

Chapter Five

Designing Solar Electric Systems

The proper design of solar electric and solar thermal systems depends on an understanding of the sun's movements through the sky and the way local site conditions and climate influence the availability of sunlight at any particular location. While the following discussion is oriented towards the design of solar electric systems, it is relevant to the design of solar thermal systems, as well.

Site Assessment:

Understanding the Path of the Sun

The specific site where a PV system will be located plays a crucial role in the design and performance of the system. The amount of power generated by a solar cell depends upon the intensity of sunlight striking it, and the amount of available sunlight varies with latitude, climate, and local conditions, such as the presence of trees. It is helpful to understand how the sun moves through the sky throughout the year when evaluating your site's solar potential.

There are three factors responsible for variations in the amount and quality of sunlight reaching the Earth. First, the Earth is round. Second, it revolves around the sun in an elliptical orbit. Third, the Earth rotates on a tilted axis. As the Earth is round, sunlight strikes its surface at differing angles ranging from 0° (just above the horizon) to 90° (when the sun is directly overhead). When the sun's rays are perpendicular to the surface of the Earth, they transmit the most energy. When the sun is low in the sky and its rays are at a very low angle, they must pass through a longer portion of the atmosphere, making the sunlight scattered, diffuse, and reducing its energy. The Earth's polar regions never see the sun high in the sky because the Earth is round. The tilted axis of rotation explains why the polar regions receive no sun at all during certain times of year.

The Earth's elliptical orbit causes the Earth to be closer to the sun during certain times of the year, allowing somewhat more solar energy to reach the planet. We are closer to the sun when it is winter in the northern hemisphere and summer in the southern hemisphere. Why isn't it hotter in the northern hemisphere when we are closer to the sun? The North Pole is tilted away from the sun at this time, which lowers the angle of the sunlight reaching the northern hemisphere, thereby reducing its energy content. Why does the northern hemisphere have summer when the

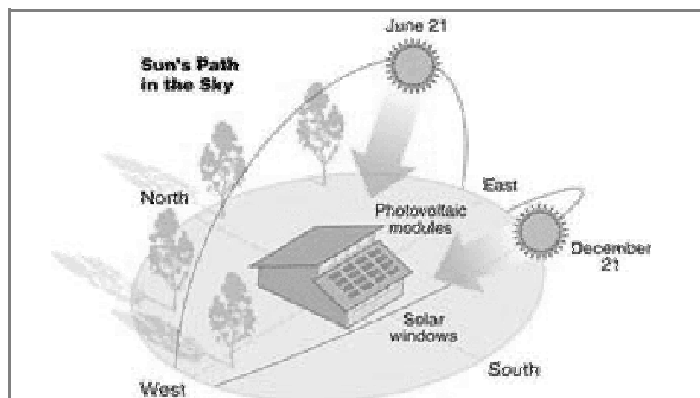


Figure 5.1: The United States receives much more solar radiation in the summer when the sun is higher overhead than in the winter when it is lower in the sky.

Energy Efficiency and Renewable Energy Clearinghouse, US DOE

Earth is farthest from the sun? Because the North Pole is tilted towards the sun at this time, increasing the angle of incoming sunlight and its energy content. Why isn't the southern hemisphere even hotter during its summer, when Earth is closest to the sun and the south pole is tilted towards it? This is explained by our vast oceans, which absorb much of the sun's energy and moderate the hotter summers and colder winters we would expect to see in the southern hemisphere as a result of these conditions.

The 23.5° tilt in the Earth's axis of rotation is a very significant factor in determining the amount of solar energy striking the Earth at a particular location. "Tilting results in longer days in the northern hemisphere from the spring (vernal) equinox to the fall (autumnal) equinox and longer days in the southern hemisphere during the other six months. Days and nights are both exactly 12 hours long on the equinoxes, which occur each year on or around March 23 and September 22.

"Countries like the United States, which lie in the middle latitudes, receive more solar energy in the summer not only because days are longer, but also because the sun is nearly overhead. The sun's rays are far more slanted during the shorter days of the winter months. The result is a big difference in the amount of direct sunlight available for solar energy systems. Cities like Denver (near 40° latitude) receive nearly three times more solar energy in June than they do in December. That's why winter is so much colder than summer.

