5-13). The I-V curve shape remains basically the same as cell temperature increases above 77°F (25°C), but it does move toward the left, indicating both a lower voltage and power output. However, even as the voltage and total power drop, the current is not changed very much. Airflow under and over the modules is critical to help keep the cell temperature as low as possible.

Remember that a PV module's wattage rating is based on 1000 W/m² of solar irradiance at a standard test condition (STC) temperature of 77°F (25°C). However, because of the high temperatures encountered on roofs or from sunlight heating the modules up over several hours, an adjustment to the module rating has to be made. A rating system called PTC (PV USA test conditions) has been developed to account for the normally high module temperatures. The PTC rating is also based on a solar irradiance of 1000 W/m², but uses 68°F (20°C) *ambient* temperature rather than cell temperature. This means that the PTC ratings

**FIGURE 5-13**

The voltage of this 12 VDC nominal module decreases as the cell temperature rises. The current output changes very little.

are about 88 percent of the STC ratings. For example, a 200-watt-rated STC module would have a 176-watt PTC rating. PV system designers often use the PTC ratings to compensate for the reduced performance of modules rated under the STC system.

PV Module Shading

Shading greatly affects the performance of PV modules (Figure 5-14). Even partial shading results in a large output reduction. In some cases, even just 10 percent shading of the area of a module (or array) can result in the loss of almost all output. Figure 5-15 shows the effect of shading on module performance for a 12-volt PV module. Shading can also affect a module's performance differently depending on where the shade is located on a module. Because solar cells are typically connected in series with each other, shading affects a module more if all strings are shaded (Figure 5-16). Don't forget that a PV array should not be shaded from 9 A.M. to 3 P.M. Some shading at other times is *not* desirable but can be tolerated.

Percent of One Cell Shaded	Percent of Module Power Loss
0%	0%
25%	25%
50%	50%
75%	66%
100%	75%
3 cells shaded	93%

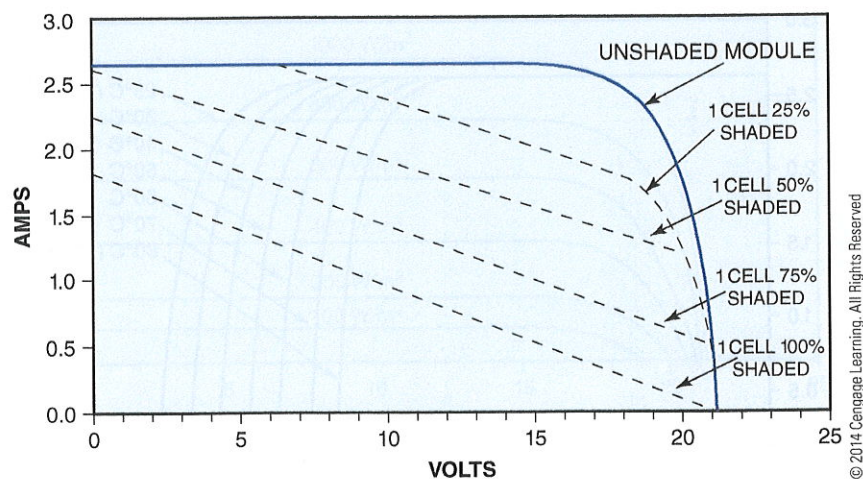
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FIGURE 5-14

The effect of shading on a single-crystalline PV module's power output. These numbers assume no bypass diodes are used.

FIGURE 5-15

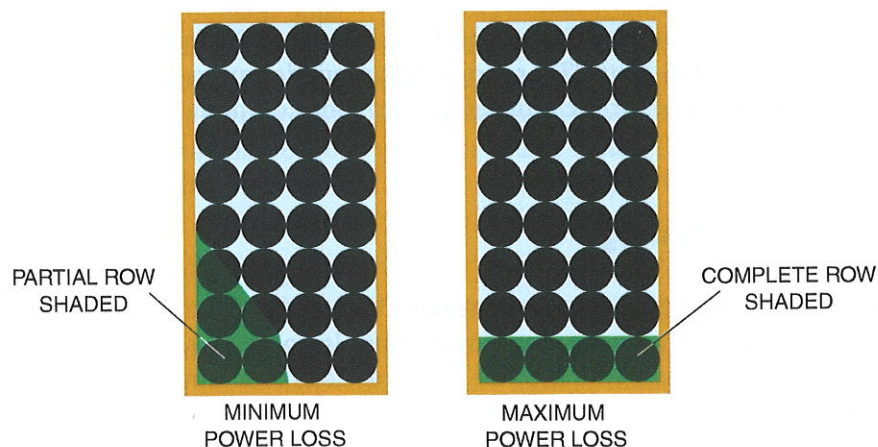
The effect of shading on a common 12-volt PV module.



