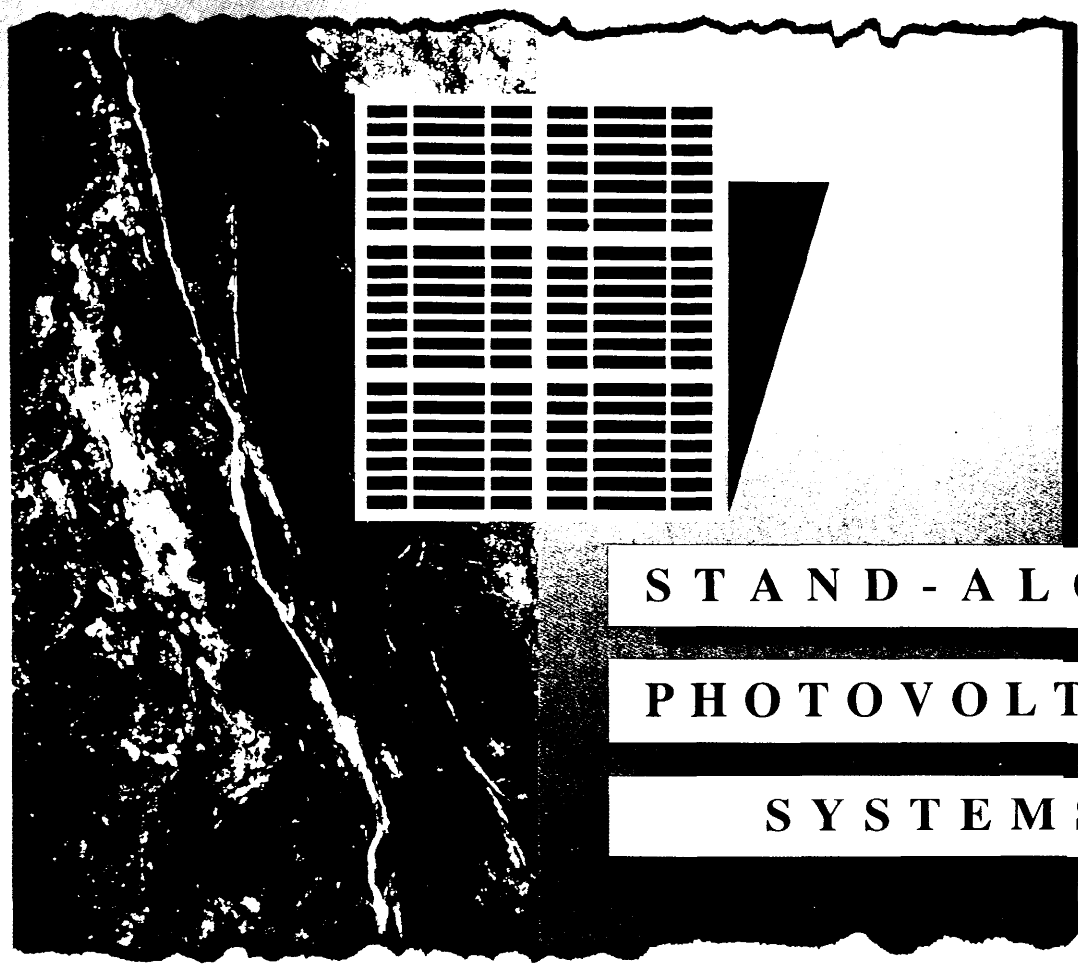


STAND-ALONE PHOTOVOLTAIC SYSTEMS

A Handbook of Recommended Design Practices

Sandia National Laboratories

Issued by Sandia National Laboratories operated for the United States Department of Energy by Sandia Corporation

The hardware available for use in photovoltaic systems will vary from country to country. The reader is urged to make comparisons between competitors' products before buying any photovoltaic systems hardware. The use of a specific manufacturer's product in these design examples is not intended as an endorsement.

Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

NTIS price codes
Printed copy: A12
Microfiche copy: A01

SAND87-7023
UNLIMITED RELEASE
Updated March 1995

Distribution
Category
UC-270

STAND-ALONE PHOTOVOLTAIC SYSTEMS
A HANDBOOK OF
RECOMMENDED DESIGN PRACTICES

PHOTOVOLTAIC DESIGN ASSISTANCE CENTER
SANDIA NATIONAL LABORATORIES
ALBUQUERQUE, NEW MEXICO

DAYSTAR, INC.
LAS CRUCES, NEW MEXICO

SOUTHWEST TECHNOLOGY DEVELOPMENT INSTITUTE
LAS CRUCES, NEW MEXICO

SOLAR ENERGY INTERNATIONAL
Carbondale, Colorado

OLIVE CORROSION CONTROL
Shreveport, Louisana

SOLAR WORKS OF VERMONT
Montpelier, Vermont

APPLIED POWER CORPORATION
Lacey, Washington

REMOTE POWER INC.
Denver, Colorado

SAND87-7023
UNLIMITED RELEASE
Updated March 1995

Distribution
Category
UC-270

STAND-ALONE PHOTOVOLTAIC SYSTEMS
A HANDBOOK OF
RECOMMENDED DESIGN PRACTICES

ABSTRACT

This document presents recommended design practices for stand-alone photovoltaic (PV) systems. Sixteen specific examples of PV systems, designed for different applications, are presented. These include warning signals, lighting, refrigeration, communications, residential, water pumping, remote sensing, and cathodic protection. Each example presents a system sizing technique that can be completed using the worksheets provided. The calculations are simple and straight-forward. In addition to sizing calculations, each example includes information about available hardware, wire sizes, and a line-drawing to illustrate installation techniques. However, the focus of this document is the presentation of a consistent system sizing technique.

Stand-alone PV systems operate reliably and are the best option for many remote applications around the world. Obtaining reliable long-term performance from a PV system requires:

- consistent sizing calculations,
- knowledge of hardware availability and performance,
- use of good engineering practices when installing equipment, and
- developing and following a complete operation and maintenance plan.

These issues and others are discussed in this handbook.

FOREWORD

This popular handbook presents a consistent method for sizing PV systems. Over 25,000 copies have been distributed worldwide since it was first published in 1988. It was written by systems engineers with hands-on experience with PV system design, installation, and operation. It has been updated several times to stay current with the latest hardware and engineering techniques. This version reflects recent field experience with component reliabilities and system lifetime.

The selection and proper installion of appropriately-sized components directly affects system reliability, lifetime, and initial cost. The designs presented here represent real applications and illustrate some of the trade-offs necessary in system design and component selection. The example systems are adequate for the application, and the initial cost is reasonable. Using more batteries and increasing PV array size may extend the life and reliability of a PV system designed for a specific application but will increase the initial cost. It's a trade-off.

This Handbook includes many details on system hardware, installation, and operation. However, exhaustive coverage of all issues is not intended. The information on operating and maintaining (O&M) a PV system is intentionally brief because Sandia National Laboratories publishes a companion document titled *Maintenance and Operation of Stand-Alone Photovoltaic Systems*. Likewise, the electrical drawings may not show all components required by the National Electrical Code (NEC). Information on applying the NEC to PV systems is discussed in the document *Stand-Alone Photovoltaic Systems and the National Electrical Code.* Both documents are noted in Recommended Reading, page 86, and are available from the PV Design Assistance Center at Sandia National Laboratories.

Brand names for components used in the representative systems were available commercially in the United States in 1994. Use of a specific product does not constitute an endorsement of that product by Sandia National Laboratories or the United States Government, nor indicate that it is the only (or best) option. Each reader is encouraged to compare component performance and cost from known vendors. The number of equipment dealers is increasing throughout the world. Most dealers have experience with system design and installation using compatible components. The PV system vendors in your country are your best information resource.

ACKNOWLEDGMENTS

The original version of this handbook, produced in 1988, was the product of a collaborative effort between the Photovoltaic Systems Design Assistance Center at Sandia National Laboratories (SNL) and its prime contractor for this work, the Southwest Technology Development Institute (SWTDI) at New Mexico State University. V. Vernon Risser, Project Manager at SWTDI, and Hal Post, Project Manager at SNL, directed the effort and served as technical editors for the handbook. Subcontractors of the Southwest Technology Development Institute were the Solar Technology Institute (now Solar Energy International); Solar Works of Vermont; Remote Power, Inc.; Solar Engineering Services (now Applied Power Corporation); and Olive Corrosion Control Inc. Many members of the solar photovoltaics community reviewed the draft document and provided substantive comments and contributions.

The handbook was revised extensively in November 1991 by V. Vernon Risser, Daystar, Inc., Las Cruces, New Mexico. Marty Lopez did the page layout and publication design. Selena Heide did the illustrations and Voni Whittier designed the cover. Hal Post was the Sandia contract manager and Anne Van Arsdall, SNL, provided editorial support.

Spanish versions were prepared in 1990 and 1993. Translation was performed Mr. Ralph Costa of Costa Foreign Language Services of San Carlos, California. Ron Pate was the Sandia Project Manager. The page layout and publication design were done by Marty Lopez. Selena Heide did the illustrations and the worksheets.

This revision was completed by V. Vernon Risser, Daystar, Inc., Las Cruces, New Mexico in March 1995. Hal Post was the project manager for Sandia. Marty Lopez did the page layout and Selena Heide did the illustrations and worksheets.

---

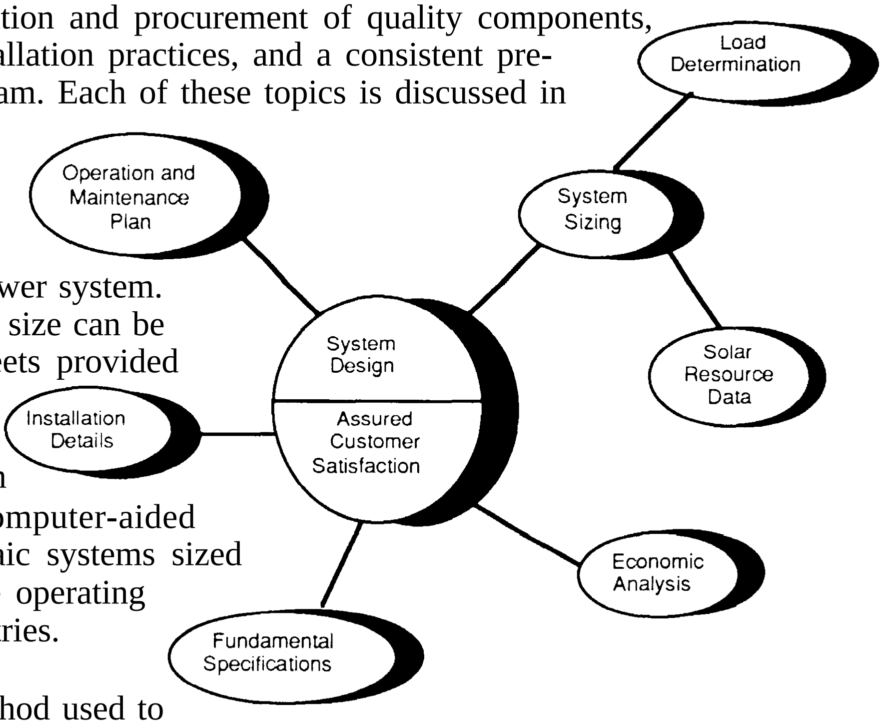
*Printed April 1988; Reprinted in November 1988; Updated in March 1990; Updated in November 1991; Updated in July 1993; Updated in January 1995. Printed in Spanish in February 1990; Updated and re-printed in Spanish in November 1993.

STAND-ALONE PHOTOVOLTAIC SYSTEMS
A HANDBOOK OF
RECOMMENDED DESIGN PRACTICES

This handbook contains:
- **Recommended practices for design, installation, operation, and maintenance of stand-alone PV systems.**
- **A consistent method of determining system size and specifications.**
- **Complete PV system designs for 16 applications.**

This handbook on photovoltaic (PV) systems is intended for a broad audience--from beginners to professionals. It includes 16 sample system designs for practical applications. The number of PV system installations is increasing rapidly. As more people learn about this versatile and often cost-effective power option, this trend will be accelerated.

The goal of a stand-alone system designer is to assure customer satisfaction by providing a well-designed, durable system with a 20+ year life expectancy. This depends on sound design, specification and procurement of quality components, good engineering and installation practices, and a consistent preventive maintenance program. Each of these topics is discussed in this handbook.



System sizing is perhaps the easiest part of achieving a durable PV power system. A good estimate of system size can be obtained with the worksheets provided and the latest component performance specifications. The resulting system sizes are consistent with computer-aided sizing methods. Photovoltaic systems sized using these worksheets are operating successfully in many countries.

Regardless of the method used to size a system, a thorough knowledge of the availability, performance, and cost of components is the key to good system design. Price/performance tradeoffs should be made and reevaluated throughout the design process. Study the example systems. They illustrate how these design decisions were made for specific applications. Then, when you start your design, obtain as much information as you can about the components you might use. You <u>can</u> design a reliable PV system to meet your needs.

SUMMARY OF RECOMMENDED DESIGN PRACTICES

Recommendations for designing, installing, and operating stand-alone PV systems are included in this handbook. These recommendations come from experienced PV system designers and installers. The best are based on common sense. Realizing that "the more specific the rule, the greater the number of exceptions," some practical recommendations are given here.

- **Keep it simple** - Complexity lowers reliability and increases maintenance cost.

- **Understand system availability** - Achieving 99+ percent availability with any energy system is expensive.