"The rotation of the Earth is responsible for hourly variations in sunlight. In the early morning and late afternoon, the sun is low in the sky. Its rays travel further through the atmosphere than at noon when the sun is at its highest point. On a clear day, the greatest amount of solar energy reaches a solar collector around solar noon."¹

Sun Hours: The Power of the Sun

When calculating how much power a PV panel can generate in a particular location, we need to know how much energy the sun can provide in that place. A "Sun Hour" is the conventional term used to express the total amount of solar energy that falls on a one square-meter surface over the course of one day. One Sun Hour is equivalent to 1 kW/m². On a typical day in June, Lexington, Kentucky will receive 6.2 Sun Hours of solar energy on a one square-meter horizontal surface (see Table 5.1). A vertical surface will receive 2.4 Sun Hours on that same day. The difference is due to the fact that the high summer sun in June will strike a horizontal surface more directly, imparting more of its energy to that surface. On a typical day in December, by contrast, a horizontal surface will receive 1.7 Sun Hours and a vertical surface 2.6 Sun Hours. This illustrates how much more solar energy is available in the summer versus the winter in Lexington. This also indicates the significance of the angle of the sun's rays as they strike the solar collector surface. Figure 5.2 illustrates the average annual solar insolation throughout the United States. Appendix B provides solar insolation data for locations in or near Kentucky.

	June	December
Horizontal Surface	6.2	1.7
Vertical Surface	2.4	2.6

Module Orientation and Tilt Angles

As the Lexington example illustrates, the orientation and tilt angle of a solar panel make a big difference in terms of the amount of solar radiation that can be absorbed. A PV panel will receive the most energy when it is perpendicular to the incoming solar rays. Ideally, a panel would rotate to follow the sun throughout the day, and there are tracking systems that can do this. A single-axis tracker will rotate from east to west following the sun. A double-axis tracker also moves to follow the sun as it gets higher and lower in the sky during the day, and from season to season. Active tracking systems use electric motors to move the panels, while passive systems do not require a power source. One type of passive system uses freon to

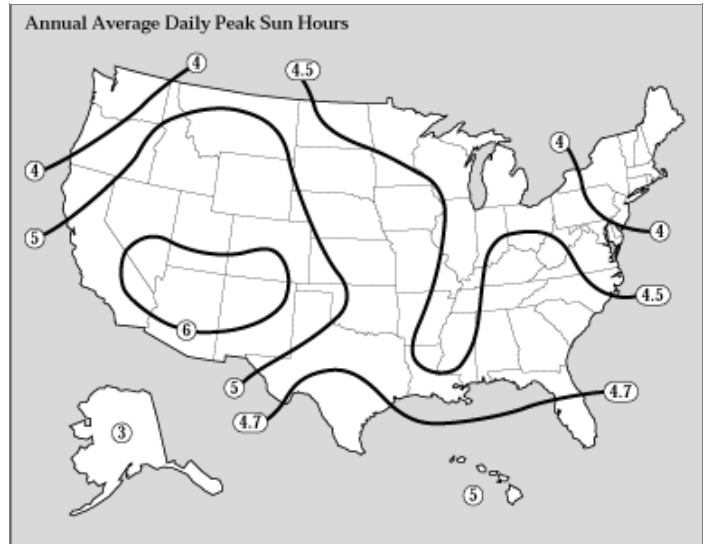


Figure 5.2: Annual Average Daily Peak Sun Hours in the US *Energy Efficiency and Renewable Energy Clearinghouse, US DOE*

move the panels.

Depending upon the circumstances, tracking PV systems can produce 20 to 40 percent more power than fixed panels. "Most tracking systems require climates with a high fraction of direct beam versus diffuse sunlight to work well. Climates with high humidity have lower fractions of direct beam sunlight."³ To choose between a tracking and a fixed PV array, one must weigh the additional power the tracking array will produce against the added expense, maintenance, and complexity it will bring to the system. In Kentucky, using a tracking rack typically only makes sense for large PV arrays (more than 450 watts of PV panels) that are in a wide-open location not exposed to any shading obstacles from sunrise to sunset, and when the extra power generated, mostly in summer, can actually be used.

PV panels with a fixed orientation should face as



Figure 5.3: The tracking PV array on the left is facing the afternoon sun, while the fixed array on the right faces due south, *Andy McDonald*

close to true south as reasonably possible. Sometimes local conditions prevent this, such as the orientation of an existing roof that will mount the panels or the presence of shade trees. In such cases, "deviating ... from true south by as much as 20° to 30° east or west will not significantly reduce the total solar radiation received."⁴ There are several options to choose from regarding the tilt angles of PV panels. To minimize maintenance on the system, panels can be permanently fixed at a given angle. For maximum annual electricity production in this situation, set the tilt angle equal to the latitude. For example, at 38° latitude, the angle between the surface of the PV module and a level line would be 38°. To maximize winter electricity production, use a tilt angle equal to the latitude plus 15°. Situations when this would be recommended would be when winter electricity demand would exceed summer demand. Another reason would be to balance year-round PV output, since solar insolation is normally lower in the winter than in the summer.

To increase overall annual power production, the tilt angles can be adjusted four times per year according to the schedule in Table 5.2. This will increase production during each season versus using a single fixed tilt angle.

