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Photovoltaics: Basic Design Principles and Components

If you are thinking of generating your own electricity, you should consider a photovoltaic (PV) system—a way to generate electricity by using energy from the sun. These systems have several advantages: they are cost-effective alternatives in areas where extending a utility power line is very expensive; they have no moving parts and require little maintenance; and they produce electricity without polluting the environment.

This publication will introduce you to the basic design principles and components of PV systems. It will also help you discuss these systems knowledgeably with an equipment supplier or system installer. Because this publication is not intended to cover everything about designing and installing a PV system, a list of additional PV resources is provided at the end.

Jim Yost / PIX01809

This stand-alone PV system consists of four modules, each with 36 cells. It provides power for lights, radios, televisions, and other loads at remote homes in New Mexico.

Introduction to PV Technology

Single *PV cells* (also known as “solar cells”) are connected electrically to form *PV modules,* which are the building blocks of PV systems. The module is the smallest PV unit that can be used to generate substantial amounts of PV power. Although individual PV cells produce only small amounts of electricity, PV modules are manufactured with varying electrical outputs ranging from a few watts to more than 100 watts of direct current (DC) electricity. The modules can be connected into *PV arrays* for powering a wide variety of electrical equipment.

Two primary types of PV technologies available commercially are crystalline silicon and thin film. In crystalline-silicon technologies, individual PV cells are cut from large single crystals or from ingots of crystalline silicon. In thin-film PV technologies, the PV material is deposited on glass or thin metal that mechanically supports the cell or module. Thin-film-based modules are produced in sheets that are sized for specified electrical outputs.

In addition to PV modules, the components needed to complete a PV system may include a battery charge controller, batteries, an inverter or power control unit (for alternating-current loads), safety disconnects and fuses, a grounding circuit, and wiring. (See *Balance-of-System Equipment* section.)

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Hundreds of cost-effective applications for PV systems have been developed.

PV System Applications

Many people are familiar with PV-powered calculators and watches, the most common small-scale applications of PV. However, there are numerous large-scale, cost-effective PV applications, including:

- **Water pumping** for small-scale remote irrigation, stock watering, residential uses, remote villages, and marine sump pumps;
- **Lighting** for residential needs, billboards, security, highway signs, streets and parking lots, pathways, recreational vehicles, remote villages and schools, and marine navigational buoys;
- **Communications** by remote relay stations, emergency radios, orbiting satellites, and cellular telephones;
- **Refrigeration** for medical and recreational uses;
- **Corrosion protection** for pipelines and docks, petroleum and water wells, and underground tanks;
- **Utility grids** that produce utility- or commercial-scale electricity; and
- **Household appliances** such as ventilation fans, swamp coolers, televisions, blenders, stereos, and other appliances.

The decreasing cost of PV systems and the increasing number of manufacturers and dealers for PV equipment have contributed to widespread use of the technology. In PV's early days, do-it-yourselfers had to search for companies that manufactured PV modules and often had to adapt or reconfigure components from other non-PV systems. Today, dealers offer ready-to-use systems and state-of-the-art equipment designed specifically for PV systems. Many dealers have computer software that helps to design systems and specify appropriate components. As PV markets expand, dealers are gaining greater experience with PV applications, making it cheaper and easier to purchase PV systems.

How Do I Select a PV Dealer?

Choosing a PV professional will be one of your most important decisions. If you choose a competent dealer, you won't need to know all the details of designing, purchasing, and installing your PV system. Instead, you can rely on the dealer's expertise to design and install a system that meets your needs. However, just like buying a car or a television, you must have confidence in the dealer's products and services and be an informed consumer. With the growth of the PV industry, the number of regional dealers, mail-order businesses, and local distributors has expanded rapidly. Many telephone directories contain listings for PV dealers under the "Solar" heading.

Professional credentials are one indication of a PV dealer's knowledge and qualifications. Ask dealers what PV-related courses they have taken, certifications they have earned, and licenses they have received.

A second consideration is the dealer's experience in the field. How long has the company been in business? The local Better Business Bureau can advise you whether any customers have registered complaints about the dealer. You should also ask the dealer how many systems like yours he or she has designed and installed. Ask to see installations, and talk with owners of systems similar to the one you want to purchase.

