

CHAPTER 4

Solar Fundamentals



Photovoltaic system installers typically do not have enough knowledge and experience to design a PV system from the ground up. Their main job focus is to take the various components of a PV system that was designed by someone else and install them in a safe and efficient manner. Learning how to design a PV system is something that installers learn how to do over time as their knowledge and experience levels increase. It is important for a PV system installer to have a good understanding of the fundamentals of solar radiation for both the design and installation of a PV system. In this chapter, solar energy fundamentals are introduced, as well as how to properly evaluate a site for a PV system installation.

Glossary of Terms

- altitude** The sun's height above the horizon.
- azimuth** The sun's apparent location in the sky east or west of true south.
- azimuth angle** The angle, clockwise from true north, that the PV array faces.
- insolation** The solar irradiation received over a period of time, typically one day.
- irradiance** A measure of how much solar power is striking a specific location.
- irradiation** The term used for the measure of solar radiation striking the earth's surface at a particular time and place.
- latitude** The distance of a specific location north or south of the equator.
- magnetic declination** The deviation of magnetic south from true south.
- profile angle** The projection of the altitude angle onto an imaginary plane that is perpendicular to the surface of an obstruction; it is used to determine the length of a shadow at a certain time.
- solar constant** The amount of solar power moving through space from the sun to the earth; it is assumed to be approximately 1366 watts per square meter in space and 1000 watts per square meter at sea level at the equator at solar noon.
- solar noon** The time during the day when the sun is at its highest point on earth.
- solar radiation** The radiation coming from the sun in the form of waves and small particles.

Objectives

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

- ▶ Demonstrate an understanding of solar radiation, solar irradiance, and solar irradiation.
- ▶ Demonstrate an understanding of magnetic declination, solar azimuth, and the solar window.
- ▶ Use sun charts to determine the sun's altitude for a specific location at different times of the year.
- ▶ Use knowledge of solar fundamentals to properly set up a PV system installation for maximum efficiency.
- ▶ Perform a proper site evaluation.

solar window The area in the sky that is between the sun path of the winter solstice (December 21) and the sun path for the summer solstice (June 21) for the hours of 9:00 A.M. to 3 P.M.

zenith The point in the sky where the sun is directly above a PV array.

Solar Energy Basics

A nuclear reaction called fusion takes place in the sun, producing energy that radiates outward all the way to earth and beyond. The radiation coming from the sun is in the form of waves and small particles and is referred to as **solar radiation**. The amount of solar power moving through space from the sun to the earth is relatively constant. It is considered to be approximately 1366 watts per square meter. On the earth and after traveling through the atmosphere, it is considered to be 1000 watts per square meter at sea level at the equator at solar noon. The time during the day when the sun is at its highest point on earth is called **solar noon**. Because the strength of the sun's rays in space and in the earth's atmosphere does not deviate much, it is often referred to as the **solar constant**.

Solar **irradiance** is a measure of how much solar power is striking a specific location. Irradiance varies throughout the year, depending on the seasons. It also varies throughout the day, depending on the position of the sun in the sky and the weather. Solar irradiance is usually expressed in watts per square meter (W/m^2), or for larger amounts, kilowatts per square meter (kW/m^2). On a clear day, the total solar irradiance striking the earth is about 1000 watts per square meter. The amount of solar irradiance changes throughout a day. At night, there is no solar irradiance, but when the sun rises, the solar irradiance starts to increase. It continues to increase until it peaks at around noon, and then the amount of solar irradiance decreases as the sun sets. Solar irradiance is used for rating the power output of PV modules and will be discussed further when PV modules are covered in Chapter 5.

Solar **irradiation** is a measure of the total amount of solar energy accumulated on an area over a period of time. Solar irradiation is expressed as a number of watt-hours per square meter (Wh/m^2) or, for larger amounts, kilowatt-hours per square meter (kWh/m^2).

Insolation is another term often used to refer to the amount of solar irradiance received over time, typically for one day. The insolation value is generally expressed as $\text{kWh/m}^2/\text{day}$ or the equivalent amount of peak sun hours and is usually given as an average daily value for each month. Peak sun hours are the number of hours per day that solar insolation equals 1000 W/m^2 . A knowledge of the number of peak sun hours for a specific location is used to estimate the PV system performance, because PV module power output is based on 1000 W/m^2 .

Solar irradiation received at the earth's surface varies because of atmospheric attenuation (loss). This loss of light is caused by air molecules, water vapor, or dust scattering the light. Ozone, water vapor, and carbon dioxide absorb the light. The amount of solar radiation that is absorbed or scattered in the atmosphere depends on how thick the atmosphere is where the sun's rays pass through it. The minimum amount of atmosphere the sun's rays have to go through is the condition in which the sun is directly above an array. This is referred to as the sun's **zenith**. When the

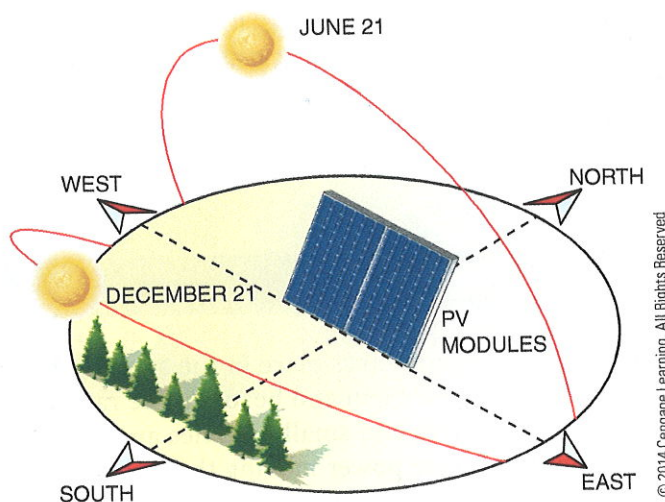


FIGURE 4-1

The sun appears to rise and set at different points on the horizon throughout the year because of the 23.5° tilt of the earth.

sun moves across the sky away from the zenith, the sun's rays must go through an increasing amount of atmosphere.

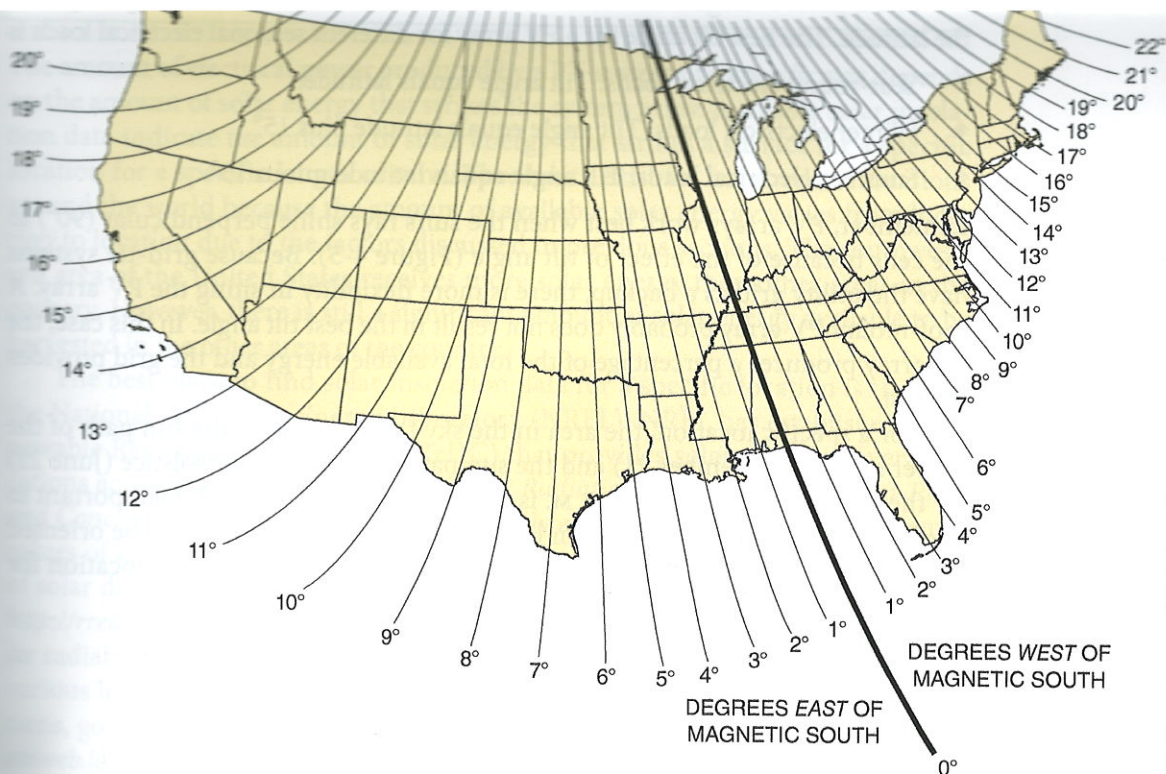
The earth's distance from the sun and its tilt affect how much solar energy is available. The tilt is approximately 23.5° from the vertical. The northern hemisphere is tilted toward the sun from June through August, so there is more available solar energy in summer than winter. In the northern hemisphere, photovoltaic modules should point toward the southern sky to collect the maximum amount of solar energy.

