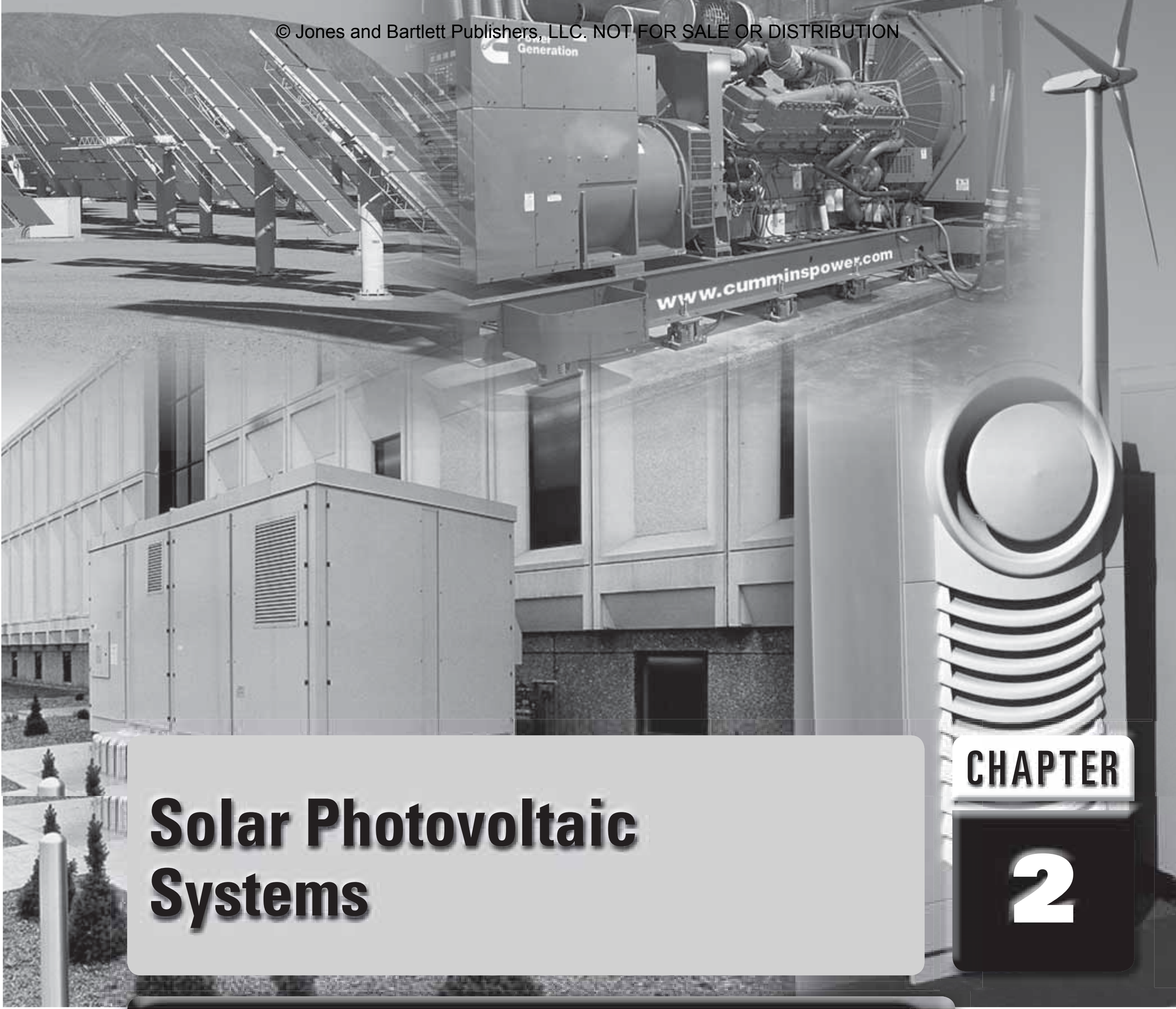

CHAPTER 2

Solar Photovoltaic Systems

OBJECTIVES

- Outline the components of a solar photovoltaic system
- Describe the operation of a solar photovoltaic system
- Understand the ratings of solar modules
- Explain the installation requirements of solar photovoltaic systems
- List the siting requirements of solar photovoltaic systems
- Understand the operational limitations of solar photovoltaic power

■ Introduction

Solar photovoltaic power is a generic term used for electrical power that is generated from sunlight. A solar photovoltaic system converts sunlight into electricity (**FIGURE 2-1**). The fundamental building block of solar photovoltaic power is the solar or photovoltaic cell. A **solar cell** is a self-contained electricity-producing device constructed of semi-conducting materials. Light strikes the semi-conducting material in the solar cell, creating direct current (dc) voltage. **Dc (direct current) voltage** is an electrical potential difference that is constant and whose magnitude does not vary with time.