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FIGURE 5-16

Because of the series connection of cells in a PV module, shading can affect a module's performance differently depending on where the shade is located on the module. When a whole row is shaded, there is very little, if any, available power.



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PV Modules and Diodes

A **diode** is a semiconductor device that allows current to pass through in only one direction. Blocking diodes (Figure 5-17) are placed in the positive line between modules and the battery bank to prevent battery current from reversing its flow from the battery bank to the array at night or during cloudy weather. Most charge controllers already have blocking diodes or can perform this function in some other way, so a PV system electrical installer does not often have to install blocking diodes. Bypass diodes (Figure 5-18) are wired in parallel with a module to divert current around the module in the event of too much shading. Even with the use of bypass diodes, shading can greatly reduce the performance of a PV module. Sometimes they are embedded in the module laminate in the manufacturing process and cannot be accessed for service. Other manufacturers install them in a junction box attached to the module. If you install them yourself, they should be sized to handle at least twice the maximum current they are expected to carry and sized for at least twice the voltage that will be applied to them.

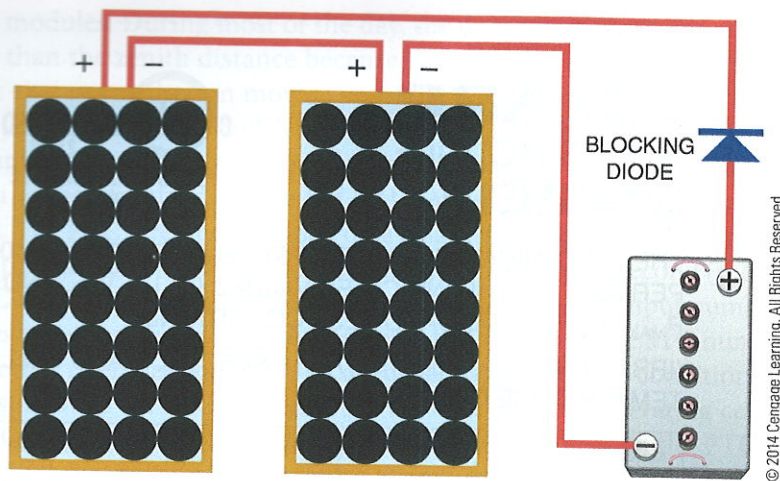


FIGURE 5-17

Blocking diodes are placed in the positive line between modules and the battery bank (if used) to prevent current from reversing its flow from the battery bank to the array at night or during cloudy weather.

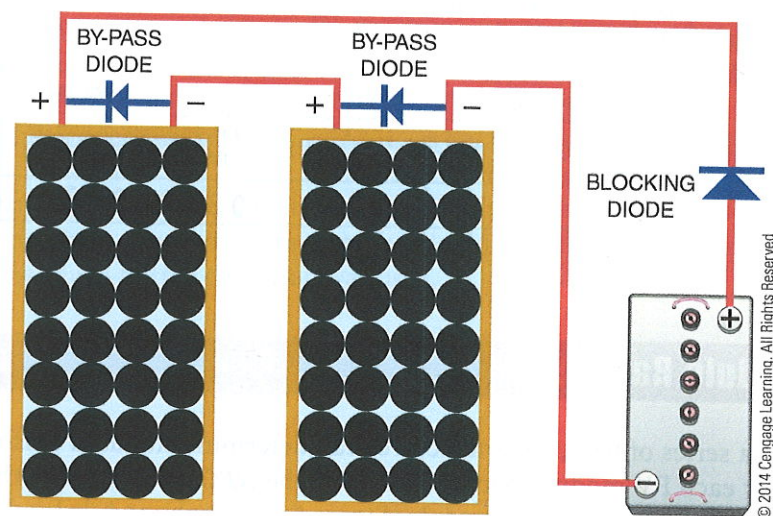


FIGURE 5-18

Bypass diodes are wired in parallel with a module to divert current around the module in the event of too much shading.

PV Module Standards and Codes

For safety reasons, PV modules installed in the United States must conform with Underwriters Laboratories (UL) 1703 Safety Standard for Flat Plate Photovoltaic Modules and Panels. This standard applies to roof-mounted, ground-mounted, pole-mounted, or integrated mounted modules used in a PV system with a voltage of 1000 volts or less.

From an installation standpoint, the *National Electrical Code*® applies. Remember that *Article 690* covers PV systems specifically, but there are many other sections in the *NEC*® that have to be applied when installing a PV system. Using the *NEC*® in the installation process is covered in detail later in this textbook.