Magnetic Declination: Finding True South

True south is not the same as magnetic south in most places. Due to the Earth's magnetic field, true south varies from magnetic south in Kentucky by about minus 4.5°. (Declination is considered positive east of true north and negative when west.) In western Kentucky, the variation is -1.5°, in central Kentucky - 4.5°, and in Eastern Kentucky -6.0°. To orient solar panels due south in central Kentucky, they should be installed 4.5° west of compass south. The degree of magnetic declination is slowly yet continuously changing.⁵ You can find the current magnetic declination, along with the latitude and longitude, for any location in the U.S. at the following website: <http://www.ngdc.noaa.gov/seg/geomag/jsp/Declination.jsp>

Microclimate, Shading Effect, and the Solar Window

The local microclimate can significantly impact the solar radiation at a site. Local conditions that dispose a site to early-morning fog, for example, might lead you to orient your solar panels towards the west to capture more of the afternoon sun. Shading produced by trees, mountains, or other buildings will also affect the performance of a PV system. "Shading of only one cell within a PV module can reduce the module's power output by as much as 75 percent."⁶ The optimum PV site will have an unobstructed "solar window" between the hours of 9 am and 3pm, when nearly 85 percent of the sun's energy is transmitted. (Note that 9am and 3pm refer to "solar time," not Eastern Standard or daylight

Table 5.2: Preferred Seasonal Tilt Angles for PV Arrays in Central KY (at 38° Latitude)

Season	Position Array	General Formula	Array Angle
Spring/ Fall	March 1/ September 1	Tilt angle = latitude	38°
Summer	April 15	Tilt angle = latitude - 15°	23°
Winter	October 15	Tilt angle = latitude + 15°	51°

savings time. For instance, in central Kentucky around the I-75 corridor, solar noon is about 12:40pm EST). The solar window is the portion of the sky that the sun passes through over the course of the year. A professional site assessment using a tool known as a Solar Pathfinder⁷ can help you determine, at a glance, the size of your solar window, for every month of the year. If there is any question as to the availability of a clear solar window on your site, a solar site assessment is highly recommended.

Sizing Stand-Alone PV Systems

The worksheets in Appendix A will help you form an initial estimate of the number of PV modules and batteries you would need for a stand-alone system. While this will give you a sense of the size and cost of the equipment you would need, we recommend that you consult with an experienced PV system designer/installer to ensure that your system is properly and safely designed.

Sizing your PV system begins with an assessment of your electricity demand. You need to know how much power you need on a daily basis and at different times of the year in order to calculate how much generation and storage capacity you need to install. This demand assessment should be followed by critical analysis of every opportunity to reduce your power needs. These opportunities come in the form of alternative, more energy-efficient appliances, alternative energy sources, and behavior changes. Remember John Robbins' advice from Chapter Two that using solar electricity is "one part solar, five parts load reduction." The money you spend on energy-efficient appliances and reducing waste will more than pay for itself by reducing the size (and therefore, initial cost) of the PV system.

Sizing Grid-Intertied PV Systems

For grid-intertied PV systems, sizing the solar system is not as critical as it is for stand-alone systems, because the electric grid provides backup power. Thus, if your PV system fails to meet all your needs, you'll still have power, albeit from the utility rather than the sun. The security provided by the utility grid might lead you to ignore the process of

analyzing your energy demands and optimizing the efficiency with which you use energy. This would be an error, however, because saving energy will still cost you less than installing PV panels, and will keep saving you money, month after month. Furthermore, the more you can reduce your demand for energy, the greater the proportion of what you use will be supplied by solar. So as you would do for a stand-alone system, begin by assessing your energy needs and reducing your demand as much as possible.

There are two approaches to sizing a grid-intertied PV system. In the first approach, you attempt to match the size of your PV system to your average annual electricity demand, so that over the course of a year, you produce just about as much electricity as you consume. This approach is based upon the "*daytime solar fraction*—the ratio between average daytime power consumption and average daily photovoltaic system output."⁸ Performing the calculations to optimize a PV system in this way can be more complex than sizing a stand-alone system, due to the many variables that influence the economics of grid-intertied systems. Refer to *The Solar Electric House* by Strong and Schaller for further information on this approach.

One could conceivably install more PV panels than you need to meet your average electricity demand, and essentially become a small, independent power producer. However, there are rarely any financial incentives for doing this, so matching your grid-intertied PV system with your electricity demand makes more economic sense.

The second approach to sizing a grid-intertied system is for people who cannot afford to install a PV system large enough to match their electricity demand. This approach typically comes down to the question, "How much can I offset my electric bill if I invest X dollars in efficient appliances and a solar electric system?" The answer depends on the efficiency of appliances currently in use, the amount of electricity used, and the size of the solar electric system being considered, as well as site conditions, such as shading. Grid-intertied systems typically cost from \$7 to \$10 per installed watt of PV generation. In central Kentucky, a 1000-watt system costing \$7000 to \$10,000 will generate, on average, 135 kilowatt-hours (kWh) per month. At 6 cents per kWh this amounts to cutting \$8 per month off the electric bill, or about \$100 per year (a 1.0 - 1.5 % return on investment).