Solar cells are typically rated 1 or 2 watts. Several cells are electrically interconnected and encapsulated as a **solar module**. Solar modules or solar panels typically have a sheet of glass on the front, or the side facing the sun, and a translucent resin barrier behind, allowing light to pass through while protecting the semiconductor wafers from the elements, such as rain, snow, and hail.

Solar panels are the smallest photovoltaic component commercially available and range in power output from approximately 10 to 300 watts. Solar panels can be grouped together in series and parallel configurations to form a solar or photovoltaic **array** and can be used to provide very large amounts of power. An array is often mounted on the roof of a building or structure, generally facing south when installed in the northern hemisphere and angled to receive the maximum average amount of sunlight. An array is connected to the electric utility grid by a **utility-interactive power inverter** that converts dc power from the array into alternating current (ac) power that is compatible with the electric utility grid (see Chapter 8).

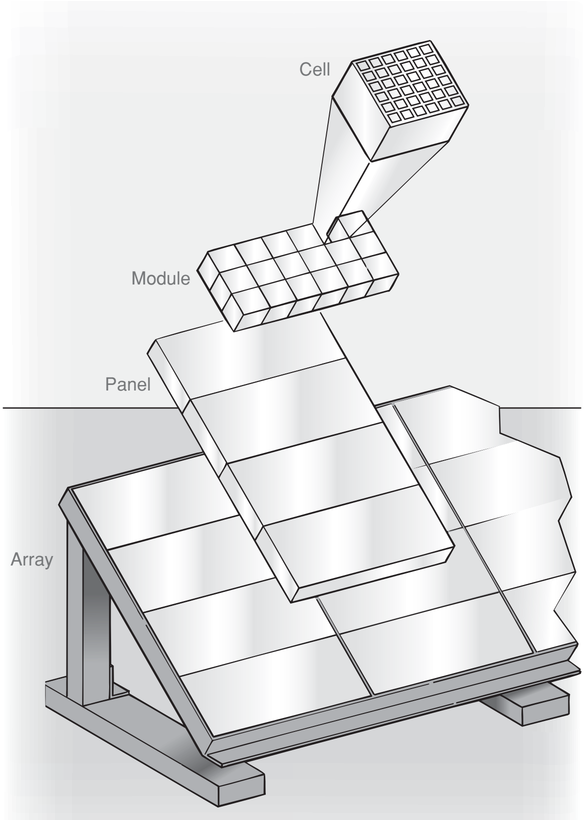

FIGURE 2-1 Solar photovoltaic array.
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Components

The major components of a solar photovoltaic system are the foundation and supports, one or more solar arrays, and one or more inverters. Understanding these components is integral to designing a safe, economical, and functional system. Arrays and inverters are modular and can be installed in different combinations to supply virtually any power requirement.

Foundation and Supports

Both ac and dc systems have a foundation and support structure for the photovoltaic array. The foundation and support depends on the type of mounting (either ground or roof mounted), the size of the array, local wind and snow loading conditions, the tilt of the array, and whether a tracking system is installed.

Fixed Arrays

Because there are no moving parts, fixed arrays are the least expensive solar photovoltaic system to install. Fixed arrays, either mounted on a roof or a stand, are installed generally facing south at a fixed tilt angle. The **tilt angle** is the orientation of the solar array with respect to the horizon, expressed in degrees (**FIGURE 2-2**). The tilt angle is the angle that the array is set to face the sun and is measured relative to a horizontal position.

The tilt angle can be set or adjusted to maximize seasonal or annual energy output. The tilt angle of a fixed array depends on the sunlight and load match. Arrays installed for summer peak loads usually have a tilt angle at or slightly less than site latitude. Arrays installed for winter loads have a tilt angle higher than site latitude.