- **Be thorough, but realistic, when estimating the load** - A 25 percent safety factor can cost you a great deal of money.

- **Cross-check weather sources** - Errors in solar resource estimates can cause disappointing system performance.

- **Know what hardware is available at what cost** - Tradeoffs are inevitable. The more you know about hardware, the better decisions you can make. Shop for bargains, talk to dealers, ask questions.

- **Know the installation site before designing the system** - A site visit is recommended for good planning of component placement, wire runs, shading, and terrain peculiarities.

- **Install the system carefully** - Make each connection as if it had to last 30 years--it does. Use the right tools and technique. The system reliability is no higher than its weakest connection.

- **Safety first and last** - Don't take shortcuts that might endanger life or property. Comply with local and national building and electrical codes.

- **Plan periodic maintenance** - PV systems have an enviable record for unattended operation, but no system works forever without some care.

- **Calculate the life-cycle cost (LCC) to compare PV systems to alternatives** - LCC reflects the complete cost of owning and operating any energy system.

HOW TO USE THIS HANDBOOK

Finding information. *Introducing the Brown Family.*

ORGANIZATION

This handbook will assist those wishing to design, specify, procure, or operate a stand-alone photovoltaic (PV) system. A straightforward sizing method is presented and illustrated with 16 detailed examples of common PV system designs. The manual has four color-coded sections as shown in Figure 1: Tan--Contents, Organization, and Use; White--System Design and Specifications; Yellow--Sample Designs; and Green-Appendices. Appendix A contains monthly solar data for selected cities in the United States plus worldwide solar insolation maps. Appendix B contains sample sizing worksheets with instructions. A glossary of commonly used terms starts on page 87. A list of recommended reading is provided on page 86 for those who desire more information.

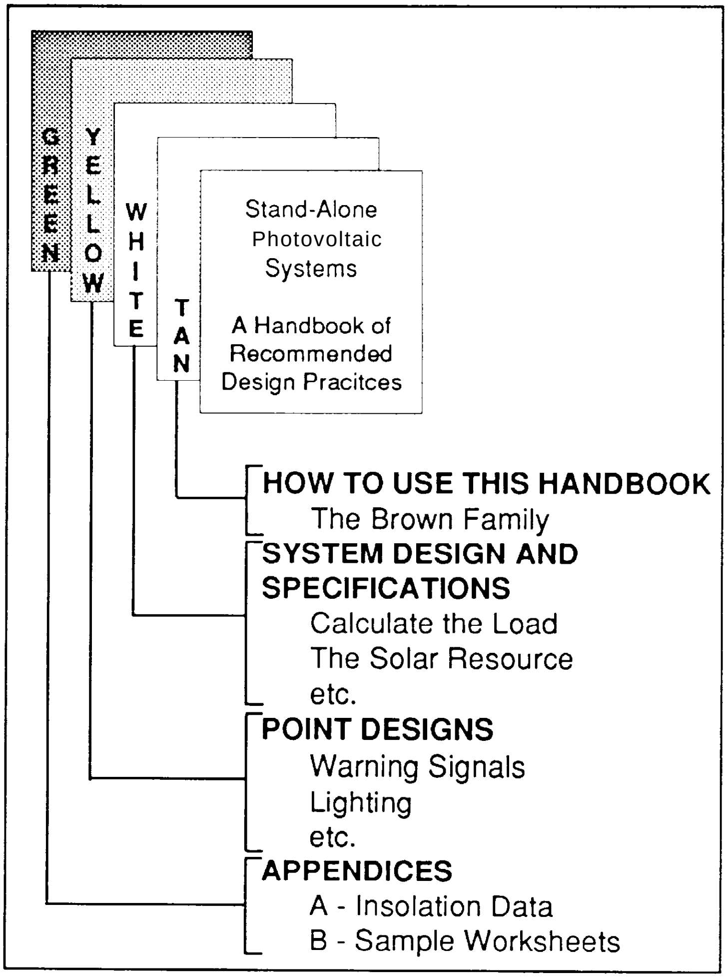
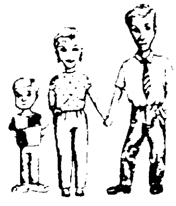


Figure 1. Handbook Layout.

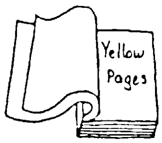
Information about designing PV systems is given in the white pages of this manual. Topics include solar insolation, system availability, different loads, system sizing, specifying components, installation techniques, maintenanceand troubleshooting procedures, and economic aspects. Many chapters include an episode about the hypothetical Brown Family who are planning a PV system to provide power for their home. The Browns' use the techniques and practices described in this manual to size, design, install, and maintain their ac/dc residential system. Their decisions and experiences are presented for those readers who do not



The Brown Family designs an ac residential PV system

want to design a system at this time but merely become familiar with the design process. By reading consecutively the Brown Family sections in each chapter, the reader can obtain an overview of PV power system design issues.

The heart of the handbookis in the yellow pages section. Sixteen specific system designs are presented and discussed. The experienced reader may wish to proceed directly to this section to study a sample design and see how the system size was determined, how system hardware was selected, and what installation practices were used. These systems were designed by experienced systems engineers who know what components are available and which ones perform reliably and efficiently. They use this knowledge to make informed design tradeoffs. The reader should do the same.

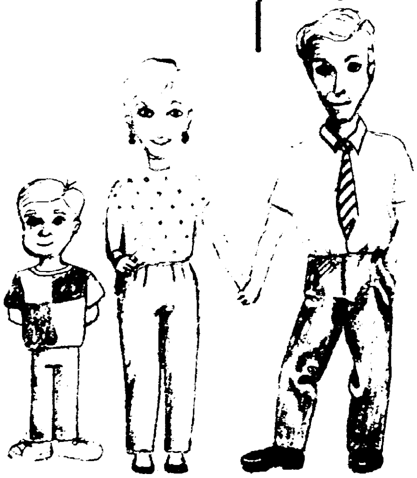


contain sample PV system designs.

The worksheets in Appendix B are accompanied by detailed instructions and rule-of-thumb estimations of key parameters (defaults). The defaults can be used if performance data cannot be obtained from other sources.

THE BROWN FAMILY ESTIMATES THEIR LOAD

The Browns and their ten-year-old son plan to build a home in a remote area of northern New Mexico. Their land is over one mile from a utility line and they have been told it might cost over $30,000 to extend the line to their property. They learn some people are using PV power systems for summer cabins in that area. They want to investigate using a PV system if it can be done without sacrificing their suburban life-style. They visit a company in town that advertises photovoltaic modules for sale. They describe their plans to the dealer and he encourages them to install a PV power system. He describes his product and gives them some literature on modules, batteries, controllers, and inverters. He also tells them about some magazines that describe owner-designed systems and presents practical advice for the owner/operator. They visited several other dealers and picked up literature on the components offered by each. They also visited those families who owned the W-powered cabins to see how they liked their power system.



Know what you want--
know what you need--
know the difference

The Brown Family liked the idea of using clean solar power but they wanted to know "How much it would cost?" They found there was no set answer--it all depended on what appliances they wanted to use. Their first step was to estimate the average daily power demand of each appliance they wanted to use. This was the first of a 3-step quick sizing method that one of the dealers told them about.

1. Estimate the energy demand of the load by multiplying the power of each appliance by the average number of hours of use. Add 20 percent to allow for losses caused by wiring, dc to ac conversion, dirty modules, etc.

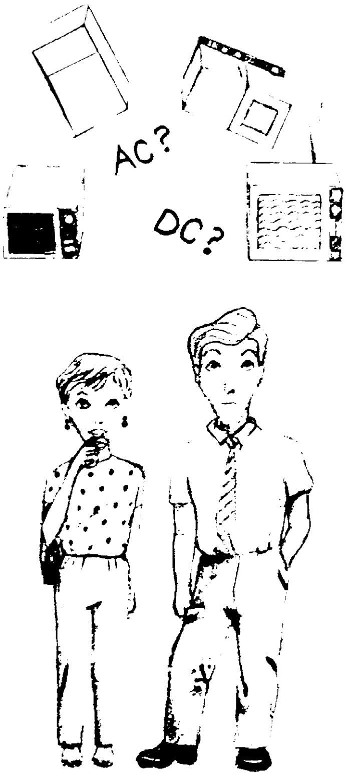
2. Set the number of continuous cloudy days that the system must supply power. Multiply this number by the energy demand estimated in Step 1. This will determine the amount of usable battery storage. Usable battery storage is typically 50-80 percent of the battery capacity claimed by a battery manufacturer. Add a factor equal to 20 percent because you have to put more energy into a battery than you can get out of it.

3. Determine the average daily solar energy (peak sun hours per day) and divide this number into the daily energy demand determined in Step 1. This will give the array size.

Average Appliance Power Demand

AC	Power (Watts)
Blender	350
Dishwasher	1,200
Freezer	450
Refrigerator	330
Iron	1,000
Microwave Oven	800
Toaster	1,190
Washing Machine	450
Coffee Maker	1,200
Vacuum Cleaner, Large	1,260
Electric Water Heater	5,000
Radio	75
Television, Color 19"	150
Lighting per Room	100
DC	**Power (Watts)**
Submersible Pump	150
Ceiling Fan	25
Refrigerator	65
Television, Color 10"	60
Swamp Cooler	50
Radio/Tape Player	35
Blender	80
Fan, 8"	15
Lighting per Room	25

For this first cut at the system size, the Browns listed all the appliances they might want to use and estimated how much time each would be used on an average day. They found a list of the power demand of some common ac and dc appliances and calculated how much energy would be required to run them for the desired amount of time. For instance, they figured the TV would run three hours per day and this would require 150 watts times three hours or 450 watt-hours of energy. When they made the list the first time, they included the use of an electric stove and dishwasher and the energy demand was over 9,000 watt-hours per day including losses. They thought the system should provide power



for 5 cloudy days, so they calculated they would need 45,000 watt-hours of usable energy stored in their battery. Using the 20 percent factor to allow for battery efficiency, they calculated they would have to put 54,000 watt-hours into the battery to get 45,000 watt-hours out. This would mean a charge of about 11,000 watt-hours into the battery on an average day. One of the PV dealers had told them that their location receives about 5,800 watt-hours per square meter on an average day in January if the PV array is tilted at 55° from horizontal. This is equivalent to 5.8 peak sun hours. They divided their daily need, 11,000 watt-hours, by 5.8 peak sun hours and estimated their PV array size at about 1,900 watts. When they next visited their PV dealer they found this system would cost more than $20,000 installed on their property. (This was the initial cost-they would learn about life-cycle cost calculation later.)

They liked the idea of burning solar fuel instead of fossil fuel but this was more than they could afford. They were learning about tradeoffs in PV system design. Cost, performance, and their own life-style and expectations would cause revisions to their design. We leave them reevaluating their use of appliances and the number of days of storage they would need.

STEP 1 - DAILY ENERGY DEMAND

Total Energy Used (Watts)		Loss Factor (20%)		Daily Load (Watt-hours)
7,500	*	1.2	=	9,000

STEP 2 - BATTERY STORAGE

Number No-Sun Days		Daily Load (Watts)		Battery Loss Factor		Battery Storage (Watt-hours)
5	*	9,000		1.2	=	54,000

STEP 3 - SOLAR INSOLATION & ARRAY SIZE

Daily Load Watt-hours		Batttery Loss Factor		Peak Sun (Hrs/Day)		Array Power (Watts)
9,000	*	1.2	÷	5.8	=	1,860

SYSTEM DESIGN AND SPECIFICATIONS

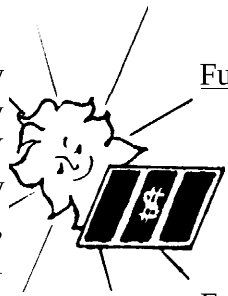
Why should I consider a PV system-aren't they expensive?

OK, life-cycle cost analysis shows PV is a good option for my application. What do I do now?

ECONOMICS

A PV system should be used if it will cost less than alternatives. This section discusses some factors that affect long-term system cost.

The cost of energy produced by PV systems has dropped significantly since 1980. However, the cost of PV energy is still higher than energy bought from your local utility. Also, the initial cost of PV equipment is still higher than an engine generator. Yet, there are many applications where the low operation and maintenance cost of PV systems outweighs the low initial cost of the generator and makes PV the most cost-effective long-term option, The number of installed PV systems increases each year because their many advantages make them the best option. A potential PV system owner should consider the following issues:



For many applications, PV power is the most cost-effective option.

Site Access - A well-designed PV system will operate unattended and requires minimum periodic maintenance. The savings in labor costs and travel expense can be significant.

Modularity - A PV system can be designed for easy expansion. If the power demand might increase in future years, the ease and cost of increasing the power supply should be considered.

Fuel Supply - Supplying conventional fuel to the site and storing it can be much more expensive than the fuel itself. Solar energy is delivered free.

Environment - PV systems create no pollution and generate no waste products.

Maintenance - Any energy system requires maintenance but experience shows PV systems require less maintenance than other alternatives.

Durability - Most PV modules available today are based on proven technology that has shown little degradation in over 15 years of operation.

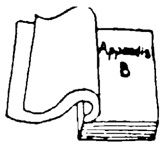
Cost - For many applications, the advantages of PV systems offset their relatively high initial cost. For a growing number of users, PV is the clear choice.