A third consideration in selecting a system installer is the variety and quality of products offered for each component of the system. Because PV systems are often designed for a specific site, one company's products may not be appropriate for all applications. Competent dealers will stock components manufactured by several companies. A variety of product options will help ensure that the most appropriate components are available for your system. When a dealer recommends a product, ask what the recommendation is based on, whether there are consumer or independent testing facility reports you can read, and whether the products are listed with Underwriters Laboratories (UL).

Fourth, consider the service agreements and performance guarantees the dealer provides and the warranties given by the product manufacturers. No system is maintenance-free, nor will all components function flawlessly forever. When problems emerge with your system, what services will the dealer provide? What warranties do the manufacturers provide? What costs should you expect to pay, and which costs will be assumed by the dealer and / or the manufacturer?

Finally, you should compare prices from different dealers. Because distribution channels and dealer networks have expanded dramatically, the opportunity to "shop around" is much greater today. If possible, approach more than one dealer about a draft design and cost estimate for your system.

In the United States, PV systems must have unobstructed southern exposure.

When Are PV Systems Appropriate?

People select PV systems for a variety of reasons. Some common reasons for selecting a PV system include:

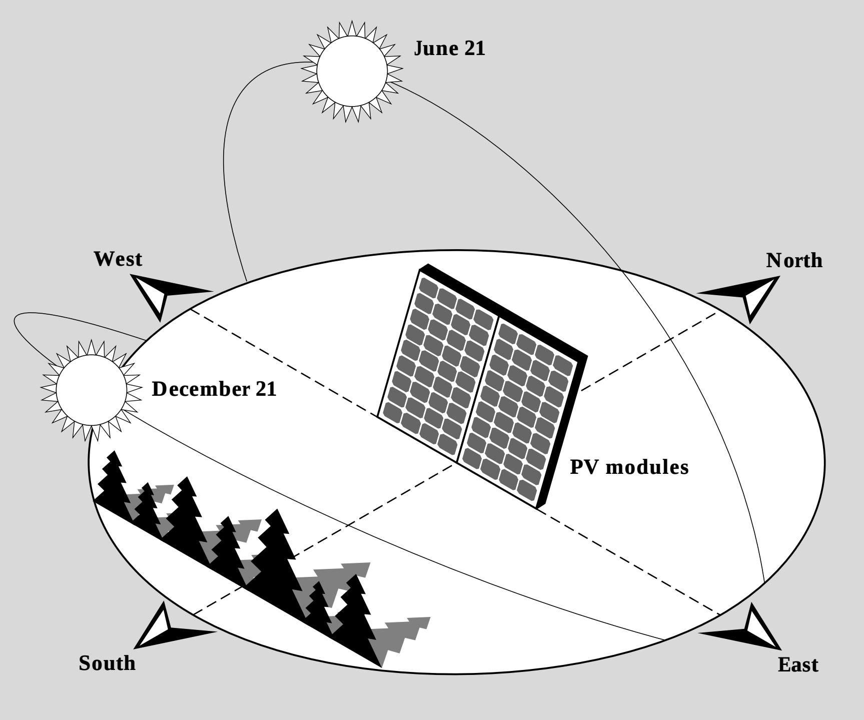
- **Cost**—When the cost is high for extending the utility power line or using another electricity-generating system in a remote location, a PV system is often the most cost-effective source of electricity.
- **Reliability**—PV modules have no moving parts and require little maintenance compared to other electricity-generating systems.
- **Modularity**—PV systems can be expanded to meet increased power requirements by adding more modules to an existing system.
- **Environment**—PV systems generate electricity without polluting the environment and without creating noise.
- **Ability to combine systems**—PV systems can be combined with other types of electric generators (wind, hydro, and diesel, for example) to charge batteries and provide power on demand.

PV systems are not cost-effective for all applications. The following discussion gives some general guidelines to consider when deciding whether a PV system is appropriate for your situation.

First, if your site is already connected to a utility grid, or within one-quarter mile of the grid, a PV system will probably not be cost-effective. Each utility company spreads the cost of its power plants and fuel costs among all its customers. Most utilities can provide electricity to consumers for about 6 cents to 14 cents per kilowatt-hour. When you install a PV system, you are essentially installing your own mini-utility system. You pay all the costs of generating the electricity you consume. Although the sun's energy is free, the PV equipment is not free. The electricity generated by PV systems at current module and balance-of-system prices can cost 20 cents to 40 cents per kilowatt-hour, depending on the installation cost and intensity and duration of the sunlight at the site.