Tracking Arrays

A tracking system actively points a solar array toward the sun. A one-axis tracking system rotates the array east-to-west to maintain orientation toward the sun as it moves across the sky. A two-axis tracking system rotates the array and changes the tilt angle with the **incident angle** of the sun, or the orientation angle of the sun with respect to the horizon, expressed in degrees. This angle changes seasonally, being lower in the sky in the winter and higher in the sky in the summer.

A tracking array has more energy output than a comparably rated fixed array but has higher installation and maintenance costs and higher complexity. The additional cost and complexity of a tracking system must be balanced with the energy requirement of a given application.

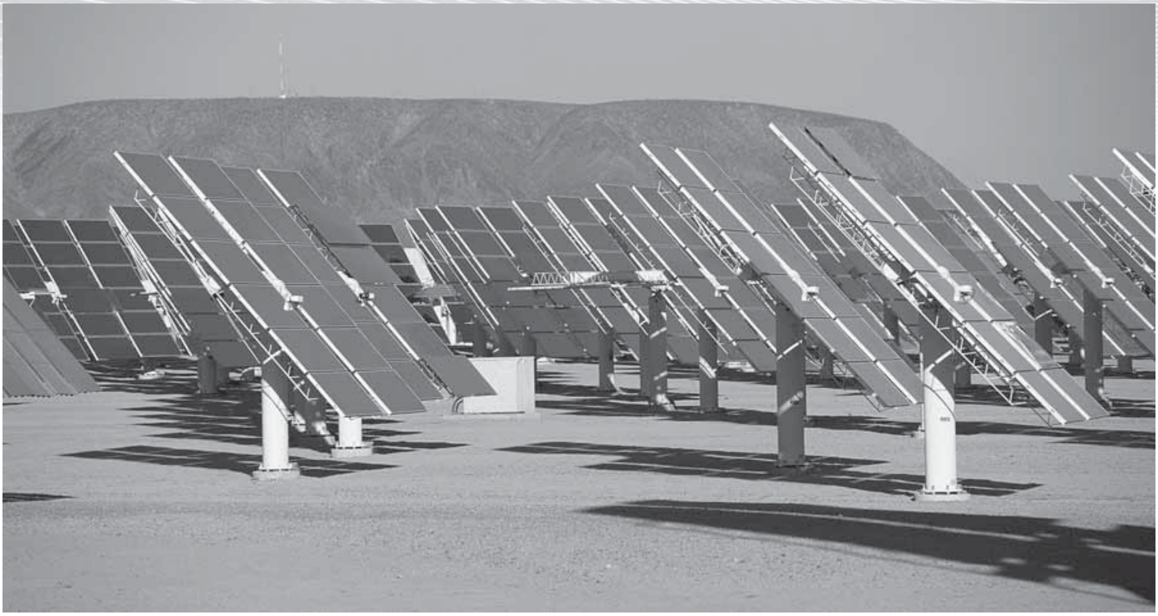

FIGURE 2-2 Tilt angle of a solar array.

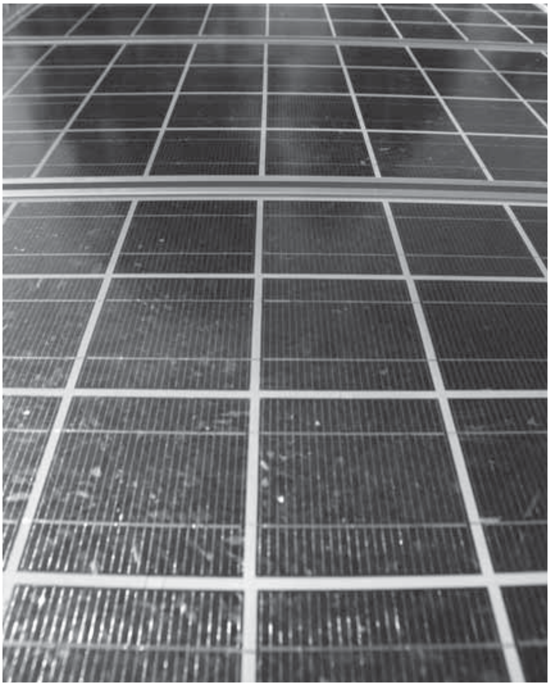

FIGURE 2-3 Flat-plate-collector array.