System designers know that every decision made during the design of a PV system affects the cost. If the system is oversized because the design was based on unrealistic requirements, the initial cost is increased unnecessarily. If less durable parts are specified, maintenance and replacement costs are increased. The overall system life-cycle cost (LCC) estimates can easily double if inappropriate choices are made during system design. Examples can be cited where PV systems were not installed because unrealistic specifications or poor assumptions created unreasonable cost estimates, As you size your PV system, be realistic and flexible.

Unrealistic requirements can drive system costs out of sight.

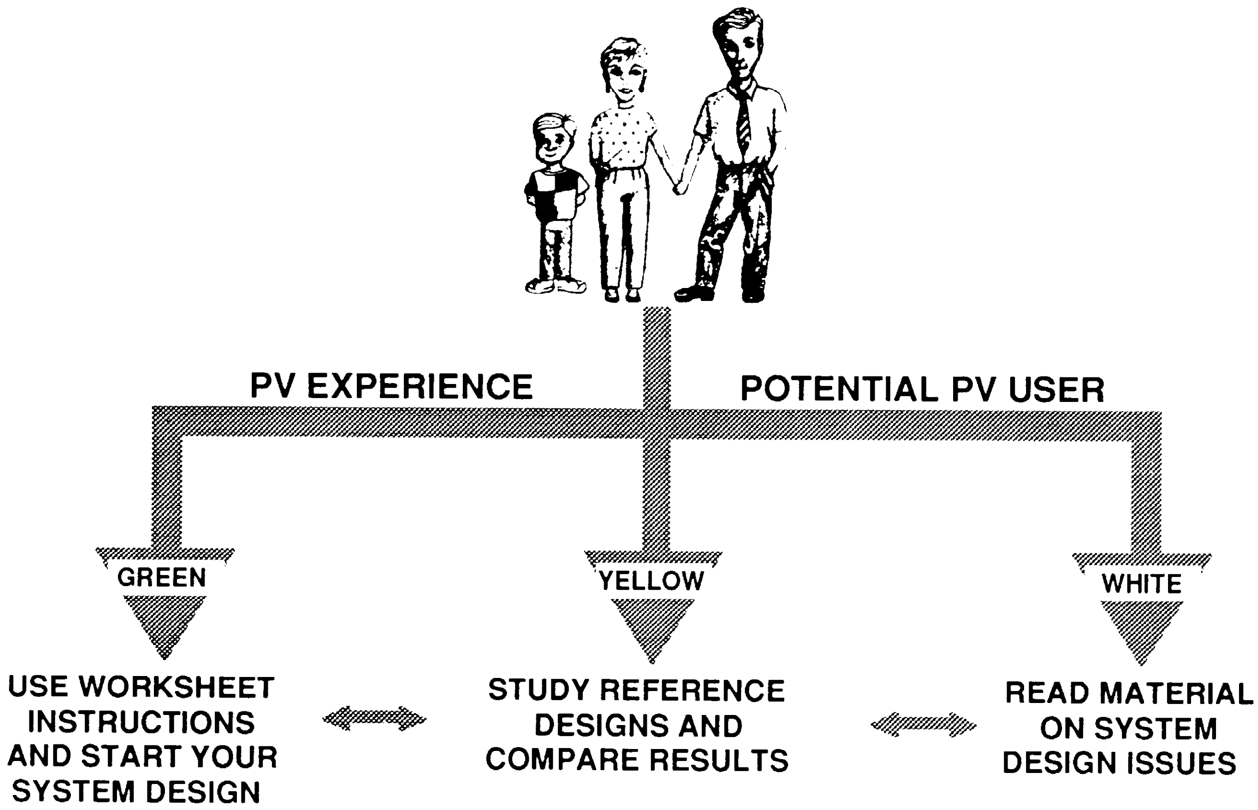
DESIGN APPROACH

After studying all the issues, you have decided that a PV system should be considered for your application. Now what? This handbook is intended to help you do an initial sizing of the PV system and give you some ideas about specifying system components. First, go to Appendix B and extract Worksheets 1-5, pages B-3 to B-8. These worksheets are basic to any design for a PV system with battery storage. Using them, you will



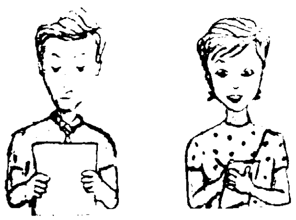
These worksheets show what you need to know to size a PV system.

- Calculate the loads,
- Determine the PV array current and array tilt angle,
- Calculate the battery size,
- Calculate the PV array size, and
- Determine if a PV/generator hybrid system should be used.

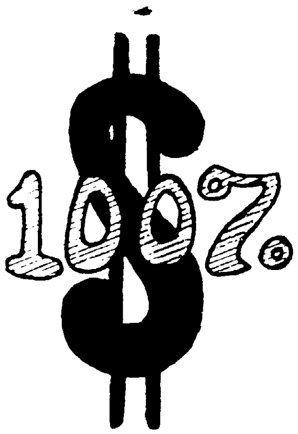


If you are familiar with the terms used above, you may elect to start your design. (Worksheet instructions begin on page B-9). However, you may want to check the yellow pages to see if there is a complete design for a similar application. Read the white pages if you are uncertain about sizing or design issues. These contain background information and discuss some of the tradeoffs necessary in any PV system design. If this is your first introduction to PV systems, you may want to read only the Brown Family episodes which are interspersed throughout the manual.

THE BROWN FAMILY STUDIES SYSTEM AVAILABILITY



It is not easy or cheap to obtain 100% availability from any system.



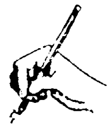
The Brown Family reassessed their plans, life-style, and their need for all those electric appliances. They eliminated the dishwasher and decided to use propane for cooking and laundry needs. They also reevaluated their ideas about having electric power available during all kinds of weather--400 percent availability. Availability has a unique meaning for a PV system because it depends not only on reliable equipment but on the level and consistency of sunshine. Because the weather is unpredictable, designing a PV system to be available for all times and conditions is expensive, and in their case unnecessary. They learned that PV systems with long-term availabilities greater than 95 percent are routinely achieved at half the cost or less of systems designed to be available 99.99 percent of the time. When the Browns thought about their life-style, they knew they could decrease their energy use during periods of cloudy weather with only minor inconvenience. They would conserve energy by turning off lights and appliances when not in use and they could do chores such as vacuuming on sunny days. This would decrease the size of their battery and array and save them many dollars.

The Browns were determined to design and install a safe system that would last 25 years or more. They understood that quality would cost more initially but would save money in the long run. Since they would not cut comers on quality they kept the initial cost low by designing a system with a 95 percent availability. Their plan for an energy conscious life-style made them feel good-they were doing their part to conserve energy.

CALCULATE THE LOAD

Make a list of all loads. ***Group the loads by type and voltage.*** ***Select the system voltage.***

ESTIMATION



Accurately estimate your load.

The first task for any photovoltaic system designer is to determine the system load. This load estimate is one of the key factors in the design and cost of the stand-alone PV system. Worksheet 1, a portion of which is shown in the insert, should be used to calculate average daily loads and the result will be the sum of the estimated loads for both ac and dc appliances. If the load demand changes significantly with time, you should complete a copy of Worksheet 1 for each month or season. Copies of all worksheets and instructions are provided in Appendix B. The following steps are required:

WORKSHEET #1 CALCULATE THE LOADS

1 Load Description	2 QTY		3 Load Current (A)		4 Load Voltage (V)		5A DC Load Power (W)	5B AC Load Power (W)		6 (HI
Transmit DC	1	x	21	x	12	=	252	N/A	x	
Receive DC	1	x	2	x	12	=	24	N/A	x	
Stand by DC	1	x	0.42	x	12	=	5	N/A	x	

- Identify each load and the number of hours of use per day. Enter the load current in amperes and the operating voltage for each load and calculate the power demand.* List the dc loads at the top of the worksheet and ac loads, if any, at the bottom. A power conditioning unit (PCU) is required for ac loads. A PCU, commonly called an inverter, adds complexity to a system and causes a 10-15 percent loss of power because of the efficiency of converting dc power to ac power. If only a small percentage of the loads require ac power, it may be better to replace those devices with ones that use dc power.

- Group the loads by type and operating voltage and sum the Dower demand for each group. The recommended voltage of the stand-alone PV system will be determined by considering this information. (See the next section for more on system voltage selection.)

- After selecting the system voltage, calculate the total daily ampere-hours required at this voltage.

The load determination is straightforward; just calculate the power requirements of any electrical device that will be included in the system and multiply by the amount of time that specific appliances will operate each day. The power required

* The power factor is not considered in the calculation of ac power. For information on calculating ac power, see any basic electrical engineering textbook.

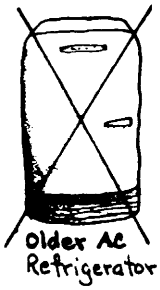
by an appliance can be measured or obtained from manufacturers' literature. (See the list on page 5.) However, the amount of time the appliance will be used per day, week, or month must be estimated. Remember for residential systems (and many others) the hours of use can be controlled by the system owner/operator. Be realistic. Resist the temptation to add 10, 20, or 50 percent to each appliance use estimate. The cumulative effect can cause the size and cost of your PV system to skyrocket.

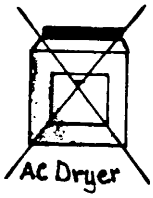
The designer should consider energy conserving substitutes for items that are used often. Identify large and/or variable loads and determine if they can be eliminated or changed to operate from another power source. Fluorescent lamps should be used in place of incandescent lamps. They provide the same light levels with much lower power demand. Consider using dc appliances to avoid the loss in the dc/ac power conversion process. DC lights and appliances usually cost more, but are more efficient and last longer. The number of ac appliances available is greater but efficiencies are usually lower because these appliances were designed for use on an "infinite" utility power supply.

Consider the following:

Electric Ranges - It is impractical to power these with PV; use a propane stove as an alternative.

The selection of appliances is an important determinant of the size and cost of a residential PV system.





Use dc appliances whenever possible—they are often more efficient than ac appliances.

Refrigerators - Older ac units are often inefficient. The compressor may operate 60-80 percent of the time. Units made after 1993 are much more efficient. Efficient dc units are an option, but they cost more than similar size ac units.

Clothes Washers - Some dc to ac inverters* may have a problem starting the large motor on the washer. A ringer type washer is an option.

Clothes Dryers - Consider a gas dryer or use an outdoor rack to dry the clothes.

Dishwashers - There are no dc units available. This is a large load, especially on the dry cycle.

Microwave Ovens - These are a large load but operating time is usually short; few dc units are available; some inverters may not start a microwave oven and/or may cause inaccurate timer operation.

Water Pumps - PV power is used for many small water pumping applications but PV may not be the best option for pumping large amounts of water for irrigating crops.

VOLTAGE SELECTION

The operating voltage selected for a stand-alone PV system depends on the voltage requirements of the loads and the total current. If the system voltage is set equal to the

*See page 39 for discussion of dc to ac inverters.

voltage of the largest load then these loads may be connected directly to the system output. However, it is recommended that the current in any source circuit be kept below 20 with a 100 amperes limit for any section of the system. Keeping the current below these recommended levels will allow use of standard and commonly available electrical hardware and wires. When loads require ac power, the dc system voltage should be selected after studying available inverter characteristics. See Table 1. Another consideration is the possible increase in the size of your system in the future. Choose a voltage that will work with the future enlarged system.

Limiting system current to less than 100 amperes will save on switches and wire.

TABLE 1
Selecting System Voltage

AC Power Demand (Watts)	Inverter Input Voltage (Volts dc)
<1,500	12
1,500-5,000	24 or 48
>5,000	48 or 120

Some general rules are:

- DC loads usually operate at 12 volts or a multiple of 12--i.e., 24 volts, 36 volts, or 48 volts, etc. For dc systems, the system voltage should be that required by the largest loads. Most dc PV systems smaller than 1 kilowatt operate at 12 volts dc. (The maximum current would be 1,000 ÷ 12 = 83.3 amperes.)

- If loads with different dc voltages must be supplied, select the voltage of the load with the highest current demand as the system voltage. Electronic dc-dc converters can be used to power loads at voltages different from the system voltage. If a lower voltage is required, it is sometimes possible to connect to only a portion of a series-connected battery string. This can cause problems with charging the batteries and should not be done without a charge equalizer if the current required at the lower voltage is more than 5 percent of the total current taken from the battery strings. A battery charge equalizer is an electronic device that keeps all batteries in a series string at the same voltage.

- Almost all ac loads for stand-alone PV systems will operate at 120 volts ac. Study inverter specifications that will provide the total and instantaneous ac power required. Select an inverter that will meet the load and keep the dc current below 100 amperes. Disregarding power facto; and losses, the following equations must balance.

ac power = (ac voltage)(ac current)
dc power = (dc voltage)(dc current)

For example, if the ac load is 2,400 watts and the ac voltage is 120 volts, the ac current will be 20 amperes. Excluding losses in the inverter, the dc power must be the same; 2,400 watts. If a 12-volt inverter is selected the dc current would be 200 amps--not recommended. Use a 24-volt inverter or a 48-volt inverter to make the input current 100 or 50 amperes respectively. Remember, the cost of wire and switches goes up as the amount of current increases. A rule of thumb for selecting system voltage based on ac power demand is given in Table 1.

Selecting the system voltage is an important design tradeoff.