A location's **latitude**, the distance north or south of the equator, determines whether the sun appears to travel in the northern or southern sky. For example, the location in Maine where the author lives is approximately 44° north latitude, and the sun appears to move across the southern sky. Use this website to get the exact latitude for your area: <http://www.ngdc.noaa.gov/geomagmodels/Declination.jsp>.

The sun appears to rise and set at different points on the horizon throughout the year because of the 23.5° tilt of the earth (Figure 4-1). The sun's apparent location in the sky east or west of true south is called the **azimuth** and is measured in degrees east or west of true south. For a PV array, the **azimuth angle** is the angle clockwise from true north that the PV array faces. For a south-facing PV array, the azimuth angle is 180° .

South on a compass is not the same as true south. Compass needles align with the earth's magnetic field. The earth's magnetic field does not align with the earth's rotational axis. The deviation of magnetic south from true south is called **magnetic declination** (Figure 4-2). PV modules should be facing true south for maximum efficiency. For example (Figure 4-3): A site in Waterville, Maine, has a magnetic declination of approximately 16° west. This means that true south is 16° west of magnetic south. On a compass with the north needle pointing at 0° , true south is in the direction indicated by 196° (180° plus 16°).

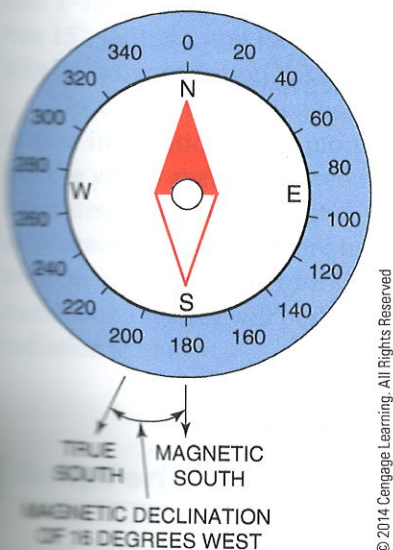
The sun's height above the horizon is called **altitude** (Figure 4-4) and is measured in the number of degrees above the horizon. Solar noon is when the sun is true south at 0° azimuth. This is the sun's highest altitude for that day. A location's latitude determines how high the sun appears above the horizon at solar noon throughout the year.



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FIGURE 4-2

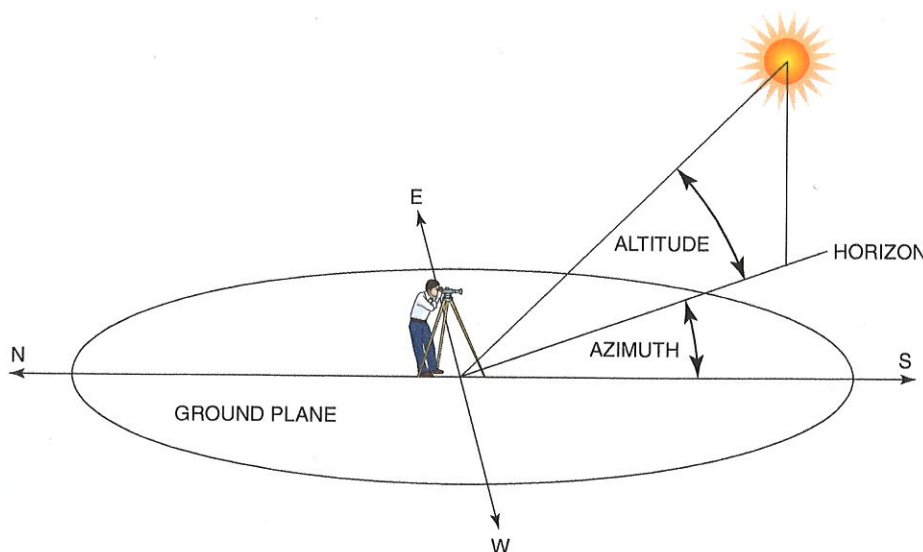
The deviation of magnetic south from true south is called magnetic declination and varies depending on where in the country you live. The amount of magnetic declination changes over time. Use this website to determine the exact amount of magnetic declination for where you will be installing a PV array: <http://www.ngdc.noaa.gov/geomagmodels/Declination.jsp>.



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FIGURE 4-3

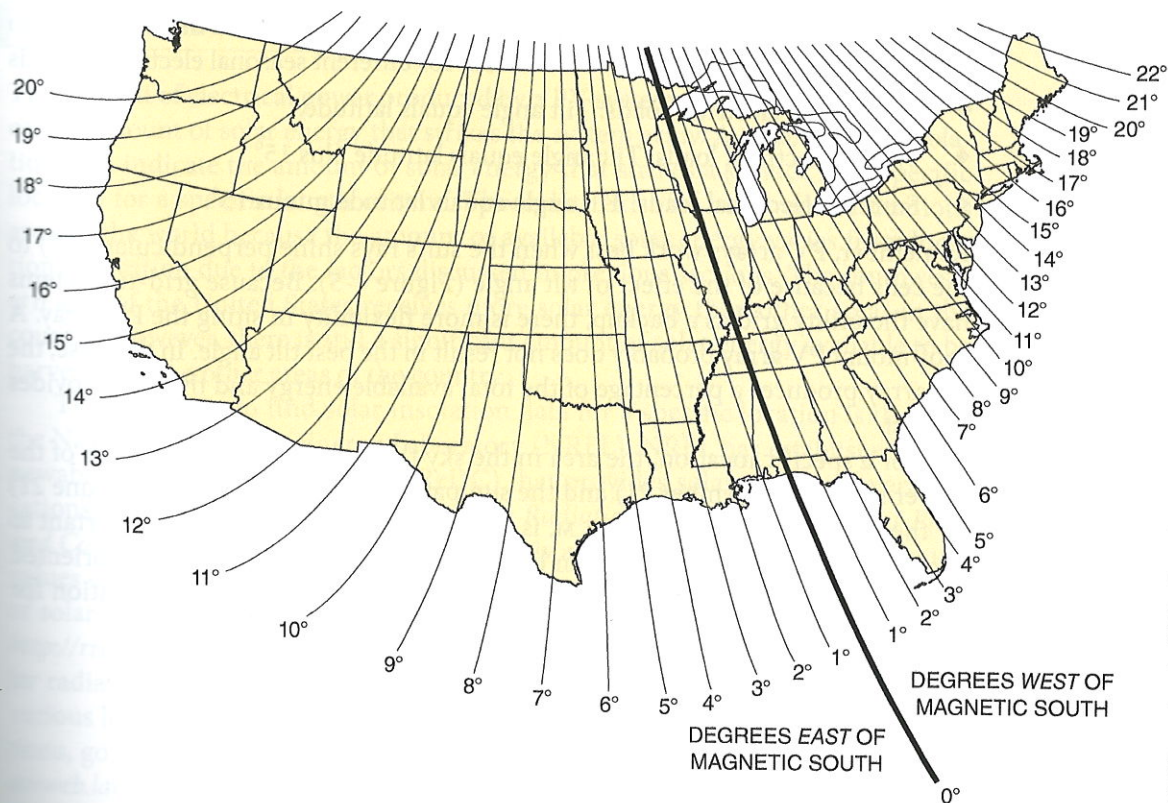
Waterville, Maine, has a magnetic declination of approximately 16° west. This means that true south would be in the direction that is 16° to the west of magnetic south or 196° on a compass.



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FIGURE 4-4

The sun's height above the horizon is called altitude. The sun's apparent location in the sky east or west of true south is called the azimuth.



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FIGURE 4-2

The deviation of magnetic south from true south is called magnetic declination and varies depending on where in the country you live. The amount of magnetic declination changes over time. Use this website to determine the exact amount of magnetic declination for where you will be installing a PV array: <http://www.ngdc.noaa.gov/geomagmodels/Declination.jsp>.

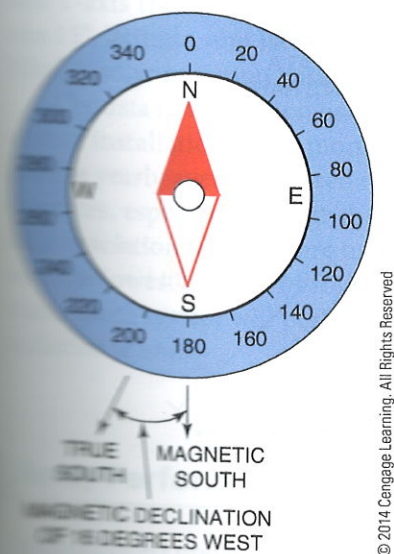


FIGURE 4-3

Waterville, Maine, has a magnetic declination of approximately 16° west. This means that true south would be in the direction that is 16° to the west of magnetic south or 196° on a compass.