Second, small PV systems are not practical for powering space-heating systems, water heaters, air conditioners, electric stoves, or electric clothes dryers. These loads require a large amount of energy to operate, which will increase the size and cost of your PV system. Therefore, select the most energy-efficient loads available. For example, if your PV system will power lights, look for the most energy-efficient light bulbs. If your system will pump water for toilets and showers, look for the most water-conserving fixtures.

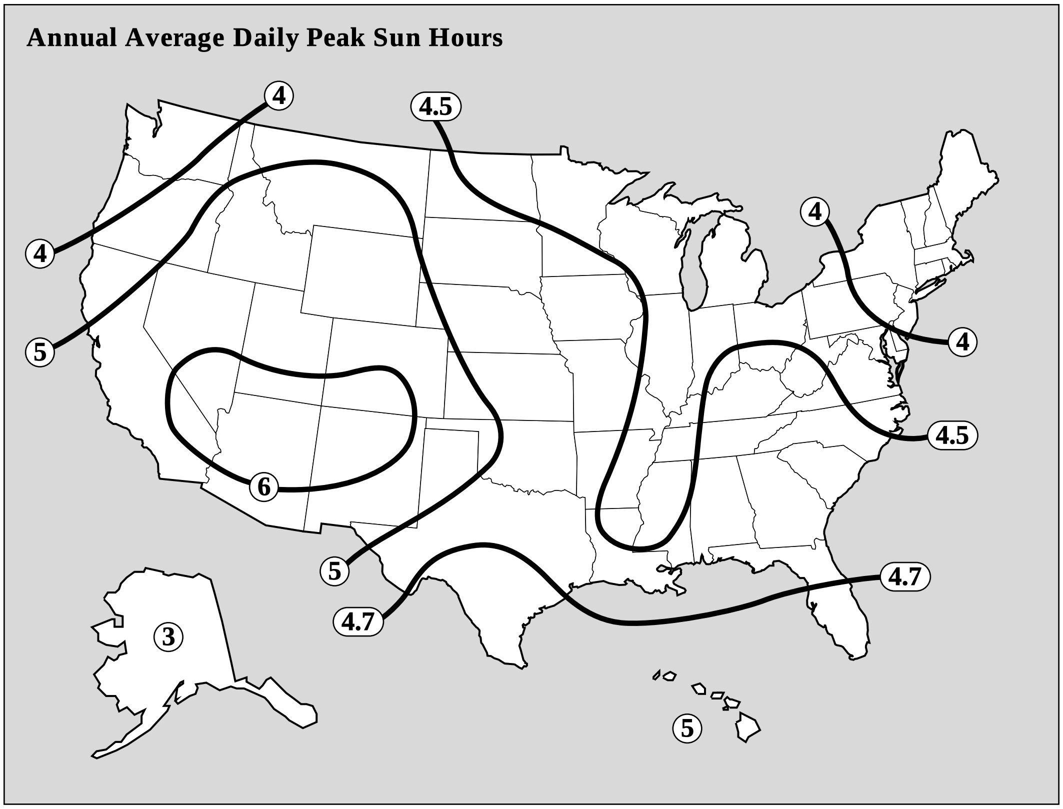
Sun's Path in the Sky



The sun's noontime height above the horizon changes seasonally. This is important to consider when siting and positioning a PV array.

Where you live will determine the number of PV modules your system will need.

Make sure you have selected the most energy-efficient loads possible.



This diagram illustrates the annual average daily peak sun hours for the United States.

Is My Site Adequate for PV?

A PV system designer can conduct a detailed site assessment for you. To save the dealer time (and possibly save yourself some money), you can conduct a preliminary assessment to determine whether your site has potential for a PV system. Contact the Energy Efficiency and Renewable Energy Clearinghouse (EREC—see *Source List*) for more information on conducting a detailed site feasibility assessment.

There are three factors to consider when determining whether your site is appropriate.

First, systems installed in the United States must have a southern exposure. For maximum daily power output, PV modules should be exposed to the sun for as much of the day as possible, especially during the peak sun hours of 10 a.m. to 3 p.m.

Second, the southern exposure must be free of obstructions such as trees, mountains, and buildings that might shade the modules. Consider both summer and winter paths of the sun, as well as the growth of trees and future construction that may cause shading problems.