Selection of an inverter is important and affects both the cost and performance of the system. Generally, the efficiency and power handling capability are better for units operating at higher dc voltages, i.e., a 48-volt unit is usually more efficient than a 12-volt unit. The designer should obtain information on specific inverters, their availability, cost, and capabilities, from several manufacturers before making the decision on system voltage. Another fact to consider is the basic building block in the array and storage subsystems gets larger as the voltage increases. For example, a 48-volt system has four PV modules connected in series to form the basic building block. Fine tuning the design, i.e., adding a little more current to the system, means buying four additional modules. However, the advantage of the higher operating voltage is the lower current required to produce the same power. High current means large wire size, and expensive and hard to get fuses, switches, and connectors. Again, a prior knowledge of the cost and availability of components and switchgear is critical to good system design.

The inverter input voltage dictates the dc system voltage.

The Brown Family Selects Their System Voltage

The Browns wanted both ac and dc appliances in their home.

$$\frac{1{,}800\ W}{24\ V} = 75\ Adc$$

$$\text{plus}\ \frac{240\ W}{24V} = 10\ Adc$$

$$\text{plus}\ \frac{24\ W}{12\ V} = 2\ Adc$$

The Browns used Worksheet 1 to make the final calculation of their load. They wanted the convenience of ac appliances, but they decided to use dc lights and some small appliances to conserve energy. They decided not to use a dishwasher and the) would hang their clothes out to dry. When they recalculated their loads, they had reduced their electrical demand to 1,800 watts at 120 volts ac, 240 watts at 24 volts dc, and 24 watts at 12 volts dc. They would get a 2,500-watt inverter that operated at 24 volts. Their 12-volt radio telephone could be operated by tapping off the center of their 24-volt battery bank since the current required at 12 volts was less than 2 percent of the total system current. They calculated the currents as shown. Considering losses, they felt their batteries would never have to supply more than 100 amperes. They knew that switches, wire, and fuses could be readily obtained to handle this current. Next they would determine the level of solar resource at their site and the amount of battery storage they would use.

THE SOLAR RESOURCE

What Insolation data are needed?
How does array tilt angle change the data?

How accurate must my estimate be?
What about tracking the PV array?

DESIGN MONTH

Completing Worksheet 2 will give a "design month" that is the worst case combination of low insolation and high load demand. The recommended array tilt angle for that design month will also be determined. Using these criteria, the stand-alone PV system will be designed to meet the load and keep the battery fully charged in the worst month of the average year.

Monthly insolation data for fixed and tracking arrays are provided in Appendix A.

WORKSHEET #2	DESIGN CURRENT AND A

21			Latit
	System Location	Iron Mountain, ID	Latit
	Insolation Location	Boise, ID	Lati

MONTH	Tilt at Latitude -15°						Til
	22A Corrected Load (AH/DAY) 20		23A Peak Sun (HRS/DAY)		24A Design Current (A)		22B Corrected Load (AH/DAY) 20
J	258	÷	2.33	=	112.7		258
F		÷		=			
M		÷		=			
A		÷		=			

Inaccurate solar data can cause design errors so you should try to find accurate solar data that will reflect the long-term radiation available at your system site. However, these data, particularly for tilted or tracking surfaces, are not widely available. Check local sources such as universities, airports, or government agencies to see if they are collecting such data or know where you might obtain these values. If measured values on a tilted surface are not available, you may use the modeled data given in Appendix A. Data for fixed and single-axis tracking surfaces at three tilt angles (latitude and latitude ±15°) are provided. Two-axis tracking data are given also, as well as a set of world maps that show seasonal values of total insolation at the three tilt angles. All data are in units of kilowatt-hours per square meter. This is equivalent to peak sun hours--the number of hours per day when the sun's intensity is one kilowatt per square meter. (These data estimate total radiation at the given orientation. They do not represent direct beam radiation and should not be used to estimate performance of concentrating PV systems.)

Determine the worst case month for insolation.

Worksheet 2, a portion of which is shown in the inset, provides a place for the load current for each month and for solar insolation data for each month at three different tilt angles. For most applications, it is possible to identify the design month without working through each of the 12 monthly calculations. For instance, if the load is constant throughout the year, the design month will be the month with the lowest insolation and the array should be installed with a tilt angle that yields the highest value of insolation during that month. If the load is variable, the design month will be that month with the largest ratio of load demand to solar insolation. Incorporated into the selection of the design month is the recommended array tilt angle that will maximize solar insolation for that month.

If tracking the PV array is an option, Worksheet 2 should be completed using tracking data. Do not mix tracking data and fixed-tilt data on the same worksheet. Completion of a preliminary sizing with both fixed and tracking data will allow an economic comparison to be made between the two techniques. Single-axis east-to-west trackers are the only ones generally used for small stand-alone PV systems. Two-axis tracking is not recommended because of the added complexity.

SELECTING DATA

The availability and amount of sunshine must be estimated because it is unlikely that long-term data will be available for your specific site. The data in Appendix A give average values for a regional area. If you can't find long-term weather records for sites near your system, these data are sufficient for initial sizing of stand-alone PV systems. Local solar conditions may vary significantly from place to place, particularly in mountainous areas. Your site may receive more or less than the weather data used for the system sizing. You may want to increase or decrease the solar data by 10-15 percent and see how this affects your system design. In other words, do a best-case and a worst-case estimate for radiation. Do not deviate from recorded data more than 20 percent unless you are certain the radiation at your site is significantly different. Remember, the estimate of the solar resource directly affects the performance and cost of the stand-alone PV system.

Check local weather sources for long-term data.

Solar conditions can vary significantly over a short distance, particularly in the mountains.

DESCRIPTION

Solar irradiance is the amount of solar power striking a given area. It is a measure of the intensity of the sunshine and is given in units of watts (or kilowatts) per square meter (w/m^2). Insolation. is the amount of solar energy received on a given area measured in kilowatt-hours per square meter (kwh/m^2)--this value is equivalent to peak sun hours. Sometimes, insolation will be presented in units of Btu's per square foot (Btu/ft^2), Langleys (L), or megajoules per square meter (MJ/m^2). The conversion factors are:

$$kWh/m^2 = \frac{\text{Langley}}{86.04} = 317.2\ Btu/ft^2$$
$$= 3.6\ MJ/m^*$$

A nearly constant 1.36 kilowatts per square meter (the solar constant) of solar radiant power impinges on the earth's outer atmosphere. This is the value obtained by integrating the area under the graph in Figure 2. The extraterrestrial radiation spectrum is shown along with an estimate of the radiation spectrum at ground level. It is evident that the atmosphere is a powerful absorber and reduces the solar power reaching the earth, particularly at certain wavelengths. The part of the spectrum used by silicon PV modules is from 0.3 to 0.6 micrometers. These wavelengths

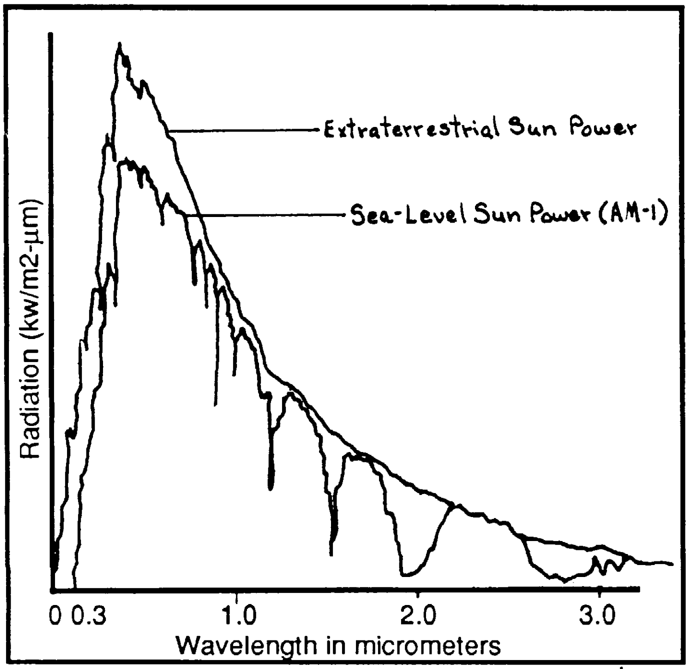
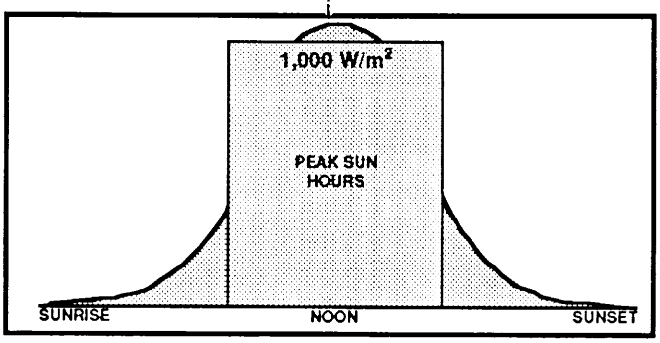


Figure 2. Radiation Spectrum.

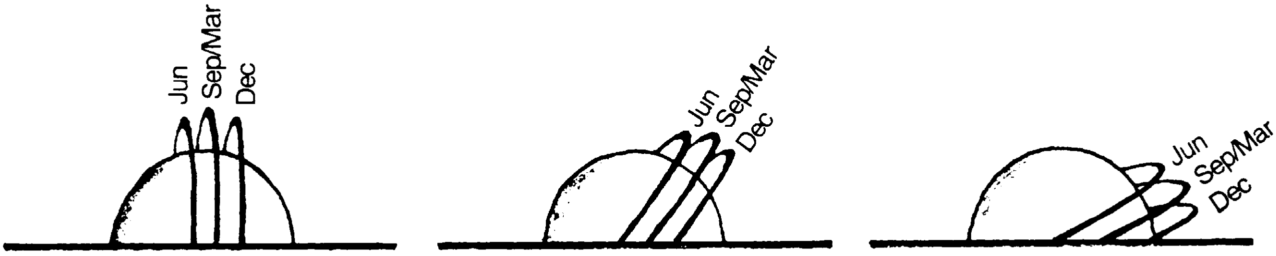
encompass the highest energy region of the solar spectrum. On a sunny day the total irradiance striking the earth will be about 1,000 w/m².

Solar radiation data are often presented as an average daily value for each month. Of course, on any given day the solar radiation varies continuously from sunup to sundown. The maximum irradiance is available at solar noon which is defined as the midpoint, in time, between sunrise and sunset. The term "peak sun hours" is defined as the equivalent number of hours per day, with solar irradiance equaling 1,000 w/m², that would give the same amount of energy. In other words, six peak sun hours means that the energy received during total daylight hours equals the energy that would have been received had the sun shone for six hours with an irradiance of 1,000 w/m². Therefore, peak sun hours correspond directly to average daily insolation in kwh/m², and the tables provided in Appendix A can be read either way.



In the southwestern United States, the solar irradiance at ground level regularly exceeds 1,000 w/m². In some mountain areas, readings over 1,200 w/m² are recorded routinely. Average values are lower for most other areas, but maximum instantaneous values as high as 1,500 w/m² can be received on days when puffy-clouds are present to focus the sunshine. These high levels seldom last more than a few seconds.

Insolation varies seasonally because of the changing relation of the earth to the sun. This change, both daily and annually, is the reason some systems use tracking arrays to keep the array pointed at the sun. For any location on earth the sun's elevation will change about 47° from winter solstice to summer solstice. Another way to picture the sun's movement is to understand the sun moves from 23.5° north of the equator on the summer solstice to 23.5° south of the equator on the winter solstice. On the equinoxes, March 21 and September 21, the sun circumnavigates the equator. These three sun paths are shown in Figure 3a on the next page. At 40°N. latitude the sun paths for the solstices and equinoxes



3a. 0° LATITUDE **3b. 32° N. LATITUDE** **3c. 64° N. LATITUDE**

Figure 3. Seasonal Sun Trajectories at Varying Latitudes.

are shown in 3b. Figure 3c shows the paths for 64°N. latitude. For any location the sun angle, at solar noon, will change 47° from winter to summer.

The power output of a PV array is maximized by keeping the array pointed at the sun. Single-axis tracking of the array will increase the energy production in some locations by up to 50 percent for some months and as much as 35 percent over the course of a year. The most benefit comes in the early morning and late afternoon when the tracking array will be pointing more nearly at the sun than a fixed array. Generally, tracking is more beneficial at sites between ±30° latitude. For higher latitudes the benefit is less because the sun drops low on the horizon during winter months.

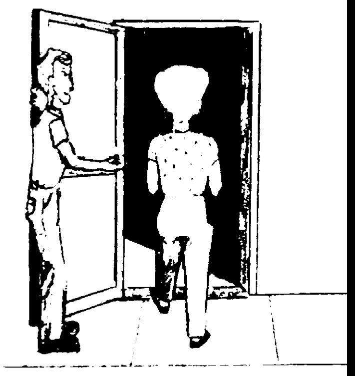
For tracking or fixed arrays, the <u>annual</u> energy production is maximum when the array is tilted at the latitude angle; i.e., at 40°N latitude, the array should be tilted 40° up from horizontal. If a wintertime load is the most critical, the array tilt angle should be set at the latitude angle plus 15° degrees. To maximize summertime production, fix the array tilt angle at latitudeminus 15° degrees.

MEASUREMENTS

A pyranometer measures both the direct and diffuse components of sunlight. These values may be integrated over time to give an estimate of insolation. Some of the more accurate pyranometers are precisely calibrated and expensive. Less expensive pyranometers that use a calibrated section of a PV cell to measure the irradiance are available. These are accurate enough for small PV system owners who want to monitor system performance. If you are able to find a record of solar insolation data at a site near your system it will most likely be from a pyranometer mounted on a horizontal surface. Unfortunately, there is no easy way to use these data to estimate the insolation on a tilted surface. If data are not available from a local source, use the data given in Appendix A.