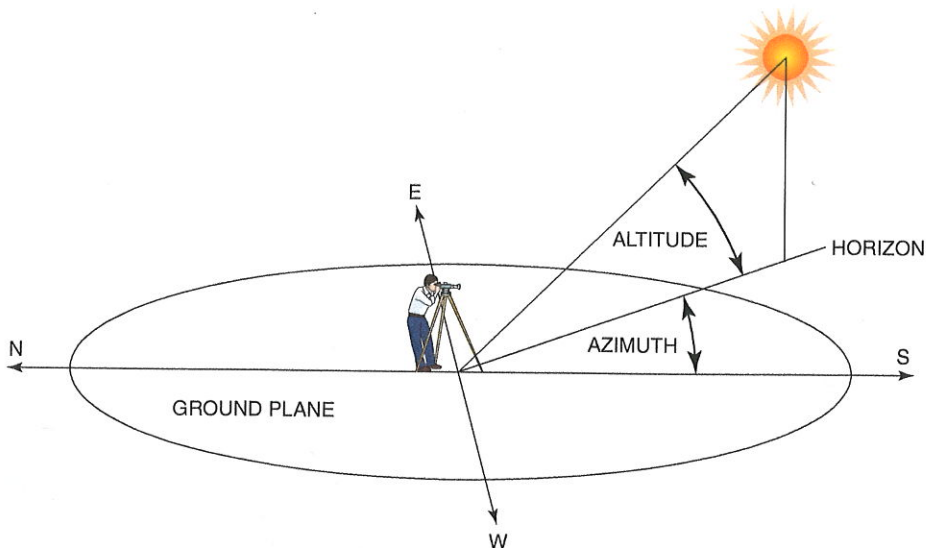


FIGURE 4-4

The sun's height above the horizon is called altitude. The sun's apparent location in the sky east or west of true south is called the azimuth.

The highest average insolation will fall on a PV module with a tilt angle equal to the latitude. The best tilt angle for a PV array for different seasonal electrical loads is

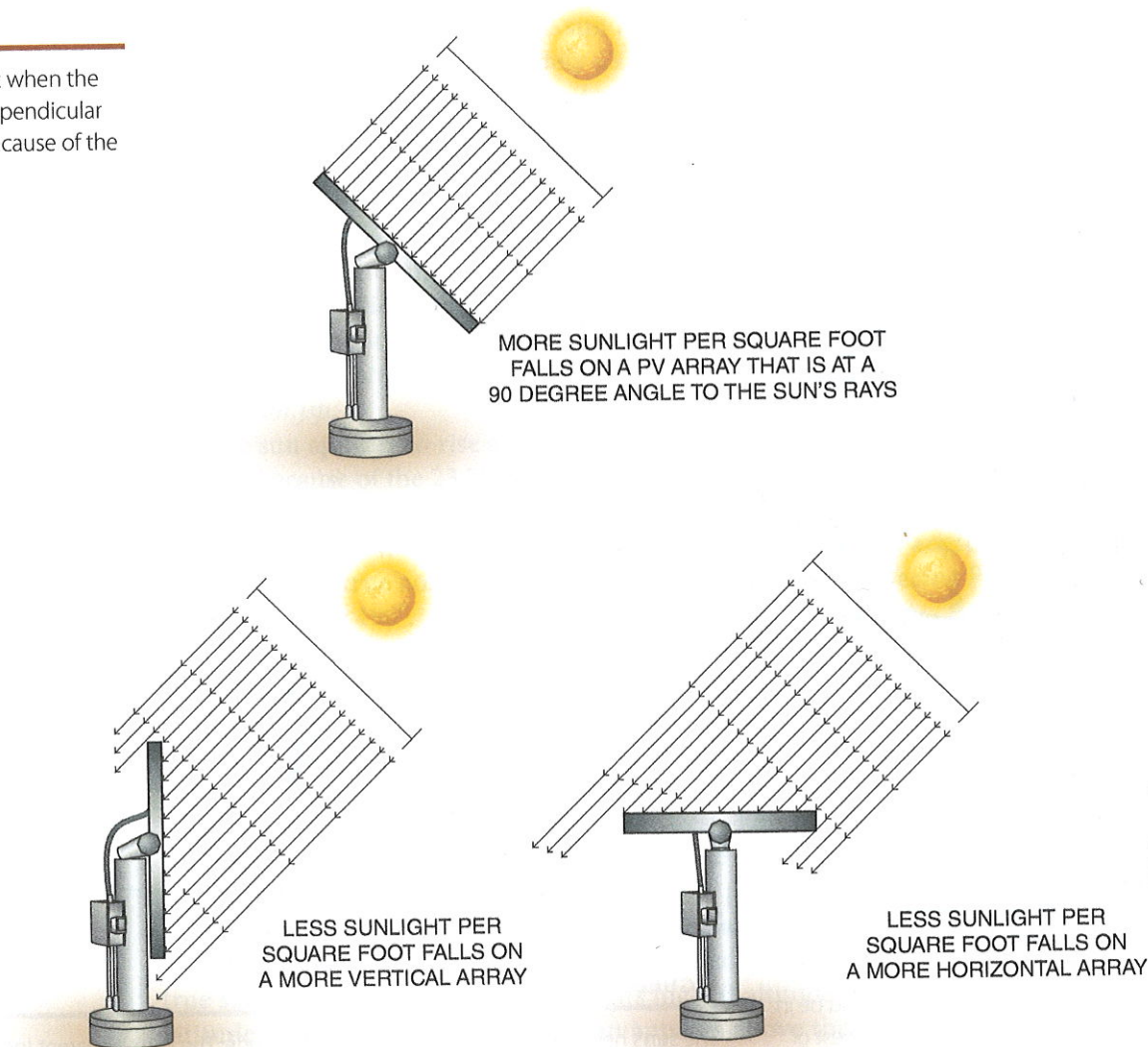
- ◆ Year-round electrical loads: Tilt angle equals latitude.
- ◆ Winter electrical loads: Tilt angle equals latitude plus 15° .
- ◆ Summer electrical loads: Tilt angle equals latitude minus 15° .

Remember, PV arrays work best when the sun's rays shine perpendicular (90°) to the cells because of the effect of tilt angle (Figure 4-5). Because grid-tie systems have the utility grid as a backup, there is more flexibility in siting the PV array. A roof-mount PV array probably does not result in the best tilt angle. In this case, the PV array produces a percentage of the total available energy and the grid provides the rest.

For a specific location, the area in the sky that is between the sun path of the winter solstice (December 21) and the sun path for the summer solstice (June 21) for the hours of 9:00 A. M. to 3 P. M. is called the **solar window**. It is important to know the solar window for a given location so that the PV array can be oriented for maximum performance. It will also help you determine the best location for the array so that there will be no shading from obstructions like trees.

FIGURE 4-5

PV arrays work best when the sun's rays shine perpendicular (90°) to the cells because of the effect of tilt angle.



Solar Insolation Data

The amount of electrical power produced by a PV system of a specific size depends on the amount of solar energy that strikes the system array. Available solar insolation data indicate the amount of solar energy that strikes a surface for a specific location for a specific length of time. These data exist for hundreds of locations around the world because the amount of available solar energy varies from location to location due to the factors discussed in previous sections. The southwestern area of the United States receives more solar energy than other areas in the country. However, there is still a significant amount of solar energy available to be harvested in the other areas of the country.

The best place to find solar insolation data for a specific location is through the National Renewable Energy Laboratory (NREL). NREL has established a Renewable Resource Data Center (RReDC) that provides solar data for several locations across the United States. The *Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors* provides monthly average, minimum, and maximum values of available solar energy. The data apply to some 239 sites and are a result of solar data collected over 30 years. You can check out the complete manual at: <http://rredc.nrel.gov/solar/pubs/redbook/>. This website also allows you to access solar radiation data for each individual State or Territory. Solar radiation maps for various locations are also available. To get insolation data for international locations, go to the NASA Surface Meteorology and Solar Energy Website at <http://eosweb.larc.nasa.gov/cgi-bin/sse/register.cgi>.

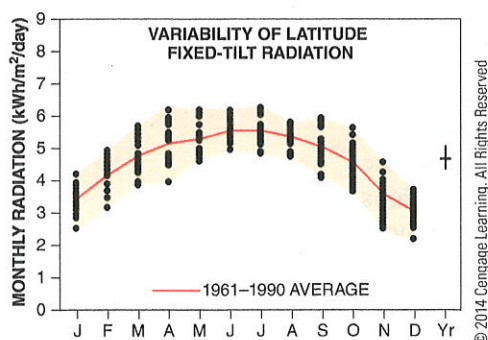
The RReDC manual has a page of tables for each location (Figure 4-6). The data tables have columns for each month of the year and an annual total. There are five tables: south-facing fixed-tilt collectors, 1-axis trackers, 2-axis trackers, direct-beam concentrating collectors, and average climatic conditions. The solar data are given in units of kWh/m²/day, which is equal to peak sun hours. The tables give average values for each month, as well as an annual average. The fixed and 1-axis tracker tables are broken down into tilts of horizontal, latitude minus 15°, latitude, and latitude plus 15°. See Appendix C for more examples of the RReDC solar radiation data manual.