During the module manufacturing process, standards are followed to ensure product quality. One such standard is the International Electrotechnical Commission (IEC) 61215 Crystalline Silicon Terrestrial Photovoltaic Modules—Design Qualification and Type Approval. Another one is IEC 61646 Thin-Film Terrestrial Photovoltaic Modules—Design Qualification and Type Approval. Following these standards allows manufacturers to produce a very high-quality module that can be warranted for 20 years or more. Typically, the warranty guarantees at least an 80 percent module output of the nameplate ratings over the 20 years. That means that there is only about a 1 percent reduction in module output each year.

FIGURE 5-19

NEC® Section 690.51 requires that each PV module be marked with the correct polarity of the leads, the maximum overcurrent protection device, and several performance ratings.

SHARP SOLAR MODULE NT-S5E1U



THE ELECTRICAL CHARACTERISTICS ARE WITHIN ± 10 PERCENT OF THE INDICATED VALUES OF I_{SC} , V_{OC} , AND P_{MAX} UNDER STANDARD TEST CONDITIONS

(IRRADIANCE OF 1000W/m^2 , AM1.5 SPECTRUM AND CELL TEMPERATURE OF 25°C)

MAXIMUM POWER	(P_{MAX})	185.0 W
OPEN-CIRCUIT VOLTAGE	(V_{OC})	44.9 V
SHORT-CIRCUIT CURRENT	(I_{SC})	5.75 A
MAXIMUM POWER VOLTAGE	(V_{PMAX})	36.21 V
MAXIMUM POWER CURRENT	(I_{PMAX})	5.11 A
MAXIMUM SYSTEM VOLTAGE		600 V
FUSE RATING		10 A
FIRE RATING		CLASS C
FIELD WIRING		COPPER ONLY 14 AWG MIN. INSULATED FOR 90°C MIN.
SERIAL No.		034090273

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PV Module Ratings

Based on a series of tests, a manufacturer can determine standard performance ratings for each PV module. Section 690.51 of the NEC® requires that these ratings be clearly labeled on each module (Figure 5-19). Each module label must be marked with the polarity of the connections, maximum fuse or circuit breaker rating, and other ratings including the open circuit voltage (V_{oc}), operating voltage (V_{pmax}), maximum permissible system voltage, operating current (I_{pmax}), short circuit current (I_{sc}), and maximum power (P_{max}). The label may contain other information if a manufacturer so chooses, such as fire class rating and wire sizes. The information on the label is used in the system design process. How to use this information in the design process is demonstrated later in this text.

PV Module Test Conditions

When determining peak performance numbers for a PV module, manufacturers test their products using specific conditions so that the data are reliable and repeatable during a series of tests. Earlier in this chapter, you were introduced to the reference condition called standard test conditions (STC). It is commonly used and assumes 1000 W/m^2 solar irradiance, AM1.5 spectrum, and a cell temperature of 77°F (25°C). AM1.5 spectrum refers to a 1.5 atmosphere thickness (air mass, or AM) that corresponds to a solar zenith angle of around 48° . Remember that the solar zenith is when the sun is directly above a PV module (or array), at which point the sun's rays have the shortest distance to travel through the atmosphere to strike

the PV modules. During most of the day, the distance through the atmosphere is greater than the zenith distance because the angle between the PV modules and the sun changes as the sun moves across the sky. AM1.5 is used to represent the overall yearly average for mid-latitude locations like the United States. As a result, the solar industry uses AM1.5 for all standardized testing of solar panels.

You were also introduced to the PVUSA test conditions (PTC) earlier in this chapter. The PTC reference is based on a solar irradiance of 1000 W/m^2 , an ambient temperature of 68°F (20°C), and a wind speed of 1 meter/second (m/s). Because the PTC reference uses more realistic parameters, the peak output numbers for PV modules tested using the PTC numbers will be lower than the STC numbers.

Another reference condition is called standard operating conditions (SOC). It is very similar to the STC reference but uses the nominal operating cell temperature (NOCT) instead of 77°F (25°C). It is also very similar to the PTC reference but uses a more realistic solar irradiance amount. The NOCT is based on a solar irradiance of 800 W/m^2 , an ambient temperature of 20°C (68°F), and a wind speed of 1 meter/second (m/s). Because the SOC reference uses more realistic parameters the peak output numbers for PV modules tested using the SOC numbers will be lower than the STC numbers. Make sure when you look at a module's I-V curve you know whether it is done under STC or SOC conditions.

Nominal operating conditions (NOC) is another reference condition that uses a solar irradiance of 800 W/m^2 , a AM1.5 spectrum, and a nominal operating cell temperature. The NOC reference is considered to give a more realistic set of operating numbers. Again, be sure that when looking at the ratings of a PV module, you know which testing condition was used.