By comparison, replacing a standard refrigerator built before 1990 with a super-efficient refrigerator, at a cost of \$2000, would also reduce your electricity bills by \$8 per month, but at a fraction of the cost of installing a PV system. This example highlights how important energy efficiency is when considering purchasing a solar PV system. It only makes sense to install PV panels on buildings whose energy use is

already streamlined. The qualifications of a PV system designer/installer should be seriously questioned if they do not address the energy demand and appliances/equipment to be powered by the solar electric system, regardless of whether a stand-alone or grid-intertied PV system is being considered.

If funding does not allow the initial size of your net metered solar system to match your electricity demand, expanding the system at a later time is likely to cost much less per additional unit of power than the initial system cost. This is because the inverters used in grid-intertied systems are typically capable of handling more power than the initial number of PV panels can produce. Additional PV panels can easily be added later without incurring the same costs involved when setting up the system, providing a much greater return than with the initial investment.

Unlike battery-based systems, which can be quite small in size, grid-intertied systems have an entry level cost between \$4,000 to \$5,000. This is primarily a function of the inverter that connects the system to the utility grid. Unlike battery-based inverters, which simply have to convert the battery direct current (DC) into usable alternating current (AC), grid-intertied inverters (with or without battery back-up) have to match the AC output to the utility grid and safely disconnect themselves from the grid when the electric grid fails. This added complexity keeps the minimum inverter size to one rated for 700-watts (a battery-less inverter) of solar electric module input. By contrast, battery-based inverters for stand-alone systems can be as small as 50-watts of rated AC output.

The smallest grid-intertied inverter currently available in the U. S. is manufactured by SMA and is known as Sunny Boy 700U. It retails for approximately \$1,800. This battery-less inverter requires PV panels with a minimum output of 300 watts, which will cost approximately \$1,400. Add to this PV panel mounts, wiring, conduit, and safety equipment and the total cost approaches \$4,000. In central Kentucky, such a system would generate, on average, about one kilowatt-hour per day. This system could be doubled in size (600 watts) for an added cost of only \$1,400. If finances allow, larger systems (greater than 5000 watts) can be installed for as little as \$5 to \$6 per installed watt.

Typically, people install net metered solar electric systems on their homes or businesses for reasons other than economics. The majority (97 percent) of electricity supplied by the grid in Kentucky comes from burning coal. The combustion of coal and its extraction from Eastern Kentucky mountains comes at a price not reflected in electric bills. The price is paid in the form of lower air quality and associated health problems, rough roads damaged by heavy trucks, damaged property, scarred mountain views, creeks filled with

coal slurry and fill dirt, and ruined watersheds.

As the price for solar equipment comes down and the price of grid supplied electricity goes up, PV's economic returns will improve and monthly utility bill savings will increase. At current electricity prices in Kentucky, a 1000-watt PV system would reduce your electric bill by about \$8 per month. If electricity prices were to double, your monthly savings would double as well, and the payback time on your investment would be cut in half. If we add in financial incentives that can reduce the up-front costs of the PV system, or that increase on-going financial returns from the power produced (such as premium payments from the utility for the solar electricity you generate), the payback time can fall dramatically. In states such as New York, New Jersey, and California, the combination of high electricity rates and generous incentives makes net metered PV systems an economically-viable, long-term economic investment. As electricity and fuel prices rise over the coming decades, a PV system will guarantee you a fixed price for your electricity for the life of the system, which can exceed 30 years.

End Notes

1. "Assessing Climate to Improve Solar Design," Energy Efficiency and Renewable Energy Clearinghouse, US Department of Energy, Document no. DOE/GO-120001-1171, FS122, August 2001, p.3.
2. *Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors*, National Renewable Energy Laboratory, U.S. Department of Energy. The manual is available on-line at:http://rredc.nrel.gov/solar/old_data/nsrdb/redbook/sum2/
3. "Photovoltaics: Electricity from the Sun," North Carolina Solar Center, Fact Sheet no. SC108, Raleigh, NC, June 2002, p.1.
4. "Siting of Active Collectors and Photovoltaic Modules," North Carolina Solar Center, Fact Sheet no. SC112, September 2001.
5. Ibid, p.1.
6. Ibid, p.3.
7. To learn more about the Solar Pathfinder or purchase one for yourself, visit their web site at: www.solarpathfinder.com/
8. Steven J. Strong and William G. Scheller, *The Solar Electric House: Energy for the Environmentally-Responsive, Energy-Independent Home*, Sustainability Press, 1993, p.175.