The data in the section on south facing fixed-tilt collectors are used in most PV system installations. The monthly solar insolation amounts are very interesting, but the yearly average is used most often for PV system sizing and performance estimates, especially for a grid-tie PV system. One instance in which the monthly solar insolation numbers are used is for a stand-alone PV system; here, the month with the lowest amount of solar insolation (typically December) is used so that the stand-alone system will perform adequately even on days when the available solar radiation is low.

Array Performance

As mentioned previously, solar radiation data is used to size and estimate the performance of a PV system. A discussion on array sizing takes place later in this textbook, but now is a good time to discuss how to estimate an array's performance. There are a couple of ways to calculate an array's performance: manually or with a computer program.

Performing a manual calculation involves using the solar radiation data found in the *Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors*. For



Baltimore, MD

WBAN NO. 93721

LATITUDE: 39.18° N
 LONGITUDE: 76.67° W
 ELEVATION: 47 meters
 MEAN PRESSURE: 1012 millibars

STATION TYPE: SECONDARY

Solar Radiation for Flat-Plate Collectors Facing South at a Fixed Tilt (kWh/m²/day), Uncertainty ±9%

Tilt (°)		Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
0	Average	2.1	2.9	3.9	4.9	5.6	6.2	6.0	5.3	4.4	3.3	2.2	1.8	4.0
	Min/Max	1.7/2.4	2.4/3.2	3.4/4.5	3.9/5.8	5.0/6.5	5.5/6.9	5.3/6.3	4.7/5.7	3.7/5.0	2.9/3.9	1.8/2.6	1.5/2.0	3.8/4.3
Latitude -15	Average	3.1	3.8	4.6	5.3	5.7	6.0	6.0	5.6	5.0	4.3	3.2	2.7	4.6
	Min/Max	2.3/3.7	3.0/4.4	3.8/5.4	4.1/6.3	5.0/6.6	5.4/6.7	5.2/6.7	4.9/6.0	4.1/5.8	3.5/5.2	2.3/4.0	2.0/3.2	4.3/4.9
Latitude	Average	3.5	4.2	4.8	5.2	5.3	5.6	5.5	5.4	5.1	4.6	3.6	3.1	4.6
	Min/Max	2.5/4.2	3.1/4.9	3.9/5.7	4.0/6.2	4.7/6.2	5.0/6.2	4.9/6.3	4.7/5.8	4.1/5.9	3.6/5.6	2.5/4.5	2.1/3.7	4.4/5.0
Latitude +15	Average	3.7	4.3	4.7	4.8	4.7	4.8	4.9	4.9	4.8	4.6	3.7	3.3	4.4
	Min/Max	2.6/4.6	3.2/5.1	3.8/5.6	3.7/5.8	4.1/5.5	4.3/5.3	4.3/5.5	4.3/5.3	3.9/5.7	3.6/5.7	2.5/4.8	2.3/4.0	4.1/4.8
90	Average	3.4	3.7	3.5	3.0	2.6	2.4	2.5	2.9	3.3	3.7	3.3	3.0	3.1
	Min/Max	2.3/4.4	2.7/4.5	2.8/4.2	2.4/3.6	2.3/2.9	2.2/2.6	2.3/2.8	2.6/3.1	2.7/3.9	2.8/4.6	2.2/4.3	2.0/3.7	2.9/3.4

Solar Radiation for 1-Axis Tracking Flat-Plate Collectors with a North-South Axis (kWh/m²/day), Uncertainty ±9%

Axis Tilt (°)		Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
0	Average	3.0	4.0	5.3	6.4	7.1	7.8	7.7	6.9	5.8	4.6	3.2	2.5	5.4
	Min/Max	2.3/3.7	3.0/4.8	4.2/6.4	4.8/8.1	6.1/8.5	6.5/9.0	6.3/8.9	5.7/7.5	4.7/6.9	3.6/5.7	2.2/4.0	1.9/3.0	5.0/5.9
Latitude -15	Average	3.7	4.7	5.9	6.8	7.2	7.8	7.7	7.1	6.3	5.3	3.9	3.2	5.8
	Min/Max	2.7/4.6	3.4/5.7	4.6/7.2	4.9/8.6	6.1/8.6	6.5/9.0	6.3/9.0	5.9/7.8	5.1/7.5	4.2/6.7	2.6/5.0	2.3/3.9	5.4/6.4
Latitude	Average	4.1	5.0	6.0	6.7	7.0	7.5	7.4	7.0	6.4	5.5	4.2	3.5	5.9
	Min/Max	2.9/5.1	3.6/6.1	4.7/7.3	4.9/8.5	5.9/8.4	6.2/8.6	6.1/8.6	5.8/7.7	5.1/7.6	4.3/7.0	2.8/5.4	2.4/4.3	5.4/6.4
Latitude +15	Average	4.3	5.1	5.9	6.4	6.6	7.0	6.9	6.6	6.2	5.6	4.3	3.7	5.7
	Min/Max	3.0/5.3	3.6/6.3	4.6/7.3	4.7/8.2	5.5/7.9	5.8/8.1	5.6/8.1	5.4/7.3	4.9/7.4	4.3/7.4	2.8/5.6	2.5/4.6	5.3/6.3

Solar Radiation for 2-Axis Tracking Flat-Plate Collectors (kWh/m²/day), Uncertainty ±9%

Tracker		Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
2-Axis	Average	4.3	5.1	6.0	6.8	7.3	8.0	7.8	7.2	6.4	5.6	4.3	3.7	6.0
	Min/Max	3.0/5.4	3.6/6.3	4.7/7.3	5.0/8.6	6.2/8.7	6.7/9.2	6.4/9.1	5.9/7.8	5.1/7.6	4.3/7.1	2.8/5.7	2.5/4.6	5.6/6.7

Direct Beam Solar Radiation for Concentrating Collectors (kWh/m²/day), Uncertainty ±8%

Tracker		Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
1-Axis, E-W	Average	2.5	2.8	3.0	3.1	3.3	3.7	3.6	3.2	3.0	3.0	2.5	2.2	3.0
	Min/Max	1.4/3.5	1.5/3.7	1.8/4.1	1.6/4.4	2.5/4.4	2.7/4.6	2.5/4.6	2.3/3.8	2.0/3.9	2.0/4.2	1.3/3.6	1.2/3.0	2.7/3.5
1-Axis, N-S	Average	1.9	2.5	3.4	4.0	4.3	4.8	4.7	4.2	3.6	3.0	2.0	1.5	3.3
	Min/Max	1.1/2.5	1.4/3.4	2.1/4.7	2.2/5.8	3.3/5.8	3.4/6.1	3.1/6.0	2.9/5.0	2.5/4.7	1.9/4.2	1.0/2.9	0.8/2.1	2.9/3.9
1-Axis, N-S Tilt=Latitude	Average	2.8	3.4	3.9	4.2	4.2	4.5	4.5	4.2	4.1	3.8	2.8	2.4	3.7
	Min/Max	1.6/3.8	1.8/4.5	2.4/5.4	2.3/6.1	3.2/5.6	3.2/5.7	3.0/5.7	3.0/5.0	2.8/5.2	2.5/5.3	1.4/4.1	1.3/3.2	3.3/4.4
2-Axis	Average	3.0	3.4	4.0	4.3	4.4	4.9	4.8	4.4	4.1	3.8	3.0	2.6	3.9
	Min/Max	1.7/4.1	1.9/4.6	2.4/5.5	2.4/6.2	3.4/5.9	3.5/6.2	3.2/6.1	3.1/5.2	2.8/5.3	2.5/5.3	1.5/4.3	1.4/3.5	3.5/4.6

Average Climatic Conditions

Element	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
Temperature (°C)	-0.1	1.6	6.7	11.9	17.4	22.5	25.0	24.2	20.3	13.7	8.2	2.6	12.8
Daily Minimum Temp	-4.8	-3.4	1.2	5.8	11.4	16.6	19.3	18.7	14.7	7.7	2.8	-2.1	7.3
Daily Maximum Temp	4.6	6.5	12.2	17.9	23.4	28.4	30.7	29.7	25.8	19.6	13.6	7.3	18.3
Record Minimum Temp	-21.7	-19.4	-14.4	-6.7	0.0	4.4	10.0	7.2	1.7	-3.9	-10.6	-17.8	-21.7
Record Maximum Temp	23.9	26.1	30.6	34.4	36.7	37.8	40.0	40.6	37.8	33.3	28.3	25.0	40.6
HDD, Base 18.3°C	572	470	360	193	60	0	0	0	16	153	303	487	2615
CDD, Base 18.3°C	0	0	0	0	33	126	207	183	74	9	0	0	632
Relative Humidity (%)	63	61	59	59	66	68	69	71	71	69	67	66	66
Wind Speed (m/s)	4.2	4.4	4.6	4.6	3.9	3.6	3.4	3.4	3.5	3.7	4.0	4.1	3.9

FIGURE 4-6

An example of the solar radiation data available from the National Renewable Energy Lab (NREL). This information applies to Baltimore, Maryland.

example, a 5.2 kW DC PV system array is to be installed in Portland, Maine, facing due south and tilted at latitude (43.65°). It is designed to produce 4 kW AC output at a peak solar radiation of 1000 watts/m^2 . According to the data manual, the average annual insolation for Portland, Maine is $4.6 \text{ kWh/m}^2/\text{day}$, or 4.6 peak sun hours per day. If the array is producing 4 kW per peak sun hour, then the average daily energy production would be 18.4 kWh ($4 \text{ kW} \times 4.6 \text{ peak sun hours} = 18.4 \text{ kWh}$). The average yearly energy production would be 6716 kWh ($18.4 \text{ kWh per day} \times 365 \text{ days per year} = 6716 \text{ kWh per year}$).