Finally, the unobstructed southern exposure must also have appropriate terrain and sufficient space to install the PV system. A flat, grassy site is appropriate terrain, whereas a steep, rocky hillside is not.

How Does Weather Affect PV Module Output?

Unlike utility power plants, which produce electricity constantly despite the time of day and year or the weather, the output of PV modules is directly related to these two factors.

Where you live will affect the number of PV modules you will need for power, because different geographic regions experience different weather patterns. Seasonal variations affect the amount of sunlight available to power a PV system. The above map shows annual average “peak sun hours” for regions in the United States.

How to Size Your PV System

To size your PV system, you must first know your energy needs, which you figure by listing all your daily loads. A load includes anything that uses electricity from your power source, such as lights, televisions, radios, or batteries. Some loads need electricity all the time, such as refrigerators, whereas others use electricity less often, such as power saws. To determine your total energy consumption, multiply the wattage of the appliance by the number of hours it is used in a day. Some appliances do not give the wattage, so you may have to calculate the wattage by multiplying the amperes times the volts. After adding the totals for each appliance, you can decide what power output you need for your PV system.

Example

Load	Daily Use (hrs)		Wattage		Total Energy Consumption (watt-hrs)
Radio	2	x	25	=	50
Lamps (fluorescent)	3	x	27	=	81
VCR	0.5	x	30	=	15
Television	6	x	60	=	360
Total Daily Energy Consumption					**506 watt-hrs**

For the items listed above, you would need a system that produces an average daily energy output of 506 watt-hours. Obviously, different parts of the country receive varying amounts of sunlight. Because sunlight is the source of power for PV, you must determine the daily amount of sunlight in your region. Remember that PV systems are rated by peak watt, which is the amount of power produced when the module receives 1,000 watts per square meter of exposure to the sun (insolation).

Let's examine two locations: Albuquerque, New Mexico, and Pittsburgh, Pennsylvania. Albuquerque is a fairly sunny area. In Albuquerque, for each peak watt that a PV module is rated, it will produce a yearly average of 6.2 watt-hrs* of electricity daily. In Pittsburgh, a cloudier area, the same module will produce an average of 2.4 watt-hrs* of electricity daily.

If you wanted to use a PV system in Albuquerque for the appliances listed in the table, you would divide 506 watt-hrs by 6.2, divide that by 0.8 to account for inefficiency of the batteries and, finally, multiply by 1.2 to cover anything that may have been overlooked. You find that you would need a PV system rated at 124 peak watts. If you were buying 50-watt modules, you would need three modules, because you round up to the next highest number.

$506 \div 6.2 = 82$

$82 \div 0.8 = 103$

$103 \times 1.2 = 124$

$124 \div 50 = 3$ modules

For Pittsburgh, you would divide 506 watt-hrs by 2.4, divide by 0.8, and multiply by 1.2, which yields 317 peak watts, or seven modules at 50 watts each.

$506 \div 2.4 = 211$

$211 \div 0.8 = 264$

$264 \times 1.2 = 317$

$317 \div 50 = 7$ modules

Determining your daily energy consumption can be done through simple calculations like the example above or with the aid of sophisticated computer programs. If you are seriously considering purchasing a PV system, there are also other factors to consider. You may want to refer to other sources (see *Source List*) for more precise ways to make your calculations.

*This is based on the winter average. For more precise calculations, consult month-by-month averages and use the lowest monthly average.

Module temperature also affects output. The conversion efficiency of crystalline-silicon modules falls significantly at elevated module temperatures.

When designing a PV system, be sure your PV installer obtains data specific to your area, rather than relying on general data. The National Oceanic and Atmospheric Administration began collecting solar data nearly 20 years ago. The National Renewable Energy Laboratory's Renewable Resource Data Center (see *Source List*) can provide solar radiation information, as can EREC. Some state energy offices also have solar data-collection programs to assist solar designers. Finally, books are available that contain solar data on most major cities in the United States, and a few of these are listed in the *Reading List*.