THE BROWN FAMILY ESTIMATES THE SOLAR RESOURCE

MONITOR



The Browns adjusted the insolation used for their system design after consulting local weather data.

The Browns acreage is located in the mountains at an elevation of 1,500 meters. The location is in a protected valley with mountains on both east and west sides. The Browns knew the mountains would limit morning and late afternoon sun, so they decided that array tracking would not be practical for them. They wanted to maximize the amount of radiation received in the winter so they thought they expected to fix their array tilt angle at latitude plus 15° and facing South.

The city nearest their building site with local weather data was Albuquerque, New Mexico. However, their site was about 1,700 feet higher than Albuquerque. They searched for local weather data and found that the newspaper in Los Alamos, New Mexico, (elevation 7,700 feet) printed the daily solar insolation received. They visited the newspaper office and listed the insolation values for each day for one year. These values were averaged for each month to get a daily average. This was compared with recorded values for Albuquerque and Denver, Colorado. The insolation at Los Alamos was consistently higher, particularly in the winter months. Since their site was somewhat protected by mountains, they elected to use 95 percent of the monthly insolation received at Los Alamos. They expected to get some increased irradiance from snow reflection because they were going to install their array with a 55° tilt. The Browns used January as the design month and estimated the insolation at 4.5 peak sun hours per day. Their design current was 94 amperes. They expected their system to give 95 percent availability during an average January.

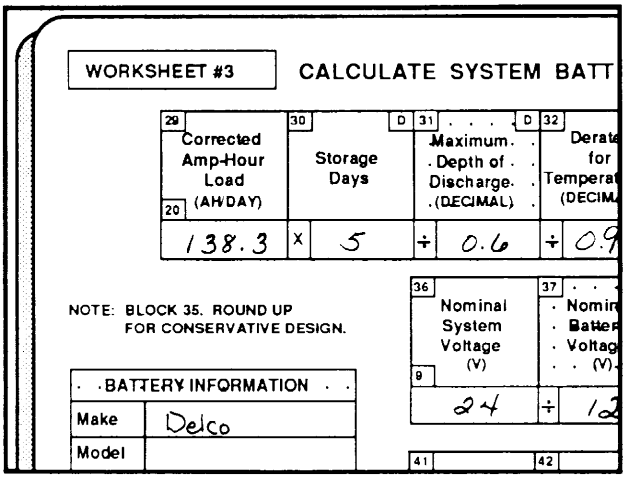
BATTERIES

How many days of storage do I need?

What system availability will I need?
How can I ensure a safe battery installation?

SIZING

Worksheet 3, a portion of which is shown in the inset, can be used to determine the size of the battery storage required for a stand-alone PV system. You will be required to make a number of decisions. Before making these choices, you should study and understand battery parameters and the concept of system availability.


WORKSHEET #3 CALCULATE SYSTEM BATT

29 Corrected Amp-Hour Load (AH/DAY) 20		30 Storage Days		31 Maximum Depth of Discharge (DECIMAL)		32 Derate for Temperat (DECIM
138.3	x	5	÷	0.6	÷	0.9

NOTE: BLOCK 35. ROUND UP FOR CONSERVATIVE DESIGN.

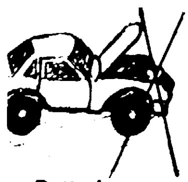
36 Nominal System Voltage (V) 9		37 Nomin Batter Voltag (V)
24	÷	12

BATTERY INFORMATION	
Make	Delco
Model	

41 42

First, you must choose the amount of back-up energy you want to store for your application. This is usually expressed as a number of no-sun days, in other words, for how many cloudy days must your system operate using energy stored in batteries. There is no "right answer" to this question. It depends on the application, the type of battery, and the system availability desired. (A discussion of system availability for PV systems is given in the next section.) When specifying the amount of storage you must be aware of the difference between rated battery capacity and usable capacity. Battery manufacturers publish a rated battery capacity--the amount of energy that their battery will provide if discharged once under favorable conditions of temperature and discharge rate. This is much higher than the amount of energy you can take out of the battery repeatedly in a PV application. For some shallow-cycle, sealed batteries the usable capacity is only 20 percent of the rated capacity, i.e., taking more than 20 ampere-hours from a 100 ampere-hour battery will cause the battery to quickly fail. Other types of batteries designed for deep cycling will have usable capacities up to 80 percent of rated capacity. For most PV applications the bigger and heavier the battery the better. The best recommendation for the number of days of storage is to put in as much battery capacity as you can afford. Obviously, if you live in an area with extended periods of cloudiness you will need more storage capacity to keep the load going during these periods of inclement weather. Also, if it is critical that your load have power at all times, you will want to have a large battery capacity. A smaller battery size can be specified if you can live with some power outage.

The PV system designer has to consider all these aspects plus more when choosing the battery type and size. Some factors can outweigh the technical sizing decision. For instance, you may be able to obtain batteries locally and the savings in shipping cost will allow you to buy more batteries. Also, there are many types of batteries with a large variance in quality and cost. You must know the performance, cost, and availability of batteries in your country. Figure 4 gives you a starting point for making your battery size selection using the design month peak sun hours for your site. Just find the peak sun hours for your design month and read up to the days of storage for system availabilities of 95 or 99 percent.



Batteries are designed for different purposes—do not use a car battery in a PV system.

It is important to buy quality batteries that can be discharged and recharged many times before failure. Automobile batteries should not be used if there is any alternative. Automobile batteries are designed to produce a high current for a short time. The battery is then quickly recharged. PV batteries may be discharged slowly over many hours and may not be recharged fully for several days or weeks. Specify a battery that can withstand this type of operation.

Finally, it is important to understand the close interrelation between the battery and the charge controller. When you buy your batteries you should also buy a compatible charge controller. A charge controller is an electronic device that attempts to maintain the battery state-of-charge (SOC) between preset limits. The battery voltage is measured and used as the primary estimator of SOC. (Some charge controllers measure battery temperature in addition to voltage to improve the estimate of SOC.) If the charge controller does not operate properly the battery may be overcharged or allowed to discharge too much. Either way the lifetime of the battery will be shortened and you will have to spend money to replace batteries. Charge controller operation is described in the section starting on page 36. Also, be sure to ask your battery dealer what charge controller she recommends.

The following terms will help you specify batteries for your PV system.

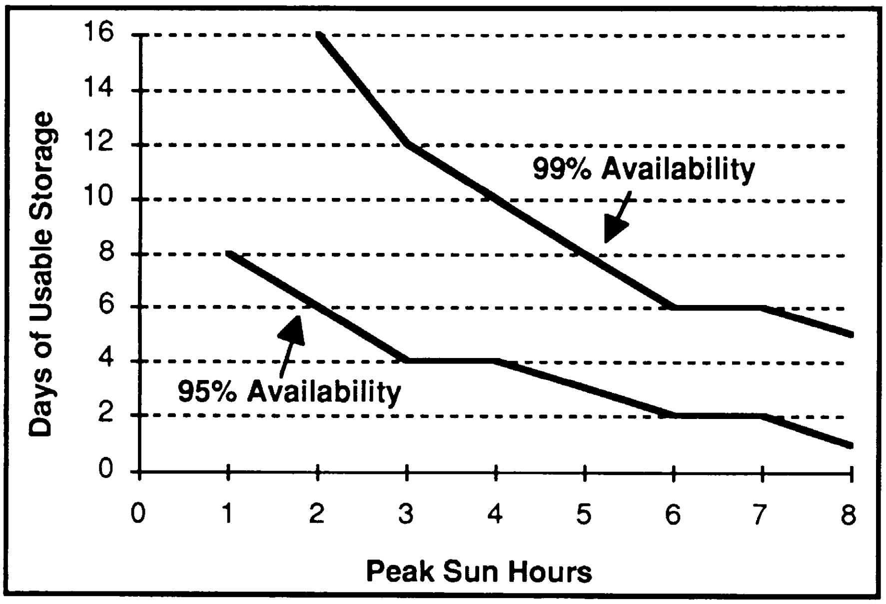
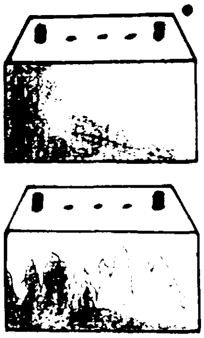


Figure 4. Days of Storage.

- **Depth of Discharge** - This term is the percentage of the rated battery capacity that has been withdrawn from the battery. The capability of a battery to withstand discharge depends on its construction. The most common batteries have electrically active lead alloy plates immersed in a mild acid electrolyte. Plate types are Planté (pure lead), pasted, or tubular. The plates can be made with different thicknesses and different alloys, such as lead calcium, or lead antimony, for different applications. Generally, the more massive the plates the better the battery will withstand discharge and recharge (cycling). Two terms, shallow-cycle and deep-cycle, are commonly used to describe batteries. Shallow-cycle batteries are lighter, less expensive, and will have a shorter lifetime particularly if recommended discharge levels are exceeded regularly. Many sealed (advertised as no maintenance) batteries are shallow-cycle types. Generally, the shallow-cycle batteries should not be discharged more than 25 percent. Deep-cycle batteries are more often used for stand-alone PV systems. These units have thicker plates and most will withstand discharges up to 80 percent of their rated capacity. Most of these are flooded batteries which means the plates are covered with the electrolyte. The electrolyte level must be monitored and distilled water added periodically to keep the plates fully covered.

Maintaining a state of charge at 80 percent is allowing a 20 percent depth of discharge. Don't confuse the two terms.



A fully charged battery will withstand -20°C. A discharged battery will freeze at temperatures slightly below 0°C.

Another type of battery using nickel cadmium (NiCd) plates can be used. NiCd batteries are more expensive but can withstand harsh weather conditions. NiCd batteries can be completely discharged without damage and the electrolyte will not freeze.

The maximum depth of discharge value used for sizing should be the worst case discharge that the battery will experience. The battery charge controller should be set to prevent discharge below this level. Because nickel cadmium batteries can be discharged nearly 100 percent without damage, some designers do not use a controller if NiCd batteries are used.

Temperature Correction - Batteries are sensitive to temperature extremes and a cold battery will not provide as much power as a warm one. Most manufacturers provide temperature correction curves like those shown in Figure 5 for their batteries. For instance, a battery at 25°C has 100 percent capacity if discharged at a current rate of C/20. (The discharge rate is given as a ratio of the rated capacity, C, of the battery.) However, a battery operating at 0°C would have only 75 percent of the rated capacity if discharged at a C/20 rate. If the discharge rate is higher, say C/5, only 50 percent of the rated capacity will be available when the temperature is minus 20°C. Although the chart shows you can get more than rated capacity from when the battery temperature is high, hot temperatures should be avoided because they will shorten battery life. Try to keep your batteries near room temperature.

operating temperatures. It would be unusual for a lead acid type battery to last longer than 15 years in a PV system but many last for 5-10 years. Nickel cadmium batteries will generally last longer when operated under similar conditions and may operate satisfactorily for more than 15 years under optimum conditions.

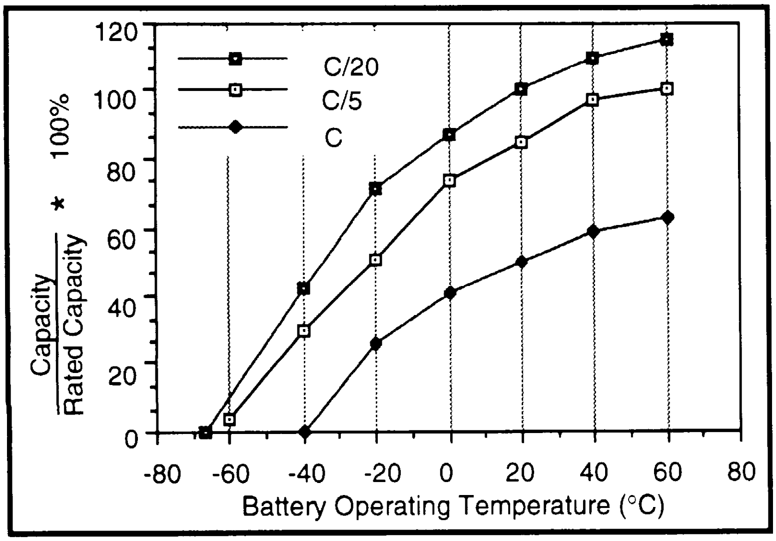


Figure 5. Lead-Acid Battery Capacity vs. Temperature.

- **Rated Battery Capacity** - This term indicates the maximum amount of energy that a battery can produce during a single discharge under specified conditions of temperature and discharge rate. You will not be able to obtain rated capacity repeatedly when the batteries are used in PV systems. However, rated capacity sets a baseline on which to compare battery performance. When comparing the rated capacity of different batteries, be sure the same discharge rate is being used.

- **State-of-Charge (SOC)** -This is the amount of capacity remaining in a battery at any point in time. It is equal to 1 minus the depth of discharge given in percent.

- **Battery Life (cycles)** - The lifetime of any battery is difficult to predict because it depends on a number of factors such as charge and discharge rates, depth of discharges, number of cycles, and

System availiability has a unique meaning for a PV system.

Battery life depends on how the battery is used and abused.

SYSTEM AVAILABILITY

System availability is defined as the percentage of time that a power system is capable of meeting load requirements. The number of hours the system is available divided by 8,760 hours will give the annual system availability. A system with availability of 95 percent would be expected to meet the load requirements 8,322 hours during an average year for the useful life of the system. Annual availability of 99 percent would mean the system could operate the load for 8,672 of 8,760 hours.