An advantage of using computer software to make this calculation is that it can take into account the amount of solar insolation available when the array is not oriented due south. It can also factor in system losses from such things as dirty modules, inverter losses, and shading. PVWattsTM is an online calculation tool developed and provided by the NREL and is used to determine energy production and cost savings of grid-connected PV systems. You can access PVWattsTM at <http://www.nrel.gov/rredc/pvwatts/>. It allows installers to easily develop estimates of the performance of proposed PV installations. The PVWatts calculator works by creating hour-by-hour performance simulations that provide estimated monthly and annual energy production in kilowatts and energy value. Users can select a location and choose to use default values or their own system parameters for size, electric cost, array type, tilt angle, and azimuth angle. In addition, the PVWatts calculator can provide hourly performance data for the selected location. Using typical meteorological year weather data for the selected location, the PVWatts calculator determines the amount of solar radiation striking the PV array and the PV cell temperature for each hour of the year. The DC energy for each hour is calculated from the PV system DC rating and the amount of solar radiation. It is then corrected for the PV cell temperature. The AC energy for each hour is calculated by multiplying the DC energy by the overall DC-to-AC derate factor and adjusting for inverter efficiency. Hourly values of AC energy are then summed to calculate monthly and annual AC energy production.

Using the PVWatts program, the 4 kW AC installation described above is shown to produce 6654 kWh for a year (Figure 4-7), which is close to the 6716 kWh the data manual method estimated. The PVWatts estimate is closer to what would actually be produced with such a system. The PVWatts program also estimates the energy value in dollars that the system will save. It is based on the latest known cost per kWh of electricity in the location you are installing the PV system. In this case, the Portland, Maine, cost of electricity is 12.2 cents per kWh. This number can be used to help determine the number of years it will take to pay for the original system installation. For example, PVWatts estimates a cost savings of about \$812 per year. If the system installation cost \$15,000, then it would take about 18.5 years of savings to equal the initial cost ($\$15,000/\$812 = 18.5 \text{ years}$). Of course, the cost of electricity will continue to rise above the 12.2 cents per kWh, so the actual time for payback will be shorter than 18.5 years.

Another software that is free to PV system installers is called HOMER. Like PVWatts, it was developed by the NREL but is now distributed and supported by HOMER Energy. You can download this software at <http://www.homerenergy.com/>. HOMER is a computer model that simplifies the task of evaluating design options for stand-alone and grid-connected hybrid applications. HOMER allows a user to evaluate the economic and technical feasibility of a large number of technology options and to account for uncertainty in technology costs, energy resource availability, and other variables.

FIGURE 4-7

An example of the type of data available when you use PVWatts™. These data apply to a 4kW AC output array located in Portland, Maine. NREL provides PVWatts™ to PV installers to use for free.



AC Energy
&
Cost Savings



Station Identification	
City:	Portland
State:	Maine
Latitude:	43.65° N
Longitude:	70.32° W
Elevation:	19 m
PV System Specifications	
DC Rating:	5.2 kW
DC to AC Derate Factor:	0.770
AC Rating:	4.0 kW
Array Type:	Fixed Tilt
Array Tilt:	43.7°
Array Azimuth:	180.0°
Energy Specifications	
Cost of Electricity:	12.2 ¢/kWh

Results			
Month	Solar Radiation (kWh/m ² /day)	AC Energy (kWh)	Energy Value (\$)
1	3.73	485	59.17
2	4.85	567	69.17
3	5.25	657	80.15
4	5.17	605	73.81
5	5.32	629	76.74
6	5.37	587	71.61
7	5.73	635	77.47
8	5.56	628	76.62
9	5.18	583	71.13
10	4.34	521	63.56
11	3.14	376	45.87
12	2.96	382	46.60
Year	4.71	6654	811.79

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Site Evaluation

A good PV system installation begins with a proper site evaluation. The site visit provides an opportunity to collect detailed information that will be used for the design and installation of the PV system. PV systems that are not oriented correctly will not produce the electrical energy they were designed to deliver. A poorly performing PV system always results in an unhappy customer. A site visit gives the installer an opportunity to review things like budgets and go over customer expectations of what the PV system can do. If the system is to be installed for an existing building, there will be an opportunity to review the current electrical loads and determine how much money the customer is spending per month on electricity. This information can be used to help determine potential energy savings with the PV system. The site evaluator will also be able to determine whether there are any potential installation problems. For example, the site evaluator may determine that the building's roof is in such bad shape that a roof mounted array is not possible.

Site Visit Equipment

When making a site visit, be sure to take all the equipment you will need. The equipment list can be quite long and will include things used to observe, measure, document, and diagram the site conditions. The following is a list of suggested site visit equipment:

- ◆ Digital camera—used to take pictures of various sections of the proposed site; can download photos back in the office for further evaluation; a digital video recorder could also be used.
- ◆ Digital voice recorder—used to record your verbal observations.
- ◆ Notebooks, graph paper, and pencils—used to record observations and make sketches of the site.

- ◆ Calculator—used to quickly calculate things such as area, perimeter, and angles.
- ◆ Compass—used to determine the direction of true south (Figure 4-8).
- ◆ Tape measure or laser distance meter—used to measure things like available array area, roof heights, and distances between equipment locations.
- ◆ Level, inclinometer, and protractor—used to determine the slope of an existing roof (Figure 4-9).
- ◆ Transit—used to calculate the angle of possible shading obstructions like trees.
- ◆ Stud finder—used to determine the location of building framing members for possible attachment of PV system components and electrical equipment.
- ◆ GPS device—used to quickly determine the latitude and longitude coordinates of the proposed array location.
- ◆ Sun path calculator—used to evaluate possible shading at array locations; two popular models are the Solar Pathfinder (Figure 4-10) and the Solmetric Sun-Eye (Figure 4-11).
- ◆ Electrical tester—used, if necessary, to take voltage and current readings of existing electrical service equipment; usually a multimeter is used.
- ◆ Ladder—used to access roof surfaces for taking measurements and determining the condition of the roof.
- ◆ Tools—a set of tools, especially electrical tools, that can be used if electrical panels or other electrical enclosures need to be accessed.
- ◆ Marking items—items like chalk, tape, paint, stakes, flags, and string, used to mark areas that will be part of the proposed PV installation
- ◆ Personal protective equipment—consists of safety glasses (sun glasses), hard hat, non-slip shoes, and gloves, as well as sunscreen to put on those skin areas exposed to the sun.
- ◆ First-aid kit—used to treat minor cuts and scratches as well as bug bites, bee and wasp stings, or snake bites.
- ◆ PV system site evaluation form—used to ensure that a systematic and thorough evaluation of the proposed site is completed (Figure 4-12).

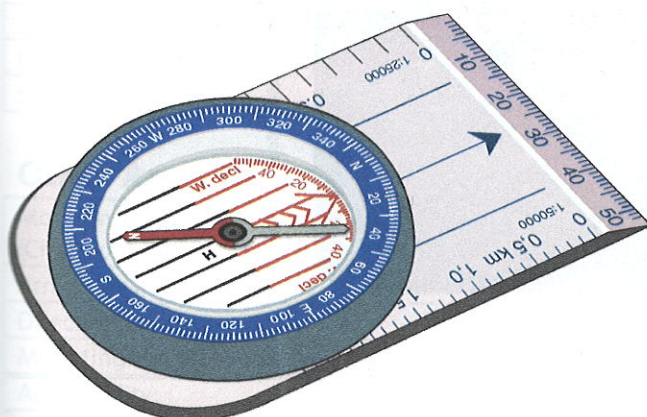


FIGURE 4-8

A compass is an important piece of equipment to take on a PV site evaluation. Notice that this compass has a ring that rotates to indicate the direction in degrees.

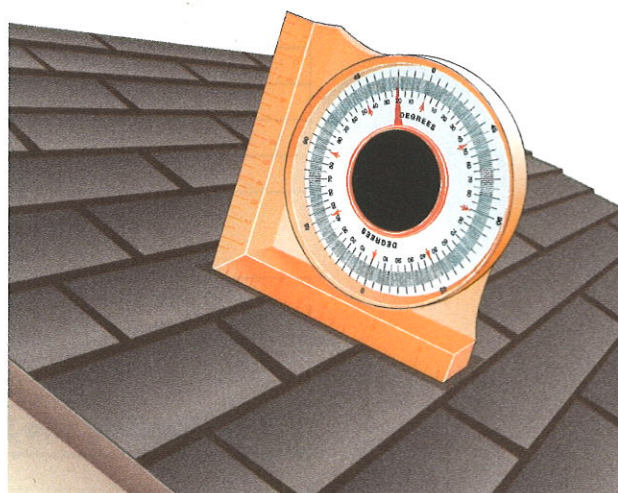


FIGURE 4-9

An inclinometer is used as an angle finder to determine the angle of a roof. It can also be used to verify that PV modules are tilted at the correct angle.