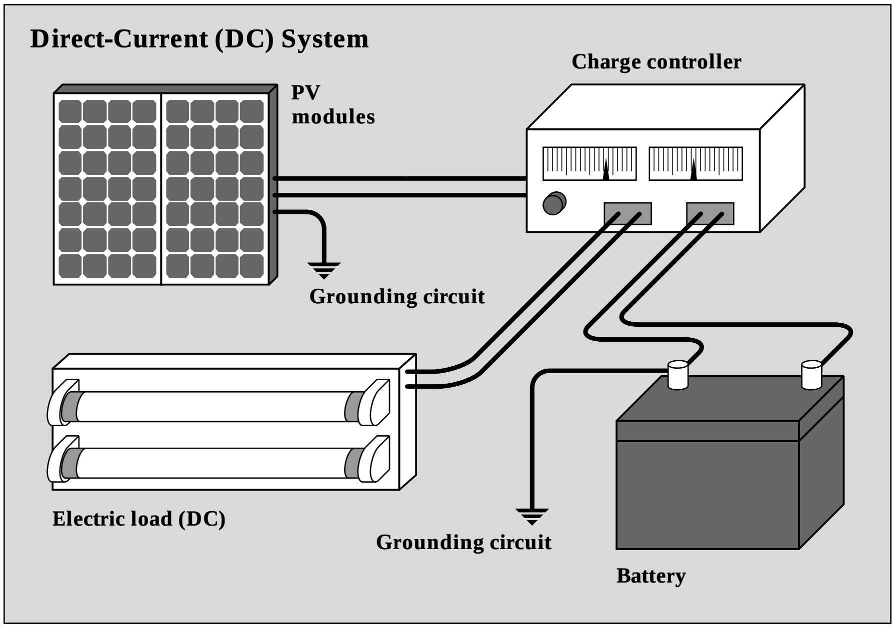
Sizing the System to Meet Your Needs

After you have assessed the appropriateness of your site, you need to determine how much electricity your PV system must generate. This depends on how much electricity your loads require. Again, your dealer can help you with sizing a system that will meet your needs. The sidebar illustrates the steps involved in sizing a PV system. You can also contact EREC for more specific information on sizing.

Balance-of-System Equipment

In addition to the PV modules, you must purchase balance-of-system (BOS) equipment. This includes battery charge controllers, batteries, inverters (for loads requiring alternating current), wires, conduit, a grounding circuit, fuses, safety disconnects, outlets, metal structures for supporting the modules, and any additional components that are part of the PV system. Below, we'll discuss PV and BOS configurations first for loads requiring direct current, then for loads needing alternating current.

Note that, in many systems, the cost of BOS equipment can equal or exceed the cost of the PV modules. When examining the costs of PV modules, remember that these costs do not include the cost of BOS equipment. Ask your PV dealer about the BOS equipment required by your system.



This figure illustrates the configuration of the PV modules and BOS equipment in a basic direct-current system with battery storage. (Circuit breakers and safety fuses are not shown.)

In addition to the PV modules, you will need to purchase balance-of-system (BOS) equipment.

Direct-Current System Equipment

Charge Controller. The charge controller regulates the flow of electricity from the PV modules to the battery and the load. The controller keeps the battery fully charged without overcharging it. When the load is drawing power, the controller allows charge to flow from the modules into the battery, the load, or both. When the controller senses that the battery is fully charged, it stops the flow of charge from the modules. Many controllers will also sense when loads have taken too much electricity from batteries and will stop the flow until sufficient charge is restored to the batteries. This last feature can greatly extend the battery's lifetime.

Controllers generally cost between $20 and $400, depending on the ampere capacity at which your PV system will operate and the monitoring features you want. When selecting a controller, make sure it has the features you need; cost should be a secondary consideration.

Battery. The battery stores electricity for use at night or for meeting loads during the day when the modules are not generating sufficient power to meet load requirements. To provide electricity over long periods, PV systems require deep-cycle batteries. These batteries, usually lead-acid, are designed to gradually discharge and recharge 80% of their capacity hundreds of times. Automotive batteries are shallow-cycle batteries and should not be used in PV systems because they are designed to discharge only about 20% of their capacity. If drawn much below 20% capacity more than a few dozen times, the battery will be damaged and will no longer be able to take a charge.

Deep-cycle batteries cost from about $65 up to $3,000. The cost depends on the type, capacity (ampere-hours), the climatic conditions in which it will operate, how frequently it will receive maintenance, and the types of chemicals it uses to store and release electricity. A PV system may have to be sized to store a sufficient amount of power in the batteries to meet power demand during several days of cloudy weather. This is known as "days of autonomy." Consult with your PV dealer before selecting batteries for your system.