Solar Arrays

Solar modules are characterized as either flat plate or concentrator systems. Flat-plate modules are an arrangement of photovoltaic cells that are mounted on a flat, rigid surface with the cells exposed to sunlight (**FIGURE 2-3**). Flat-plate-collector arrays can use direct, indirect, and diffuse sunlight, generating close to their output power rating in direct sunlight and some smaller portion of their power rating in indirect or diffuse sunlight. Flat-plate arrays can be installed as fixed-mounted or tracking arrays.

Concentrator arrays use optical components to direct and concentrate light onto the solar cells (**FIGURE 2-4**). Concentrator arrays use only direct sunlight and must directly face or track the sun. Concentrator arrays are more complex to design than flat-plate arrays because of the necessity of a tracking system. However, because concentra-

FIGURE 2-4 Concentrator-collector array.

tor arrays intensify direct sunlight, a much smaller concentrator array can be installed than a similar flat-plate array for a given application.

Utility-Interactive Power Inverter

Photovoltaic arrays are typically assembled from solar modules that generate dc electricity. Several modules are connected in series and parallel to obtain the necessary dc voltage, power, and current ratings for any given application. That dc power is converted into ac power that is compatible with the electrical utility grid by the utility-interactive power inverter (see Chapter 8). Some photovoltaic modules are designed with an ac output, which the *National Electrical Code*® (*NEC*®) considers the same as the output of a utility-interactive power inverter.

■ Operation

The operation of a solar photovoltaic system is straightforward. When the sun is shining, the solar array generates dc voltage. The inverter automatically connects to the electric utility grid and delivers ac power to the grid.

Solar arrays generate electricity in proportion to the amount of sunlight that strikes them. Solar arrays in full, direct sunlight generate electricity near their full power output ratings. Solar arrays not in direct sunlight, such as when obscured by trees, shadows, clouds, and other obstructions, generate proportionately less power. Consequently, solar arrays should be located in full sunlight, clear of all obstructions.

The goal of solar photovoltaic system operation is to optimize the energy output of the system for the application. Two-axis tracking arrays automatically point the array directly at the sun, maximizing the output of the array. The azimuth of fixed arrays and the tilt angle of fixed and one-axis tracking arrays, however, must be adjusted to optimize the power output of the system.

Azimuth of the Array

The **azimuth** is the orientation angle of the solar array with respect to solar north, or 0°, expressed in degrees (**FIGURE 2-5**). The incident angle of the sun at the earth's surface changes daily as the sun rises in the east and sets in the west. Peak solar photovoltaic power production typically occurs within a 6-hour window of daylight centered at an azimuth of 180°, or solar south, with reduced power output occurring both before and after the peak window. Before and after this window, power is produced at much lower levels. Typical solar photovoltaic power output ramps up during morning hours as the sun rises, peaks during the middle of the day, and declines as the sun sets (**FIGURE 2-6**).

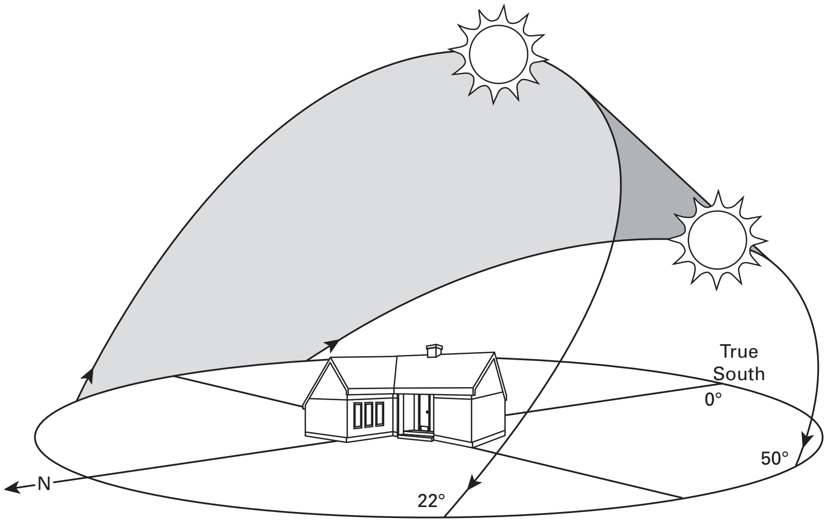

FIGURE 2-5 Azimuth.