FIGURE 4-10

A Solar Pathfinder sun path calculator is used to evaluate shading at a PV site.



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FIGURE 4-11

The Solmetric SunEye is another very good tool for evaluating shading at a PV site. It has a built-in digital camera with a fish-eye lens for taking a photo of the entire sky and horizon around the PV site at the same time.



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Evaluating the Site for Shading

In evaluating a site to determine the location for a PV array installation, one of the most important considerations is whether there are any shading obstacles. Shading greatly affects the performance of a PV array, and as a general rule a PV array should be free of shade from 9:00 A. M. to 3:00 P. M. This time frame

PV System Site Evaluation Form

FIGURE 4-12

A sample PV system site evaluation form that is used to help document the information gathered on a PV site visit.

General Information

Site Address:		
Customer Name:		
Customer Address:		
Phone:	Fax:	Email:
Type of PV System:		System Size (kW):

Utility Information

Utility Name:		
Contact Person:		
Phone:	Fax:	Email:

Permit Information

Permitting Agency:		
Contact Person:		
Phone:	Fax:	Email:

Solar Resource Information

Site Latitude:		Site Longitude:	
Insolation (kW/m ² /day)	Average:	Maximum:	Minimum:
Temperature (° F)	Average:	Maximum:	Minimum:

Roof Mounting Information

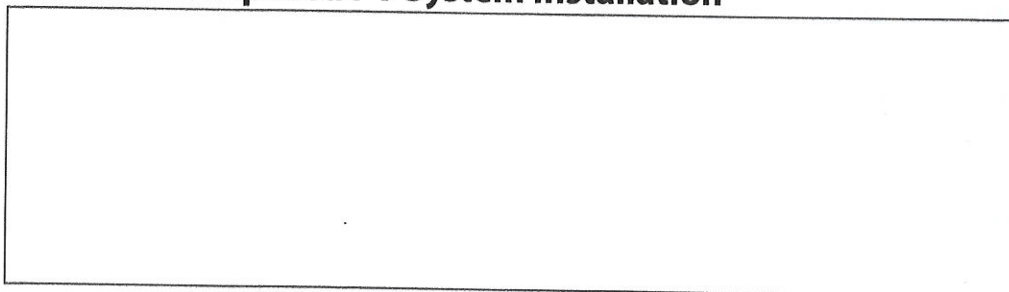
Array roof area available (sq. ft.):	Roof Slope (Degrees):
Roof Facing Direction:	Array Azimuth (Degrees):
Roof Height (Eave):	Roof Height (Ridge):
Accessibility:	
Potential for Shading:	
Type of Roofing Material:	Age of Roof:
Roof Surface Condition:	
Type of Roof Supporting Structure:	
Condition of Roof Support Structure:	
Structural Concerns:	

Other Array Mounting Information

Mounting Type (Check one)	Ground Mount:	Pole Mount:	Integrated Mount:
Array area available (sq. ft.):		Slope (Degrees):	
Direction Facing:		Array Azimuth (Degrees):	
Mounting Height (bottom):		Mounting Height (top):	
Accessibility:			
Potential for Shading:			
Mounting Concerns:			

FIGURE 4-12
(Continued)**Electrical Information**

System Voltage:		Service Entrance Rating:	
Service Entrance Type (Check One)	Overhead:	Underground:	
Other Connected Renewable Energy Sources:			
Point of Connection to Building Electrical System:			
Proposed Combiner Box Location:			
Proposed Array DC Disconnect Location:			
Proposed Charge Controller Location:			
Proposed Inverter Location:			
Proposed Location of the AC Disconnect:			
Proposed Battery Location:			
Proposed Battery Disconnect Location:			
Access Concerns:			
Other Electrical Concerns:			

Sketch of Proposed PV System Installation


Site Evaluator: _____ Date: _____
 Signature: _____

is considered to be the peak sun harvesting hours. Shading is usually a greater problem in the winter because of the sun's low altitude and the fact that shadows are longer. Use December 21, the shortest day of the year, for worst-case shadow calculations in the northern hemisphere. Specific information about how shading affects PV module performance is covered in Chapter 5.

Sun Path Charts

One method for finding a site with good year-round exposure is through long-term observation. Because of the amount of time involved, this is not practical. Fortunately, there are more practical ways to determine whether shading will be a problem at the proposed site. One way is to use sun path charts (Figure 4-13) and the altitude angle method to determine specific sun altitudes at different times of day and on different days of the year. Use the sun path chart that is based on the same latitude as the site you are evaluating. If you can't find a sun path chart based on the exact latitude, use one that is as close as possible. Then determine whether there are any objects such as trees that could cause shading of the array. A compass is used to determine the direction of the possible shading object.

The altitude angle can be found using a transit (a measuring instrument usually used by surveyors) or a protractor. The transit is easier to use and will indicate the angle directly on its dials when properly leveled (Figure 4-14). However, a transit is fairly expensive and not many PV installers own one. Using a protractor

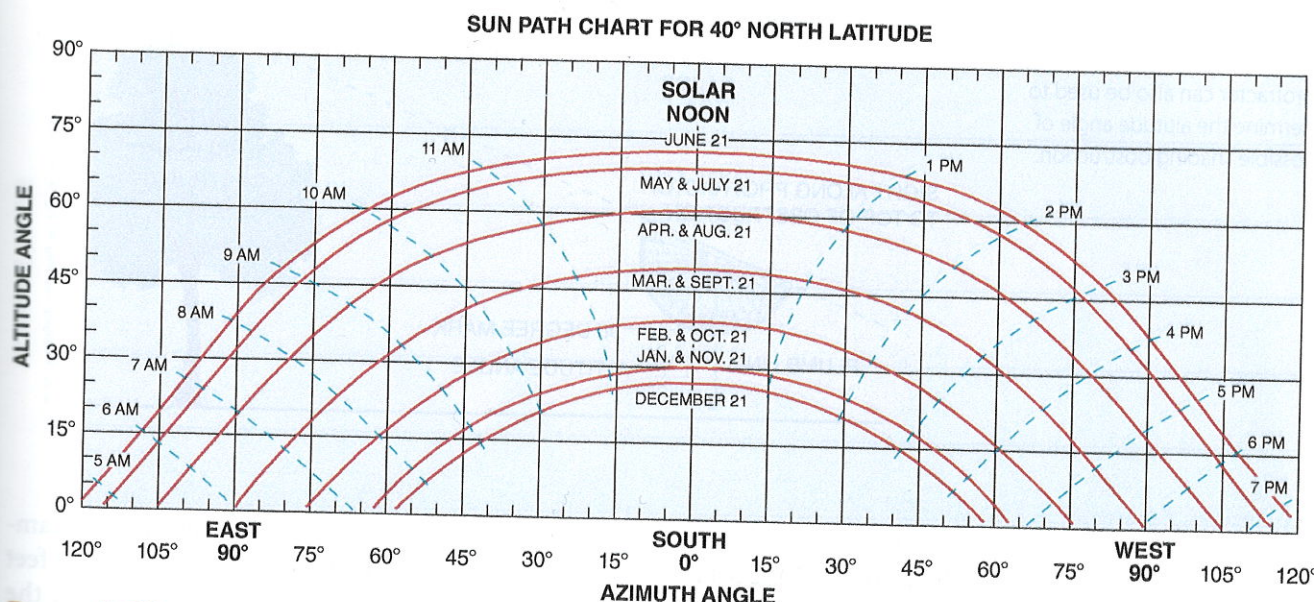


FIGURE 4-13

Sun path charts show the path of the sun at different dates and times for a specific location.