Most types of batteries contain toxic materials that may pose serious health and safety problems. The National Electric Code (NEC), battery companies, and PV system designers recommend that lead-acid and wet cell batteries, which give off explosive hydrogen gas when recharging, be located in a well-ventilated space isolated from the other electrical components of the system and away from living spaces. Allow enough space for easy access during maintenance, repair, and replacement. Most important, maintain the battery according to the manufacturer's instructions, and recycle the batteries properly when they wear out.

Alternating-Current System Equipment

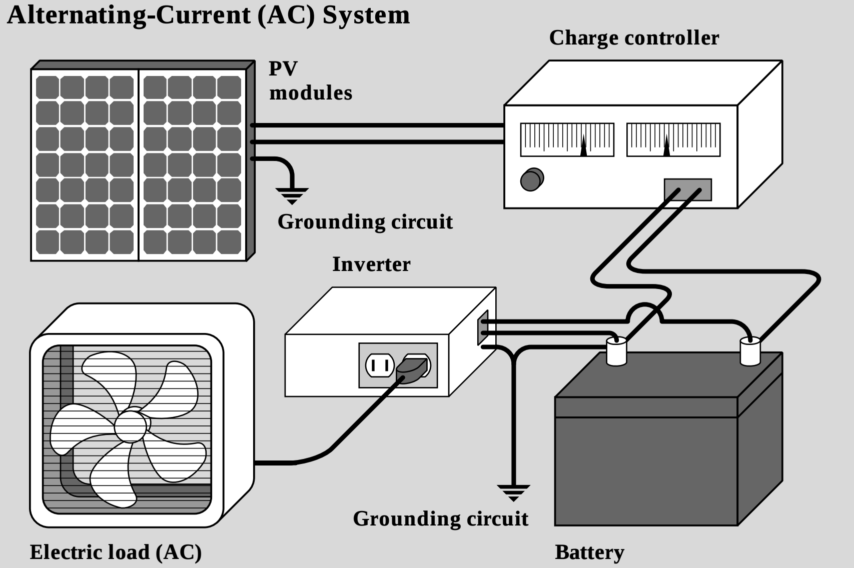
Inverter. AC systems also require an inverter, which changes the DC electricity produced by PV modules and stored in batteries into AC electricity. Different types of inverters produce a different "quality" of electricity. For example, lights, televisions, and power tools can operate on lower-quality electricity, but computers, laser printers, and other sophisticated electronic equipment require the highest-quality electricity. So, you must match the power quality required by your loads with the power quality produced by the inverter.

The National Electric Code contains provisions and requirements for PV systems.

Inverters for most stand-alone applications (i.e., those systems not connected to the utility grid) cost less than $1 per rated output watt. The cost is affected by several factors, including the quality of the electricity it needs to produce; whether the incoming DC voltage is 12, 24, 36, or 48 volts; the number of AC watts your loads require when they are operating normally; the amount of extra surge power your AC loads need for short periods; and whether the inverter has any additional features such as meters and indicator lights.

Tell your PV dealer if you plan to add additional AC loads in the future. If you are considering building another room onto your house or adding electrical loads, consider purchasing an inverter with a larger input and output rating than you currently need. This may be less costly than replacing it with a larger one later.

Alternating-Current (AC) System



Most household appliances operate on alternating current (AC). This illustrates a basic configuration of the PV modules and BOS equipment in an AC system. (Circuit breakers and safety fuses are not shown.)

The National Electric Code

The National Electric Code (NEC) was established in 1897 to ensure safety in all systems that generate, store, transport, and consume electricity. You or the dealer who installs your PV system should be careful to follow NEC's equipment requirements so that the PV system can be approved by local electric code officials. Be aware that many states require all electrical equipment to be installed by a licensed electrician.

However, many local code officials are not familiar with PV systems. Though you follow the provisions of NEC, you may have difficulty convincing a code official that you have installed a code-approved system. Contact and educate (if necessary) local code officials before you purchase and install the system. Throughout the installation process, invite them to observe what you or your dealer have done before you build any enclosure around wiring, connections, or other components. This will help ensure that your system receives approval and will also help future PV installers to get code approval.

Local insurance providers and lenders may also need to be educated about the safety, reliability, and cost-effectiveness of PV systems. Obtaining insurance will be easier in states where PV systems are more common.