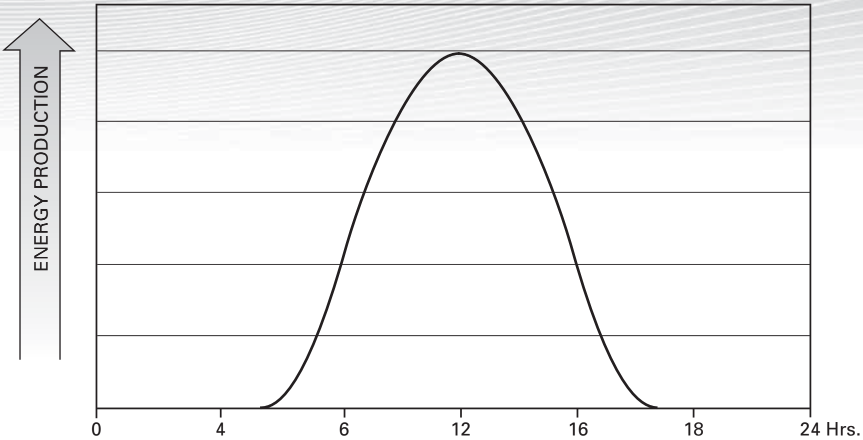

FIGURE 2-6 Solar power production.

Solar south is determined empirically by the location of the sun at the time halfway between sunrise and sunset. Fixed arrays in the northern hemisphere should be oriented toward solar south to maximize the average daily exposure to sunlight.

Tilt Angle of the Array

The incident angle of the sun at the earth's surface changes seasonally. The sun is higher in the sky in the summer and lower in the sky in the winter. The seasonal power output of the array can be biased to either summer or winter, depending on the tilt angle of the array.

The tilt angle of a fixed-mounted or one-axis tracking solar array is determined by geographic location, with a general range of site latitude plus or minus 15° (**FIGURE 2-7**). With a tilt angle of site latitude plus 15° the array is more

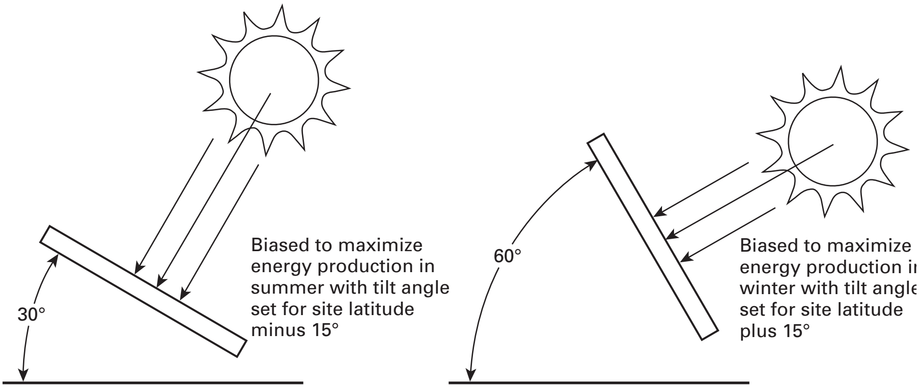

FIGURE 2-7 Tilt-angle of an array set for seasonal operation.

vertical and is winter biased for more direct sunlight when the sun is lower in the sky. With a tilt angle of site latitude minus 15° the array is more horizontal and is summer biased for more direct sunlight when the sun is higher in the sky. For the best year-round performance, the tilt angle of the solar array should be adjusted to site latitude. Rain, hail, and snow loading are not normally concerns because of the tilt angle required in most installations.

Stand-Alone Solar Photovoltaic Power

When designing a stand-alone solar photovoltaic system, the array must be designed very closely to the size of the load. An array that is too small cannot power the load and one too large can overheat, causing protective devices, such as the utility-interactive power inverter, to disconnect the array from the system. Typically, one or more alternative sources of power—such as energy storage batteries or an engine generator—are required to power loads at night and when the load exceeds the output of the array. Solar arrays with energy storage batteries should be sized slightly larger than the connected load to charge the batteries during the day for nighttime operation.