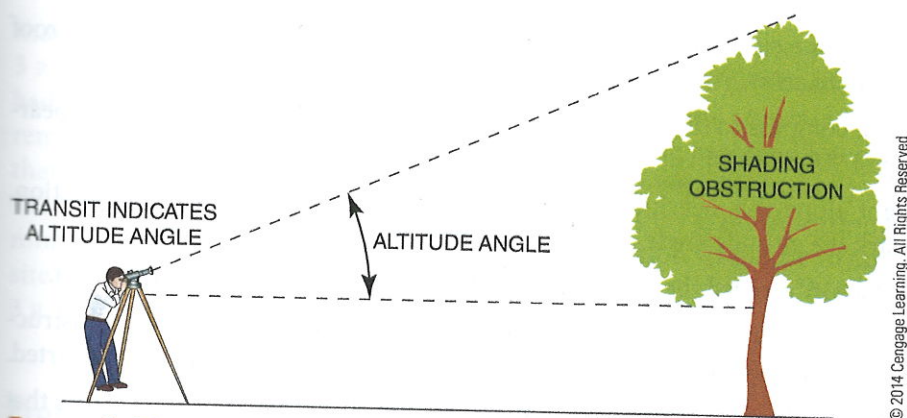


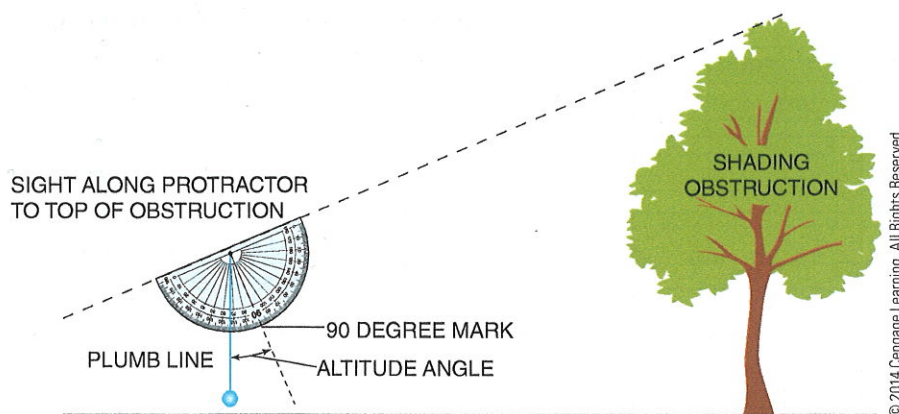
FIGURE 4-14

A transit being used to determine the altitude angle of a possible shading obstruction.

is more complicated, but much less expensive. The top of the shading obstruction is sighted along the flat edge of the protractor (Figure 4-15). A plumb line (a string with a weight on the end) is attached to the hole in the middle of the protractor and allowed to hang freely. The altitude angle is the difference between the plumb line and the 90° mark on the protractor. There is also a right-angle trigonometry formula that can be used to calculate the altitude angle. To use this formula, you need to know the height of the shading obstruction in feet (h) and the distance from the array to the obstruction in feet (d). This gives you the opposite side and adjacent side of a right triangle. Basic right-angle trigonometry tells us that the tangent of the angle is the opposite side divided by the adjacent side ($\tan \theta = \text{opposite side} / \text{adjacent side}$). So, by dividing the height (h) by the distance (d), you get the tangent of the altitude angle. Using the inverse tangent

FIGURE 4-15

A protractor can also be used to determine the altitude angle of a possible shading obstruction.



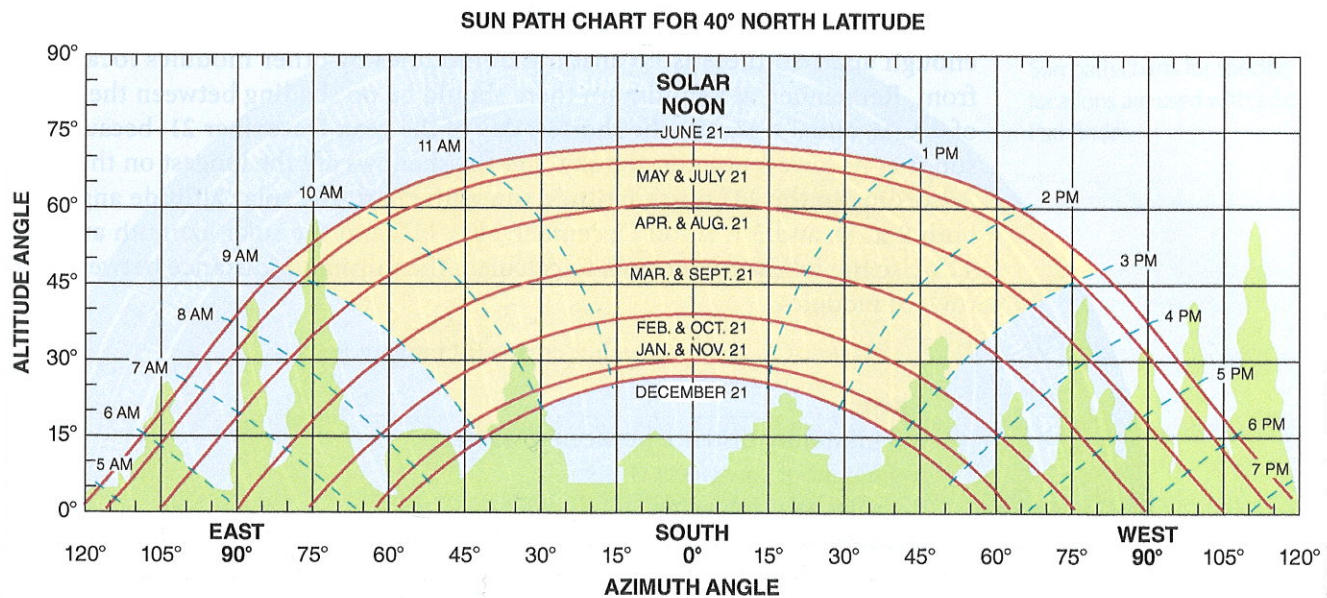
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function on your calculator, you can obtain the actual altitude angle. For example, a tree is 50 feet (15¼ m) away and it is determined that the tree is 40 feet (12 m) tall. Use a scientific calculator to divide 40 feet by 50 feet to get the tangent of the altitude angle, which is 0.80. Now, press the inverse function and then tangent buttons, and the altitude angle will be displayed. For this example it is 36.65°.

The following steps are used when using a sun path chart to determine shading:

1. Place yourself at the center of the proposed array site. If evaluating a roof mounted array, you need to be on the roof.
2. Use a compass to locate the direction of true south. Then determine the bearing of 90° due east.
3. Sight along this bearing to determine the altitude angle of any obstruction. Mark the altitude angle of any obstruction on the sun path chart.
4. Rotate 15° toward the west and mark the altitude angle of any obstruction.
5. Continue rotating 15° at a time and marking the altitude angles for all obstructions until you have reached 90° due west. This is 180° from where you started.
6. Connect all of the altitude angle marks on the chart to make a jagged line that runs from east to west.
7. With a pencil or highlighter, shade in everything below the line.
8. A good array site has no shading between 9 A. M. and 3 P. M. on any day of the year. If your sun path chart shaded area overlaps any of the 9 A. M. to 3 P. M. lines on any day of the year, it will mean that shading occurs and will have an adverse effect on the performance of the PV system. You then need to either eliminate the shading obstruction (for example, cut down a tree) or move the proposed array location to an orientation that is not shaded.

Let's look at an example. Figure 4-16 shows a sun path chart for 40° north latitude. Assume that the proposed array location is on a roof that happens to be facing true south and it has been determined that there are several possible shading obstructions that could cause a problem. Following the steps outlined above, a site evaluator marks the altitude angles for the possible shading obstructions on the sun path chart, connects the marks together, and then shades in the area under the line. Even though there are several trees that cause



An example of a sun path chart for 40° north latitude. This chart shows that three trees will cause minor shading in the 9 A. M. to 3 P. M. solar window at certain times of the year.

shading, there are only three trees that cause minor shading in the 9 A. M. to 3 P. M. solar window time frame. Overall, this proposed array location isn't too bad. An analysis of the sun path chart indicates that some trimming, or actual removal, of the three trees would eliminate the shading problem. Keep in mind that if the shading obstructions are trees or other vegetation, they may not shade the array now but they could in the future as they grow. Additional trimming may be in order. Another option in this situation would be to adjust the site location until there are no obstructions causing shading in the 9 A. M. to 3 P. M. window.

Profile Angle Calculation

Sometimes it is necessary to perform a profile angle calculation to determine whether there will be shading from one object on another object at a certain time of day. For example, flat roof-mounted PV modules on racks that are tilted at a specific angle need to be placed a certain distance apart from each other so that a row of modules does not shade any of the modules located behind it. This is also a concern with ground-mounted arrays and pole-mounted arrays.

The **profile angle** is the projection of the altitude angle onto an imaginary plane that is perpendicular to the surface of an obstruction. The profile angle is used to determine the length of a shadow at a certain time. This shadow length is the minimum distance that a module must be placed from a shading obstruction. Profile angles change as shadows lengthen and shorten as the sun moves across the sky.

Let's look at an example where a PV array will consist of several rows of modules on a flat roof of a school located at 44° north latitude. The array will be facing due south, and the tilt of the modules causes them to have a row height

of 2 feet. The installer needs to make sure that the module racks are spaced far enough apart so there is no shading of modules by other modules located in front. Remember, at a minimum there should be no shading between the hours of 9 A. M. and 3 P. M. Use the shortest day of the year, December 21, because the sun is at its lowest point in the sky, and the shadows are the longest on that day. According to the 44° north latitude sun path chart, the solar altitude angle for both 9 A. M. and 3 P. M. on December 21 is 11°, and the solar azimuth angle is 42°. Use the following formula to calculate the minimum distance between the rows of modules:

$$d = h \times \cosine \theta / \tangent \psi$$

where:

d = minimum distance between rows (feet)

h = height of row (feet)

θ = solar azimuth angle

ψ = solar altitude angle

$$d = 2 \text{ feet} \times \cosine 42^\circ / \tangent 11^\circ$$

$$d = 2 \text{ feet} \times 0.74 / 0.19$$

$$d = 7.8 \text{ feet}$$

Therefore, the minimum distance between the rows of modules in this example must be 7.8 feet (2.4 m). Any closer than this distance apart will result in the front rows shading modules in the rows behind them sometime during the day.