Failures and maintenance time are the primary contributors to lowering system availabilities for any energy system. However, for PV systems, availability takes on added uncertainty because of the variability of the system's fuel source. PV system design requires an estimate of the average amount of sunlight available. Using these average values means that in a year with above average solar insolation, the system may not experience any downtime (due to fuel supply--obviously, failures cannot be predicted). However, in a year with much cloudy weather the system may be unavailable more than the expected number of the hours per year. A PV system designed to have 95 percent availability will, on the average, provide power to the load 95 percent of the time. The number of hours when the system is unavailable will likely be in the winter months when solar radiation is the lowest.

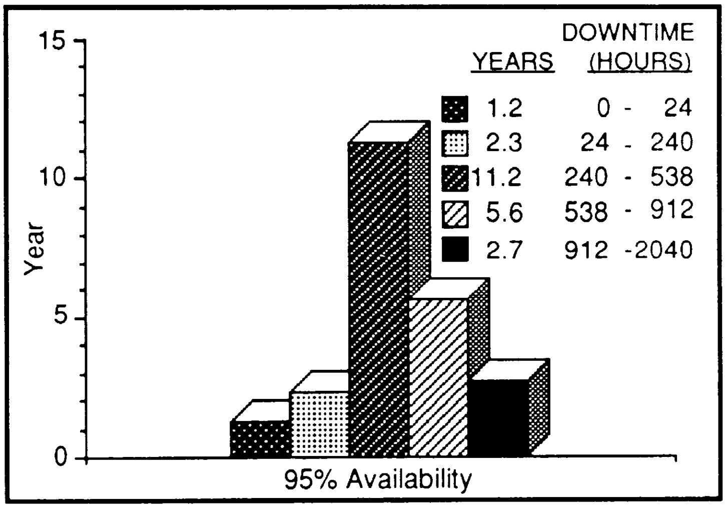


Figure 6. Downtime Per Year (95%).

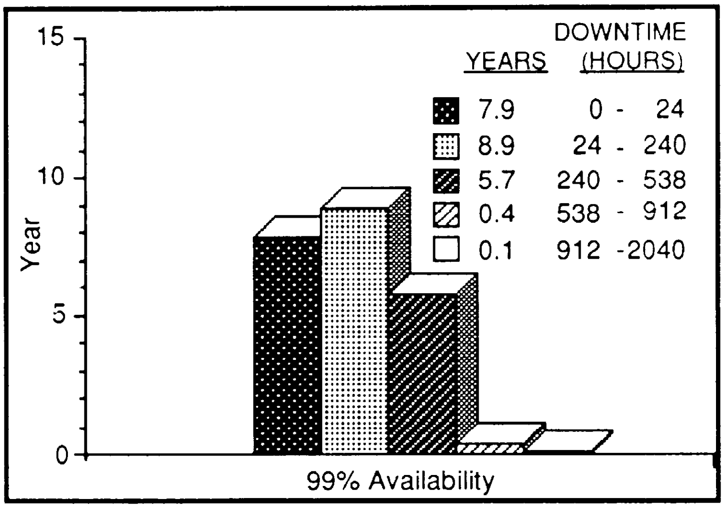


Figure 7. Downtime Per Year (99%).

The plots shown below were developed by studying the variation in year-to-year weather for selected sites. For any location, there will be a distribution of weather patterns over the years. This variation gives an indication of possible downtime over a PV system's lifetime. A study of this weather distribution shows that for a system with 95 percent availability, the 5 percent downtime (Figure 6) will be distributed over the assumed 23-year system life as follows: 1.2 years will have less than 24 hours downtime per year, 2.3 years will have 25-240 hours, 11.3 years will have 241-538 hours, 5.6 years will have 539-912 hours and 2.7 years will have over 913 hours.

A similar chart is shown as Figure 7 for 99 percent availability. Note the different distribution. The system designed for 99 percent availability will have less than 240 hours of downtime in 17 of the 23 years, whereas the 95 percent available system will have less than 240 hours of downtime in only 3.5 years. However, the system designer must consider the cost required to increase the system availability. If the system size is increased to lower the downtime in winter, more energy will be wasted in summer when the array will produce more than is needed by the load. The system cost increases rapidly--and the efficient utilization of energy decreases--as you try to obtain the last few percent, i.e., increasing availability from 95 to 99 percent. This is particularly true for locations where the difference between winter and summer insolation values is large. An example of system cost increase for two sites is given in Figure 8. For a

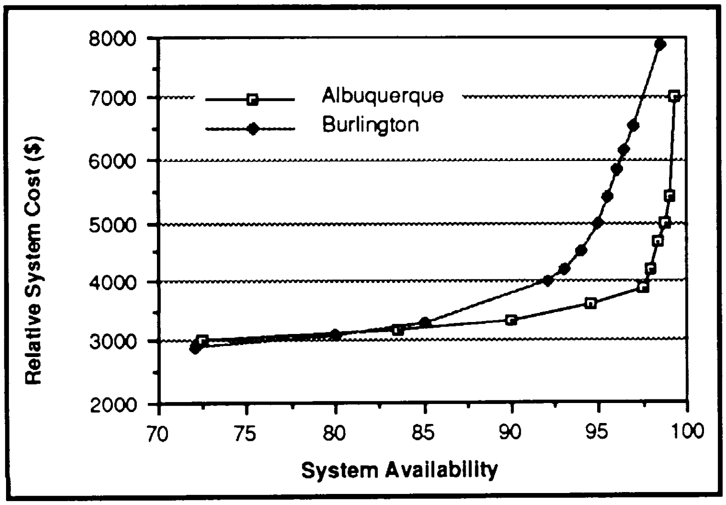
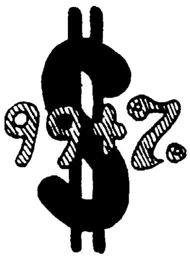


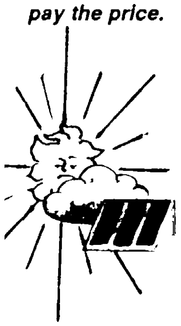
Figure 8. Cost vs. Availability–Albuquerque, New Mexico, and Burlington, Vermont.

sunny site, the incremental cost does not climb steeply until about 98 percent availability. For a site with poor solar insolation in winter the cost of increasing availability starts to climb rapidly after 90 percent.

In the PV system designs presented here, two levels of system availability are defined and used; 95 percent for noncritical loads and 99 percent for critical loads. Critical loads are those where a system failure might cause loss of life or expensive equipment. A railroad crossing signal or a navigation beacon for aircraft would be examples of critical loads. A residential system and most water pumping systems would not.



Do not specify 99+ percent availability unless you are ready to pay the price.



In summary, the system designer should understand the relationship between cost and availability. Experience shows that PV system customers have a tendency to over-specify the requirements and thereby drive the initial system cost unreasonably high. They should keep in mind that no energy producing system is available 100 percent of the time. Utilities obtain high system availability by using multiple and redundant power sources. There are few single generators, coal fired, nuclear, or hydropower, that achieve 90 percent availabilities. Many PV systems exceed this figure even when component reliability, maintenance, and solar variability are accounted for.

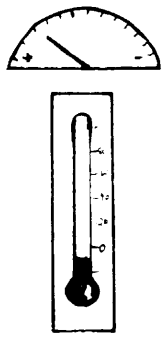
MAINTENANCE

Any battery requires periodic maintenance; even sealed "maintenance-free" batteries should be checked to make sure connections are tight and the cases are clean and intact. For flooded batteries, the electrolyte level should be kept above the plates, and the voltage and specific gravity of the cells should be checked for consistent values. Variations between cells of 0.05 volts/cell or 0.05 points of specific gravity may indicate problems with the battery. The specific gravity of the cells should be checked with a hydrometer with the SOC of the battery about 75 percent.

Most manufacturers of flooded batteries recommend overcharging their batteries every few months to reduce stratification of the electrolyte. This may occur if the battery operates in the same regime, say 60-90 percent state of charge, for a long period. This equalization charge, 30-60 minutes long, thoroughly mixes the electrolyte. It is usually done with a generator but can be done with a PV array if the controller and load are disconnected. Ask the battery manufacturer for recommendations on equalization charges.

In cold environments, the electrolyte in lead-acid batteries may freeze. The freezing temperature is a function of the battery's state of charge. When a battery is completely discharged, the electrolyte is nearly water and the battery may freeze at a few degrees below 0°C. However, a fully charged battery will have a specific gravity of about 1.24 and could withstand temperatures as low as minus 50°C. In cold climates, batteries are often buried below the frost line in an insulated battery box to maintain a constant temperature. Nickel cadmium batteries will not be damaged by cold weather.

The temperature at which a battery will freeze depends on its state of charge.



TYPES

Many terms are used to describe batteries.

You should be familiar with commonly used terms such as deep-cycle or shallow-cycle, gelled or captive electrolyte, liquid electrolyte, and sealed or flooded. Deep-cycle batteries are made with larger plates and are rated to withstand a specified number of charge/discharge cycles. The number of cycles depends on the depth of discharge, the rates of discharge, the length of time before recharge, and the recharge rate, among other things. Shallow-cycle batteries use lighter plates and cannot be cycled as many times as the deep-cycle batteries. Completely discharging them once or twice will often ruin them. For this reason, they should not be used in some PV systems. Some batteries have captive electrolyte. One of the most common ways of constraining electrolyte is the gel-cell battery. The captive electrolyte battery is easy to maintain because it is usually sealed and there is no possibility of spillage should the battery be tipped. Most sealed batteries are actually valve regulated and permit the release of hydrogen gas but do not allow electrolyte to be added. They may be rated as deep-cycle batteries but they will usually withstand fewer cycles than the industrial-grade flooded batteries. Batteries with liquid electrolyte may be sealed or have caps where distilled water may be added to the electrolyte. Usually if the capacity is greater than about 100 ampere-hours, the batteries are open. Electrolyte can (and should) be added regularly to flooded batteries,

The batteries used in stand-alone photovoltaic systems should be deep-cycle heavy-duty types. These batteries may be available with either liquid electrolyte (flooded or sealed) or captive electrolyte (gel cells). Because lead is a soft metal, other elements such as antimony or calcium are often added to strengthen the lead plates and customize the characteristics of the batteries. The lead-antimony battery will withstand deeper discharge cycles but require regular maintenance because they have higher water consumption, Lead-calcium batteries can be used for applications in which few deep discharges are anticipated. Their initial cost is less, but the lifetime is shorter than for the lead-antimony batteries.

Nickel cadmium batteries are available in some countries. They usually cost more than lead-acid batteries. Some advantages of the nickel cadmium batteries, include their long-life expectancy, low maintenance requirements, durability, their ability to withstand extreme hot or cold temperatures, and their tolerance to complete discharge. Because of this tolerance, the controller can be eliminated in some applications. A design note: if a controller is to be used with NiCd batteries, the controller supplier should be told. Commonly available controllers are designed to work with lead-acid batteries and the charging regimen is different for NiCd batteries. The controllers are not interchangeable.

NiCd batteries can be discharged and recharged many times.

Nickel cadmium batteries are more expensive but offer many advantages.

HAZARDS

Most batteries contain acid or caustic materials that are harmful or fatal if mishandled. Also, open batteries with caps produce explosive hydrogen gas when charging. These batteries must be located in a well-ventilated area. Other electric system components should not be installed in the battery compartment since sparking could ignite the gases. Also, the gases from lead-acid batteries are corrosive and may damage electrical components. Recombiners or catalytic converter cell caps that capture the vented hydrogen gas, recombine it with oxygen, and return the liquid water to the battery electrolyte are available. These caps have a life expectancy of three to five years, but they must be checked and cleaned periodically to ensure proper operation.

Use care when working with batteries.

Batteries produce explosive gas when charged--keep them in a well ventilated place.

Any battery should be considered dangerous, particularly to children and animals. Access should be limited to experienced persons. Keep the terminals covered--a typical battery used in a PV system can produce over 6,000 amperes if the terminals are shorted. Although this high current will last only a few milliseconds, it is enough to arc weld a tool to the terminals. The higher the voltage the more the hazard. Above 24 volts a shock hazard exists that can be fatal in worst-case conditions. Even at 12 volts, the high current can cause burns if the battery is inadvertently shorted. Use insulated tools and wear protective gloves, footwear, and goggles when working around batteries. Finally, remember batteries are heavy. Use your legs--not your back when lifting and moving the batteries.

SELECTION AND BUYING

In some countries there are many types of batteries available and the variation in manufacturers specifications make it difficult to compare performance characteristics. In other countries, the battery selection may be limited to batteries for automotive uses. In these cases, try to get a battery designed for trucks or heavy equipment. These are usually heavier and should give better performance in a PV system. The best advice is to talk to people who have used batteries in similar applications and conditions. If you cannot find such people, prepare a list of questions for your battery supplier. See the dialog of the Brown Family for some sample questions.