Grid-Connected Solar Photovoltaic Power

Sizing the solar array is not as critical when grid connected in a distributed generation application because the load on the electrical utility grid always exceeds the capacity of the array. A grid-connected solar photovoltaic system supplies power to the onsite load and delivers excess power to the electrical utility grid through the utility-interactive power inverter.

Photovoltaic Module Ratings

NEC® Link

690.51 Marking of Solar Modules

DC solar modules are required to be labeled with the open-circuit voltage, operating voltage, maximum permissible system voltage, operating current, short-circuit current, and maximum power.

Voltage Ratings

The open-circuit voltage rating is the voltage rating of the module when open circuited and exposed to full, direct sunlight. The operating voltage rating is the nominal voltage rating of the module, which is typically a multiple of 12 volts dc. The maximum permissible system voltage is the peak operating voltage of the module.

Current Ratings

The operating current rating is the current rating at maximum power and maximum permissible system voltage. The short-circuit current rating is the maximum current that the module can deliver to a short circuit at the terminals of the module.

Power Rating

The maximum power rating is the power output of the module at the maximum permissible system voltage and operating current. The maximum power rating is typically the same as the rated power and peak power ratings of the module.

Maximum Open-Circuit Voltage

Conductors for solar photovoltaic systems must be rated for the maximum open-circuit voltage of the solar array. When a solar array is disconnected from the load during daylight hours, the array generates dc voltage somewhat higher than the nominal operating voltage of the array under load, although no current or power is drawn from the array. The maximum system voltage is the sum of the rated open-circuit voltages of the series-connected modules corrected for the lowest expected ambient temperature.

NEC® Link

690.7(A) Maximum Photovoltaic System Voltage

Tip

The maximum open-circuit voltage of a solar array can exceed the voltage ratings of conductors, inverters, and equipment. Carefully size conductors and equipment considering the maximum open-circuit voltage of the array.

Ambient Temperature Correction Factors

Generic correction factors for the open-circuit voltage of crystalline and multicrystalline silicon solar photovoltaic modules are found in *NEC* Table 690.7, reprinted here as **TABLE 2-1**. When supplied, the open-circuit voltage temperature coefficients

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Table 690.7 Voltage Correction Factors for Crystalline and Multicrystalline Silicon Modules
690.7(C) Photovoltaic Source and Output Circuits

TABLE 2-1 *NEC* Table 690.7 Voltage Correction Factors for Crystalline and Multicrystalline Silicon Modules

Correction Factors for Ambient Temperatures Below 25°C (77°F) **(Multiply the rated open circuit voltage by the appropriate correction factor shown below.)**		
Ambient Temperature (°C)	Factor	Ambient Temperature (°F)
24 to 20	1.02	76 to 68
19 to 15	1.04	67 to 59
14 to 10	1.06	58 to 50
9 to 5	1.08	49 to 41
4 to 0	1.10	40 to 32
–1 to –5	1.12	31 to 23
–6 to –10	1.14	22 to 14
–11 to –15	1.16	13 to 5
–16 to –20	1.18	4 to –4
–21 to –25	1.20	–5 to –13
–26 to –30	1.21	–14 to –22
–31 to –35	1.23	–23 to –31
–36 to –40	1.25	–32 to –40

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in the instructions for listed photovoltaic modules must be used to calculate the maximum photovoltaic system voltage as given by

$$V_{\text{O-C}} = (C_F)(N_{SM})(V_{\text{O-C/SM}})$$

where $V_{\text{O-C}}$ is the maximum open-circuit voltage of the array, C_F is the correction factor from NEC Table 690.7, N_{SM} is the number of solar modules in the array, and $V_{\text{O-C/SM}}$ is the maximum open-circuit voltage of each solar module.

Where the expected ambient temperature falls below –40°C (–40°F) or where other than crystalline or multicrystalline silicon photovoltaic modules are used, the manufacturer's instructions should be used to adjust the maximum system voltage. The temperature-corrected maximum system voltage must also be used in determining the voltage rating of conductors, cables, overcurrent protective devices, disconnects, etc.