Solar Site Selector Devices

Even though the sun path chart method described above works to determine whether shading will be a problem for a proposed array location, many installers today use commercially available solar site selector devices with sun charts built in. The two that are the most popular are the Solar PathfinderTM and the Solmetric SunEyeTM. Both are much more expensive than using sun path charts, but they are easy to use and work quickly to determine the potential shading of the proposed array site. The Solar PathfinderTM is less expensive than the Solmetric SunEyeTM. The price difference between them is the main reason why the Solar PathfinderTM is more commonly used by solar PV system installers.

Both devices work by comparing the solar window for a specific location to an image of the different shading obstructions around the proposed array site. The Solar Pathfinder uses sun charts that are made for specific latitudes (Figure 4-17). The chart is covered by a see-through dome that reflects the sky and horizon on its surface (Figure 4-18). The Solar Pathfinder is placed at the center of the proposed array location, oriented toward true south, and leveled. When observed from directly above the see-through dome, the reflection of the surrounding area on the dome shows any shading obstructions. To determine whether shading will be a problem, a special marker is used to reach in under the dome and trace around the various obstructions directly on the sun chart. Once the tracing is done, the sun chart is removed and analyzed to determine the amount of potential shading. An easier way to use the Solar Pathfinder is to take a digital photo of the image reflected on the dome and

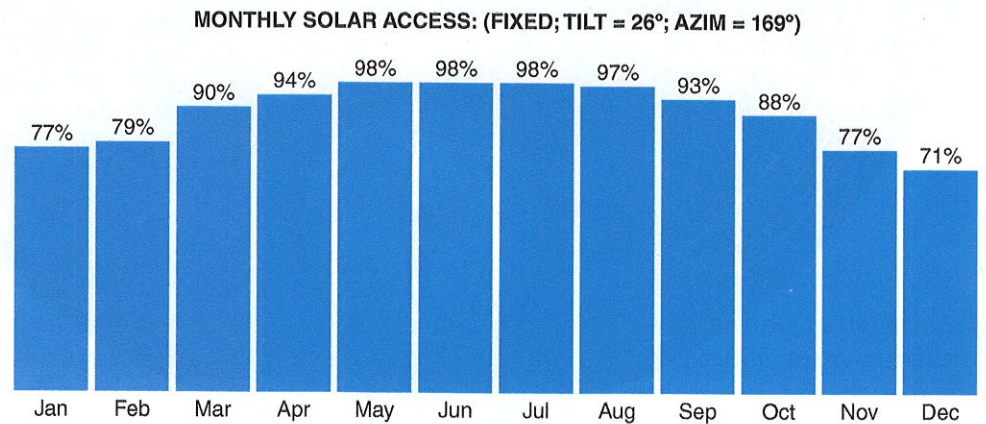
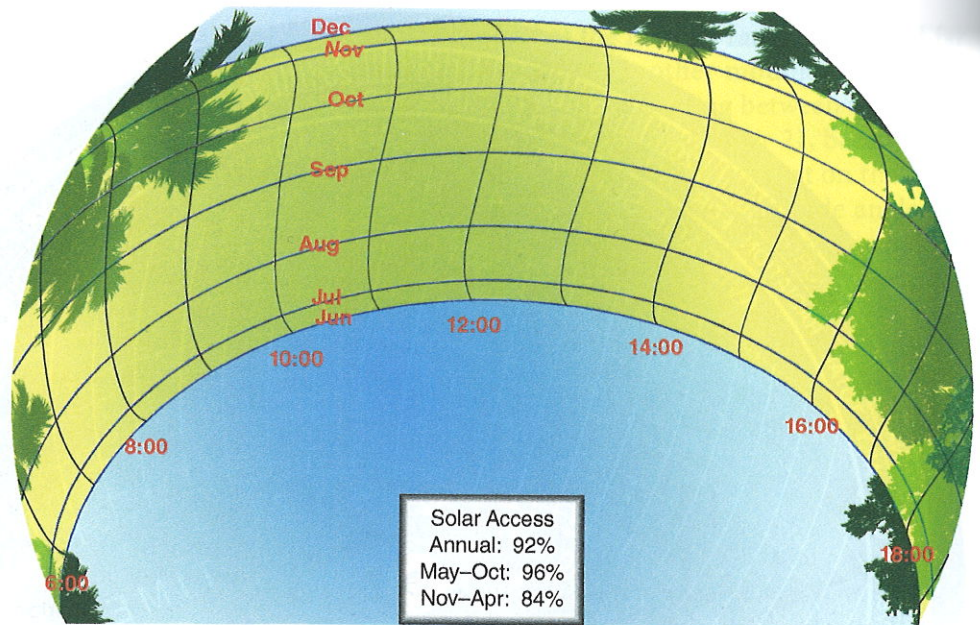


FIGURE 4-19

A SunEye can analyze the shading information and display a detailed report.

upload it to a computer. The analyzing software is an optional part of the Solar Pathfinder package but is well worth it. Once the photo is uploaded, the software analyzes the image and creates a report that can be printed out, pointing out any possible shading problems for specific days and times. Check out the demonstration videos of the Solar Pathfinder at <http://www.solarpathfinder.com/video>.

The SunEye also uses a digital photo of the array location's sky area but it is taken with a built-in camera. The software that comes already loaded in the SunEye analyzes the photo for possible shading obstructions for specific days and times. Like the Solar Pathfinder, the SunEye is placed at the approximate center of where the array will be installed. You have to input your location, level it, and orient it to true south. One advantage of the SunEye is that the software automatically accounts for magnetic declination. The device shows the analyzed photo or you can upload the photo and shading data to a computer for generating detailed reports (Figure 4-19). Check out the demonstration videos of the Solmetric SunEye solar site analyzing device at <http://www.solmetric.com/videos1.html>.

Chapter Summary

- ◆ Solar irradiance is a measure of how much solar power is striking a specific location.
- ◆ Solar irradiance is expressed as a number of watts per square meter (W/m^2).
- ◆ Solar irradiation is a measure of the total amount of solar energy accumulated on an area over a period of time.
- ◆ Solar irradiation is expressed as a number of watt-hours per square meter (Wh/m^2).
- ◆ Insolation is another term often used to refer to the amount of solar irradiance received over time, typically for one day.
- ◆ The insolation value is generally expressed as $\text{kWh}/\text{m}^2/\text{day}$ or the equivalent amount of peak sun hours.
- ◆ Peak sun hours are the number of hours per day that solar insolation equals $1000 \text{ W}/\text{m}^2$.
- ◆ Solar irradiation received at the earth's surface varies because of atmospheric attenuation (loss).
- ◆ The sun's zenith occurs when the sun is directly above an array, resulting in the minimum amount of atmosphere the sun's rays have to go through.
- ◆ The earth's distance from the sun and its tilt affect how much solar energy is available.
- ◆ A location's latitude determines whether the sun appears to travel in the northern or southern sky.
- ◆ The sun's apparent location in the sky east or west of true south is called the azimuth.
- ◆ The azimuth angle is the angle clockwise from true north that the PV array faces.
- ◆ The deviation of magnetic south from true south is called magnetic declination.
- ◆ The sun's height above the horizon is called altitude.
- ◆ The highest average insolation falls on a PV module with a tilt angle equal to the latitude.
- ◆ The amount of electrical power produced by a PV system of a specific size depends on the amount of solar energy that strikes the system array.
- ◆ The best place to find solar insolation data for a specific location is through the National Renewable Energy Laboratory (NREL).
- ◆ NREL has established a Renewable Resource Data Center (RReDC).
- ◆ PVWatts™ is an online calculation tool developed and provided by the NREL and is used to determine energy production and cost savings of grid-connected PV systems.
- ◆ A good PV system installation begins with a proper site evaluation.
- ◆ For a specific location, the area in the sky that is between the sun path of the winter solstice (December 21) and the sun path for the summer solstice (June 21) for the hours of 9:00 A. M. to 3 P. M. is called the solar window.
- ◆ When evaluating a site to locate where the PV array will be installed, one of the most important items to determine is whether there are any shading obstacles.
- ◆ Shading is usually a greater problem in the winter because of the sun's low altitude and the fact that the shadows are longer.
- ◆ One way to help determine whether a site would work well for a PV array is to use sun path charts.
- ◆ The two solar site selection devices that are the most popular are the Solar Pathfinder™ and the Solmetric SunEye™.
- ◆ Both devices work by comparing the solar window for a specific location to an image of the different shading obstructions around the proposed array site.