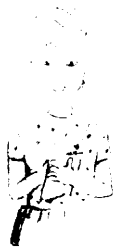
THE BROWN FAMILY SELECTS A BATTERY

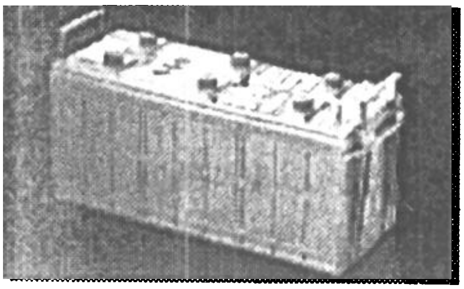
The Browns had to choose the number of days of storage and select the batteries they were going to use. Like many others, the Browns knew little about what characteristics were important for PV system batteries. They obtained specification sheets from several battery manufacturers and found there was no commonly accepted method of presenting performance data. They also found the wide range of prices confusing. In many instances it was difficult to find a correlation between features and price. Their first visit to a battery dealer was not helpful. Even though the dealer had advertised as a solar supplier, they found he had not sold any batteries for PV systems. However, their visit did allow them to come up with a set of questions they would ask each dealer they contacted.

	BROWNS		SELLER
Q	Do you sell batteries for photovoltaic systems?	A	For what?
Q	PV systems–solar electric systems.	A	Oh yes, our company has a solar battery.
Q	Have you sold any batteries locally for PV systems?	A	No, but I will call the company and ask how many have been installed.
Q	What kind of battery is it?	A	Lead calcium.
Q	What is the rated capacity?	A	The 12-volt battery has 105 ampere-hours.
Q	At what hourly rate?	A	10 hours.
Q	At what temperature?	A	Room temperature.
Q	Is the battery sealed?	A	Yes, it is a no maintenance battery.
Q	What's the maximum depth of discharge?	A	No more than 20 percent.
Q	OK, if we keep the state of charge greater than 80 percent, what lifetime can we expect?	A	I don't like to discuss battery lifetime, because I don't know how the battery will be used.
Q	Five years? Ten years?	A	It should last more than five years–if you're careful.
Q	How much does it weigh?	A	44 pounds.
Q	How much does the battery cost?	A	$100 for one unit.
Q	That's about $1 per rated ampere-hour. Is there a discount if I buy ten batteries?	A	I will make you a good deal.
Q	Thanks, we will get back to you after we have talked to some of your competitors.	A	Take this brochure–it gives a description of the battery.

The Browns generated the list shown. They knew the batteries were a key subsystem. They wanted to buy the best batteries available. They wanted to check out nickel cadmium batteries because of their long life and ability to handle deep discharges. They found some NiCd batteries listed in a catalog but the cost was about 4 times higher than the lead-acid batteries available locally. After considering cost, size, availability, and local service, they decided to use flooded deep-cycle batteries. They knew they would be available to do preventive maintenance and add water as needed. Their local dealer recommended a controller that had been used with their type of battery before. He suggested they limit the depth of discharge to 50 percent to extend the life of the battery. They thought this would allow them to keep the batteries operating for over 8 years. They continued their design assuming three days of storage, and a maximum allowable discharge of 50 percent.

QUESTIONS	MANUFACTURER 1	MANUFACTURER 2	MANUFACTURER 3
Type of Plates?			
Type of Electrolyte?			
Open or Sealed?			
Rated Capacity?			
Allowable Depth of Discharge?			
Number of Cycles?			
Equalization Charge Required?			
Allowable Temperature Range?			
Temperature Derate?			
Cost?			
Size?			
Weight?			
Expected Life?			
$/Ampere-Hour?			
$/kg?			
Shipping Charges?			
Salvage Value?			





PHOTOVOLTAIC ARRAYS

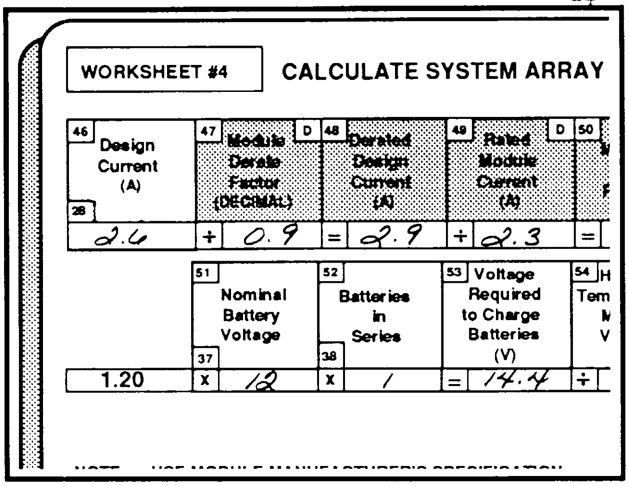
How many modules do I need? *How do I compare module performance?* *How should I install the modules?*

SIZING

Completion of Worksheet 4, a portion of which is shown in the inset, will determine the size of the PV array for your system. This sizing technique is designed to generate enough energy during the design month to meet the load and cover all losses in the system. This means that in an average year the load will be met and the battery state-of-charge will be the same on the last day of the design month as on the first day.

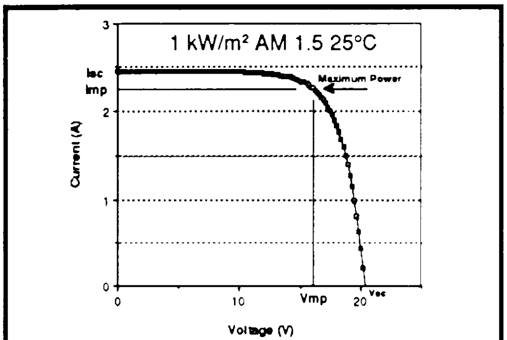
The design method uses current (amperes) instead of power (watts) to describe the load requirement because it is easier to make a meaningful comparison of PV module performance, i.e., ask for PV modules that will produce 30 amperes at 12 volts and a specified operating temperature rather than try to compare 50 watt modules that may have different operating points. You should obtain module specifications for available modules so you can compare performance, physical size, and cost. Generally, there are several modules that will meet a given set of requirements.

Consult several module manufacturers and distributors.



The worksheet requests the entry of rated module current. This is the current produced at standard test conditions (STC) of 1,000 w/m² irradiance and 25°C temperature. The module specifications given by one module manufacturer are shown in Figure 9. The current values given are at short circuit, I_{SC}, and at the peak power point, I_{mp} The value used in the worksheet for rated module current should be I_{mp}. The voltage at the peak power point is stated as 16 volts. However, the operating voltage of a PV array is determined by the battery voltage. This varies over a narrow range depending on the battery state-of-charge and ambient temperature but is usually 1 to 4 volts

In a PV system with batteries, the modules seldom operate at their peak power point.

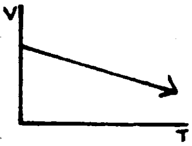


Short Circuit Current, I_{sc}	2.44 A
Open Circuit Voltage, V_{oc}	20.1 V
Current at Peak Power Point, I_{mp}	2.2 A
Voltage at Peak Power Point, V_{mp}	16 V
Power	35.2 W

Figure 9. PV Module Specifications.

lower than the voltage at which peak power figures are quoted by module manufacturers. Fortunately, the current changes little from the peak power voltage (17 volts) to normal system operating voltages (12 volts).

For crystalline silicon modules, the operating voltage will decrease about one-half of one percent for each degree centigrade rise in temperature. The module described in Figure 9 has a peak power voltage of 16 volts at 25°C. If this module operates at 50°C in a specific application, the peak power voltage would drop to about 14 volts. This is still adequate for use in a nominal 12-volt battery system, but the designer must make sure the current supplied by the module is adequate under the hottest expected conditions. Also, if a blocking diode is used between the module and the battery, this will cause a voltage drop of about 0.7 volts. The module must be able to sustain this drop plus any voltage drop caused by the wires and still supply enough voltage to fully charge the battery. The module parameters at standard test conditions and at the highest expected temperatures should be recorded in the space provided on the worksheet.



Voltage of a PV module decreases 0.5 percent per degree centigrade increase in operating temperature.

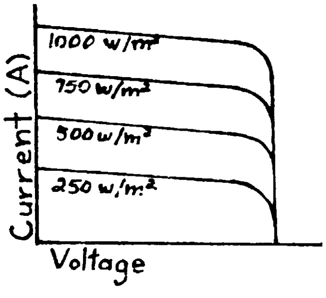
The number of parallel-connected modules required to produce the design current is rarely a whole number. Obviously, the designer must make a decision whether to round up or round down. The system availability requirements should be considered when making this decision. Since the design presented here is intended to just meet the load during the design month of an average year, the conservative approach is to round up to the nearest whole module.

The number of series-connected modules is calculated by dividing the system voltage by the nominal module voltage--12 volt modules are commonly used for stand-alone PV systems.

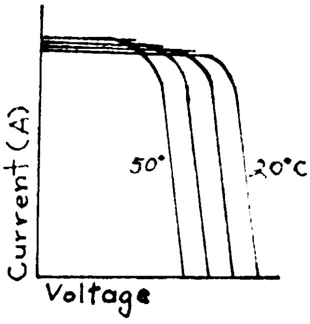
CHARACTERISTICS

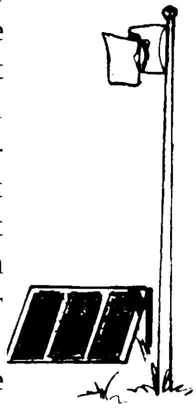
A photovoltaic array consists of two or more PV modules connected to obtain a desired voltage and current. A photovoltaic module is an encapsulated group of solar cells and is the least replaceable unit in the array. The majority of PV modules are manufactured using single crystal or polycrystalline silicon cells. These cells are embedded in a laminate, usually with a tempered-glass front plate and a soft pliable covering to seal the back.

There are four factors that determine any photovoltaic module's output--load resistance, solar irradiance, cell temperature, and efficiency of the photovoltaic cells. Theoutput of a given module can be estimated by studying a family of current and voltage (I-V) curves like those shown in the center column. Three significant points of interest on the I-V curve are the maximum power point, the open-circuit voltage, and the short circuit current. For a given



solar cell area, the current is directly proportional to solar irradiance (S) and is almost independent of temperature (T). Voltage and power decrease as temperature increases. The voltage of crystalline cells decreases about 0.5 percent per degree centigrade temperature increase. Therefore, arrays should be kept cool and mounted so air is not restricted from moving over and behind the array. Do not mount modules flush on a roof or support structure. Testing results show that modules mounted 3 inches above a roof will operate up to 15°C cooler than a directly mounted array -- a difference of 7.5 percent in power. See the installation section for details on mounting PV arrays.





Shading of a single cell can lower the array's power significantly.

No part of a PV array can be shaded. Unlike solar thermal collectors, the shading of small portions of a PV module may greatly reduce output from the entire array. PV modules connected in series must carry the same current. If some of the PV cells are shaded, they cannot produce current and will become reverse biased. This means the shaded cells will dissipate power as heat, and over a period of time failure will occur. However, since it is impossible to prevent occasional shading, the use of bypass diodes around series-connected modules is recommended. You do not need bypass diodes if all the modules are in parallel, i.e., a 12-volt array using 12-volt modules and many designers do not use them on 24-volt arrays. However for array voltages higher than 24 volts, bypass diodes should be used around each module to provide an alternative current path in case of shading. Figure 10 shows the use of bypass diodes on a 48-volt series string. Note the bypass diodes are reverse biased if all modules are operating properly. Many module manufacturers will provide modules with the bypass diodes integrated into the module junction box. If you need to connect modules in series, ask the supplier for this feature. Using bypass diodes may postpone failure, but it does not prevent the loss of energy production from the shading. It is important to check for potential shading before installing the PV array. Consider the seasonal changes in foliage and sun angle. After installation, the area must be maintained to prevent weeds or tree branches from shading the array.

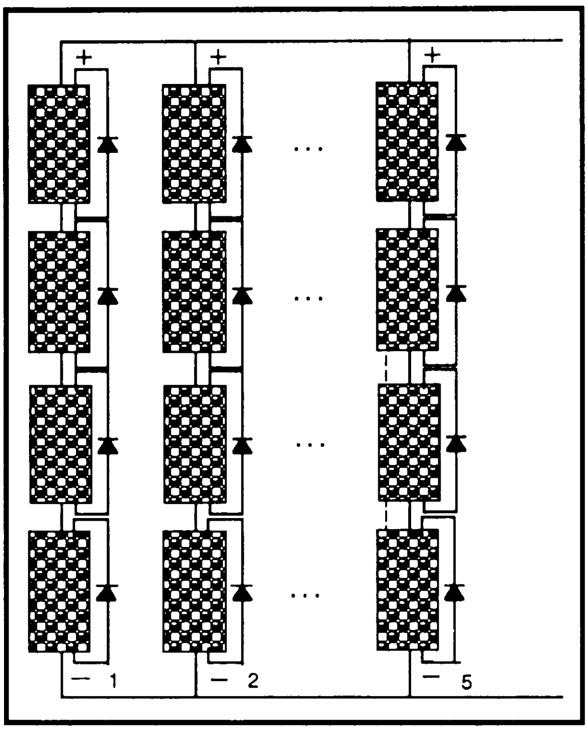


Figure 10. Series String with Bypass Diodes.

PV arrays include panels and source circuits. A panel is a group of PV modules packaged in a single name. Each panel should be sized for easy handling and mounting. A source circuit, sometimes called a string, may include any number of PV modules and panels connected in series to produce the system voltage.

All PV modules should have durable connectors on the module. The connectors should be sturdy, and the method of attaching the wire should be simple, yet provide a secure connection. Most modules have sealed junction boxes to protect the connections. Field testing experience shows that PV cells and connections between cells within the module laminate rarely fail. Most problems occur in the module junction box where the interconnections between modules are made. These can often be repaired in the field without replacing the module. Before buying a PV module, look at the junction box and see if it is easy to make the connections. Are the terminals rugged and is there a place to connect bypass diodes? Is the junction box of good quality?