What Else Do I Need to Consider?

No PV system is maintenance-free. Schedule regular inspections of your system to ensure that the wiring and contacts are free from corrosion, the modules are clear of debris, and the mounting equipment has tight fasteners.

You should also monitor the power output of your PV modules, the state-of-charge and electrolyte level of your batteries, and the actual amount of power that your loads use. Writing this information in a notebook is a good way to track your system's performance and help you determine whether your system is operating as designed. Monitoring will also help you understand the relationships between your system's power production, storage capability, and load requirements.

PV Can Power Your Future

PV systems can be cost-effective options for providing electricity to your home or remote site. However, they are not appropriate for all situations. Deciding whether a PV system is right for you depends on many factors. Therefore, conduct careful research and consult with PV equipment dealers and others who have installed these systems. If you then decide that a PV system is right for you, the power of the sun will take on a new meaning in your life.

Source List

The following are just a few of the many organizations that can help you with locating PV equipment dealers in your area and designing and installing PV systems.

The Energy Efficiency and Renewable Energy Clearinghouse (EREC)
P.O. Box 3048
Merrifield, VA 22116
(800) 363-3732
Fax (703) 893-0400
E-mail: doe.erec@nciinc.com

EREC provides free general and technical information to the public on the many topics and technologies pertaining to energy efficiency and renewable energy, including PV systems, solar energy, and solar radiation data.

Equipment, Dealers, and Installers

Renewable Energy & Efficiency Training Institute (RETI)
1800 M Street, NW
Suite 300
Washington, DC 20036
(202) 496-1417
Fax: (202) 496-1494

RETI offers customized PV design, installation, and maintenance programs to meet the needs of a wide range of customer groups.

Solar Energy Industries Association (SEIA)
122 C Street, NW
4th Floor
Washington, DC 20001
(202) 383-2600
Fax: (202) 383-2670

SEIA is the national trade organization of PV and solar thermal manufacturers and component suppliers.

Training Programs

Florida Solar Energy Center (FSEC)
Photovoltaic System Design Assistance and Training Center
1679 Clearlake Road
Cocoa, FL 32922-5703
(407) 638-1000
Fax: (407) 638-1010

FSEC offers workshops on a variety of topics related to PV system design and use.

Siemens Solar Industries (formerly Arco Solar)
Photovoltaic Technology and System Design Training Course
4650 Adohr Lane
Camarillo, CA 93012
(805) 388-6561
Fax: (805) 388-6395

Siemens offers a one-week training program on PV technology and system design.

Solar Energy International (SEI)
P.O. Box 715
Carbondale, CO 81623
(970) 963-8855
Fax: (970) 963-8866

SEI offers training programs on PV system design and installation, as well as on wind energy, mini-hydro systems, and solar home design. SEI also sells books on a variety of renewable energy topics.

On-Line Renewable Energy Information

Energy Efficiency and Renewable Energy Network (EREN)
http://www.eren.doe.gov

EREN is the Department of Energy's premier resource for information about renewable energy and energy efficiency technologies, including solar radiation and photovoltaic data.

National Renewable Energy Laboratory (NREL)
http://www.nrel.gov

NREL, one of the Department of Energy's national laboratories, leads the nation toward a sustainable energy future by developing renewable energy technologies. Its Web site includes information on many renewable energy topics. See NREL's Renewable Resource Data Center, at http://www.rredc.nrel.gov, for solar radiation information.

Reading List

Periodicals, Books, Pamphlets, and Reports

Consumer Guide to Solar Energy, S. Sklar, Bonus Books, Chicago, 1991.

Home Power Magazine: The Hands-On Journal of Home-Made Power, Home Power, Inc., P.O. Box 520, Ashland, OR 97520; (916) 475-3179; www. homepower.com.

Photovoltaic Fundamentals, National Renewable Energy Laboratory, Document No. DE-91015001, available from National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Road, Springfield, VA 22161, 1991.

The Solar Electric House, S. Strong, Sustainability Press, Still River, MA, 1993.

Solar Electricity: A Practical Guide to Designing and Installing Small Photovoltaic Systems, S. Roberts, Prentice Hall, NJ, 1991.

Stand-Alone Photovoltaic Systems: Handbook of Recommended Design Practices, Sandia National Laboratory, Document No. SAND87-7023, available from National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Road, Springfield, VA 22161, 1991 (revised).