PUT IT TO THE TEST

Applying the Temperature Correction Factor

A 12-kilowatt solar photovoltaic system is comprised of sixty 200-watt, polycrystalline solar modules. Each 200-watt module has a nominal voltage rating of 24 volts, an open-circuit voltage of 35.5 volts dc, a peak current rating of 7.02 amperes, and a short-circuit current of 7.82 amperes. The modules are configured as a 3 × 20 array for a total system output rating of 480 volts, with each 20-module string rated 4 kW.

Using available meteorological data, the lowest recorded temperature at the site to date is –33°C (–27°F). Using a multiplier of 1.23 from *NEC* Table 690.7, the maximum open-circuit voltage of the solar array is the product of the multiplier and the sum of the open-circuit voltage of the series-connected modules, or 873.3 volts dc, as given by

$$V_{\text{O-C}} = (1.23)(20)(35.5\text{V}_{\text{dc}}) = 873.3\ \text{V}_{\text{dc}}$$

The minimum voltage rating of the conductors from the solar array to the inverter is 1000 volts, but the maximum open-circuit voltage rating of the inverter is 600 volts dc. A different array configuration is required.

For a 4 × 15 array, each 15-module string has an output rating of 3 kilowatts, 360 volts dc, with a maximum open-circuit voltage of the solar array of 676.3 volts dc, as given by

$$V_{\text{O-C}} = (1.23)(15)(35.5\text{V}_{\text{dc}}) = 676.3\ \text{V}_{\text{dc}}$$

For a 5 × 12 array, each 12-module string has an output rating of 2.4 kilowatts, 288 volts dc, with a maximum open-circuit voltage of the solar array of 524 volts dc, as given by

$$V_{\text{O-C}} = (1.23)(12)(35.5\text{V}_{\text{dc}}) = 524.0\ \text{V}_{\text{dc}}$$

The maximum open-circuit voltage of the 5 × 12 array is within the voltage ratings of the conductors and the utility-interactive power inverter. The maximum voltage for dc photovoltaic source and output sources is 600 volts for one- and two-family dwellings, although other installations over 600 volts are permitted.

Installation Requirements

Wiring Methods

The circuits and conductors of a solar photovoltaic system must be physically separated from conductors of other systems. Solar panels and arrays must be arranged and connected such that their removal does not interrupt the grounded conductor of another panel or array. Interrupting the grounded conductor, or neutral, would cause the system to lose its electrical reference to ground. The ungrounded system would continue to operate, but overcurrent protective devices might not operate in the event of a phase-to-ground fault (see Chapter 13).

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Article 690: Solar Photovoltaic Systems
690.6(A) Alternating-Current (ac) Modules: Photovoltaic Source Circuits
690.4(B) Installation: Conductors of Different Systems
690.4(C) Installation: Module Connection Arrangement

Alternating-Current Solar Modules

The source circuit, conductors, and inverters of ac solar modules are considered internal wiring. The output of ac solar modules is considered a utility-interactive power inverter output for conductor sizing (see Chapter 10), overcurrent protection (see Chapter 12), etc.

Siting Requirements

For a successful solar photovoltaic system installation, solar arrays must be located where they are:

- Facing the sun (e.g., south in the northern hemisphere)
- Exposed to lots of sunshine (e.g., long days, few clouds, limited inclement weather)
- Clear of obstructions (e.g., buildings, shadows, trees)

Solar modules and arrays are relatively immune to hail and collecting rainwater or snow because of the required tilt angle of most installations.

Operational Limitations

Solar photovoltaic power is a passive generation technology. Passive generation is a generation technology that has no control over the fuel input or the power output of the system. In other words, the power output of a solar power system cannot be controlled. When the sun shines the solar cells generate voltage and the inverter delivers ac power to the grid, without regard to the connected load.

Tip

Always treat solar photovoltaic system components as if they are energized.

Solar power production ramps up as the sun rises, peaks during a 6-hour window centered at solar noon when the sun is at the apex of its arc across the sky, and decreases as the sun goes down at night. Solar arrays stop generating electricity when the sun goes down at night. Solar cells do not store energy and will not generate electricity until sunlight is again available. For a stand-alone solar photovoltaic system, one or more alternative sources of power (such as energy storage batteries or an engine generator) are required to power loads at night and when the load exceeds the output of the array.