Blocking diodes are used to control current flow within a PV system. Any stand-alone PV system should have a method to prevent reverse current flow from the battery to the array and/or to protect weak or failed strings. Individual blocking diodes are sometimes used for this purpose if the controller used does not contain this feature. Figure 11 shows the location of blocking diodes that can be installed in each parallel-connected string or in the main wire connecting the array to the controller. When multiple strings are connected in parallel, as in larger systems, it is recommended that blocking diodes be used in each string as shown on the left to prevent current flow from strong strings into weak strings (due to failures or shading). In small systems, a single diode in the main connection wire is sufficient. Do not use both. The voltage drop across each diode, 0.4-0.7 volt, represents about a 6 percent drop in a 12-volt system.

Blocking diodes are used to prevent unwanted current flow.

Fuses and switches are used to protect wires, equipment, and people.

A switch or circuit breaker should be installed to isolate the PV array during maintenance. This same recommendation applies to the battery circuit so another switch or circuit breaker is required. Also circuit breakers are normally installed to isolate each load. Fuses are used to protect any current carrying conductor. Fuses and cables in the array circuit should be sized to carry the maximum

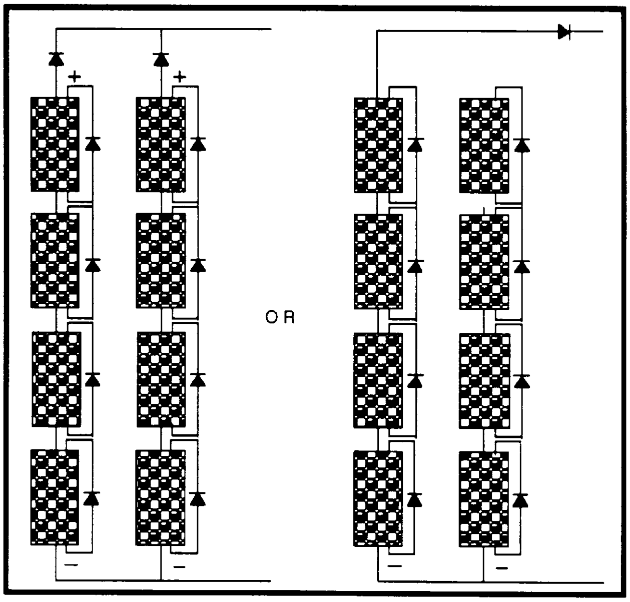
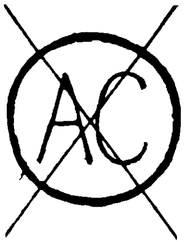


Figure 11. 48-Volt Array Showing Use of Blocking Diodes.

current that could be produced by short-term "cloud focusing" of the sunlight--up to 1.5 times the short circuit current at 1,000 w/m^2 irradiance. Slow-blow fuses are recommended. Only fuses rated for dc current should be used. (Automotive fuses should not be used.) All metal in a PV array should be grounded to help protect the array against lightning surges, and as an added safety feature for personnel working on the system. The negative conductor on most PV systems is also grounded to the same grounding electrode used for the equipment ground. Other disconnect and grounding requirements are given in the National Electrical Code® (NEC). This code is intended to ensure that safe, durable PV systems are installed.

Use only dc rated components.



ORIENTATION

A photovoltaic array can be mounted at a fixed angle from the horizontal or on a sun-tracking mechanism. The preferred azimuth for arrays in the northern hemisphere is true south. The decrease in energy production for off-south arrays roughly follows a cosine function, so if the azimuth of the array is kept to ±20° of true south, annual energy production is not reduced significantly. Some arrays are sited west of south to skew the production toward an afternoon peak load demand. The effect of array tilt angle on annual energy production is shown in Figure 12. For most locations, a tilt angle near the latitude angle will provide the most energy over a full year. Tilt angles of latitude ±15° will skew energy production toward winter or summer, respectively.

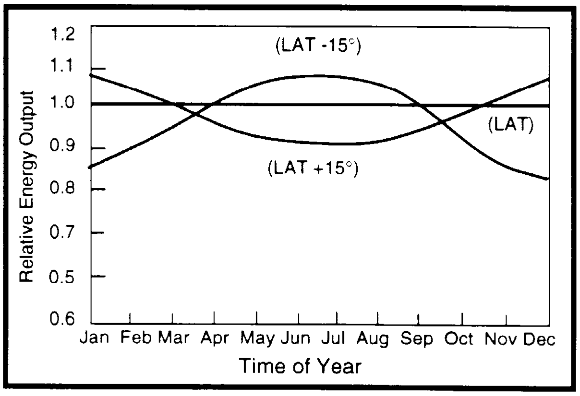
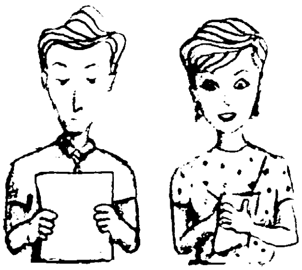


Figure 12. Effect of Array Tilt Angle on Annual Energy Production.

THE BROWN FAMILY SELECTS THEIR PV MODULES

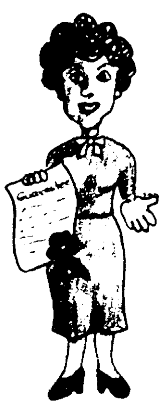
The Browns obtained performance data for two different crystalline silicon modules. They completed Worksheet 4 and selected a candidate module that would meet their requirements. Because they considered their load noncritical, they rounded down the number of modules from 13.5 to 12 modules. Using a rule of thumb that the array might be 20°C warmer than the peak ambient temperature, they thought their array would reach about 55°C on the hottest day. They made sure that the



voltage of the module would be greater than 14.5 V when it was operating at 55°C. This would give them enough voltage to fully charge the battery. They intended to use a controller that would give them reverse current protection so they did not have to allow for blocking diode voltage drop.

Before they made their final decision they carefully inspected the module junction boxes. They wanted an easy-to-make connection, but they also wanted a rugged connection that would last more than 20 years. When they were satisfied, they bought modules from the local dealer.

The Browns planned to configure their array with six parallel strings of two series connected modules (6P X 2S). With this configuration, they would not use bypass diodes across the modules. They asked about array mounting structures, and their dealer was able to supply some that were tailored to the mechanical and electrical characteristics of the modules. They were less expensive than any the Browns could make themselves so they ordered all the hardware they needed to do a ground mount of their PV array. They used cables to anchor the array frames so they would withstand the winds in their area.



They asked the dealer how they could tell if the array was performing as specified without installing a great deal of expensive instrumentation. He suggested installing only an ammeter and told them to expect greater than 80 percent of the module rating at noon on a clear day. The Browns calculated that this meant their array should produce over 15 amps on the meter. If it dropped below this value consistently, they would look for problems. The modules had a warranty and would be replaced in the first 10 years at no cost if they failed.

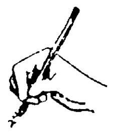
With their major purchases made, the Browns were ready to install their system. They studied the local electrical codes on wiring, grounding, and disconnecting power sources. They talked to a local electrical supply store and asked for recommendations on wire type and installation techniques. They visited their site and marked the location for the array and the wire runs to the control center. They were excited and anxious to get their system operating.

HYBRID INDICATOR

When should I consider using a generator with my PV system?

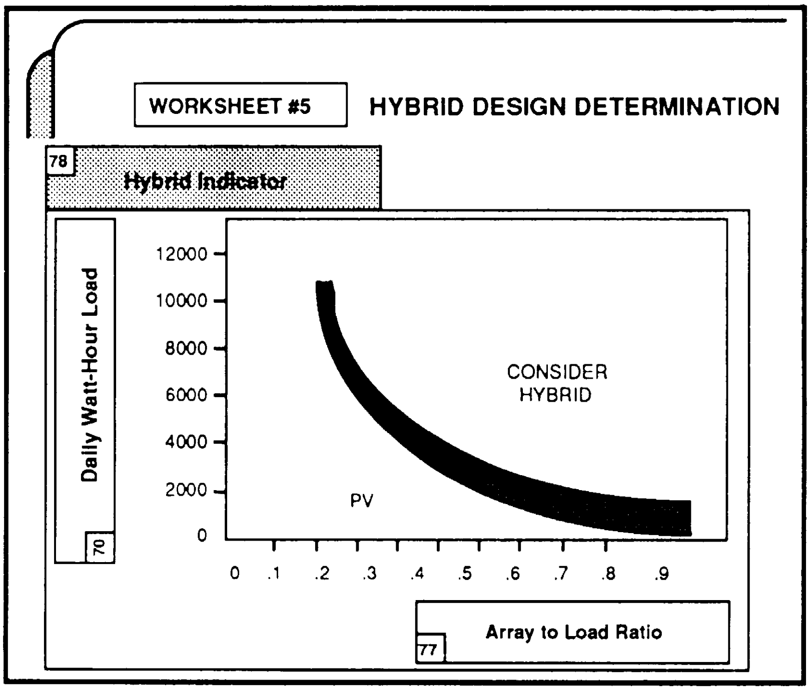
ARRAY TO LOAD RATIO

At this point, the basic PV system configuration and size have been determined. Before proceeding to specify components for the system, a simple test is recommended to see if the application might be a candidate for a hybrid system. Two main indicators work together to alert the designer to a possible hybrid application; the size of the load, and the seasonal insolation variability at the site. These two factors have been combined into the graph on Worksheet 5 (see inset below), which plots the daily load in watt-hours versus the array/load ratio. The larger the load the more likely a hybrid PV-generator system will be a good economic choice. Likewise, in cloudy climates you need a larger system to meet the load demand; thus having a higher array/load ratio. Plotting the load versus the array/load ratio gives an indication of whether a hybrid system should be considered. If the point falls in or above the gray area, then sizing a hybrid system is recommended so that cost comparisons with the PV-only design can be made.



Calculate the array-to-load ratio and check the hybrid indicator graph.

There may be other reasons to consider a hybrid system. For example, systems with high availability requirements, or applications where the load energy is being provided by an existing generator. Request a copy of the booklet *"Hybrid Power Systems--Issues and Answers"* from Sandia for more information on hybrid systems. The worksheets for hybrid systems, provided in Appendix B, can be used to size a PV/generator hybrid system if one is desired. A word of caution--the controls required for a hybrid system are more complex because the interaction between engine generator, PV array, and battery must be regulated. Obtaining advice from an experienced designer is recommended if you decide to install a hybrid system.

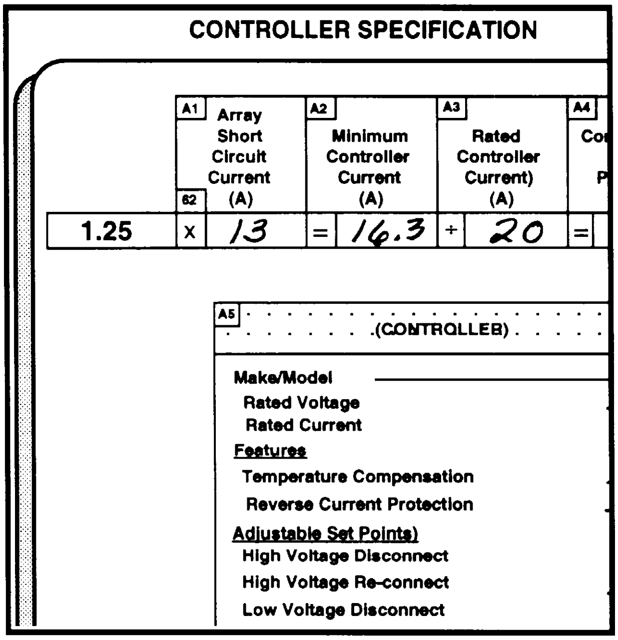


Do I need a controller? *What features are required?* *Where should it be installed?*

SPECIFICATION

Charge controllers are included in most photovoltaic systems to protect the batteries from overcharge or excessive discharge. Overcharging can boil the electrolyte from the battery and cause failure. Allowing the battery to be discharged too much will cause premature battery failure and possible damage to the load. The controller is a critical component in your PV system. Thousands of dollars of damage may occur if it does not function properly. In addition, all controllers cause some losses (tare loss) in the system. One minus these losses, expressed as a percentage, is the controller efficiency.

A controller's function is to control the system depending on the battery state-of-charge (SOC). When the battery nears full SOC the controller redirects or switches off all or part of the array current. When the battery is discharged below a preset level, some or all of the load is disconnected if the controller includes the low voltage disconnect (LVD) capability. Most controllers use a measurement of battery voltage to estimate the state-of-charge. However, this does not give a precise indication because, as shown in Figure 13 on the next page, the voltage changes little until the battery nears the extremes of SOC. Battery temperature, age, type, and rate of charge/discharge also affect this curve. Measuring battery temperature improves the SOC estimate and many controllers have a temperature probe for this purpose. These compensated controllers are recommended if the battery temperature is expected to vary more than ±5°C from ambient.



Keep it simple—added features lower reliability.

Determining battery state of charge under all conditions is virtually impossible, but battery voltage is a commonly used indicator.

There are two voltage thresholds or activation setpoints, at which the controller will take action to protect the battery. Each threshold has a complementary-action setpoint. For instance, the array disconnect voltage is usually set near 14 volts for a nominal 12-volt battery. When the array is disconnected, the battery voltage will drop immediately to about 13 volts. The array re-connect voltage is usually set near 12.8 volts.

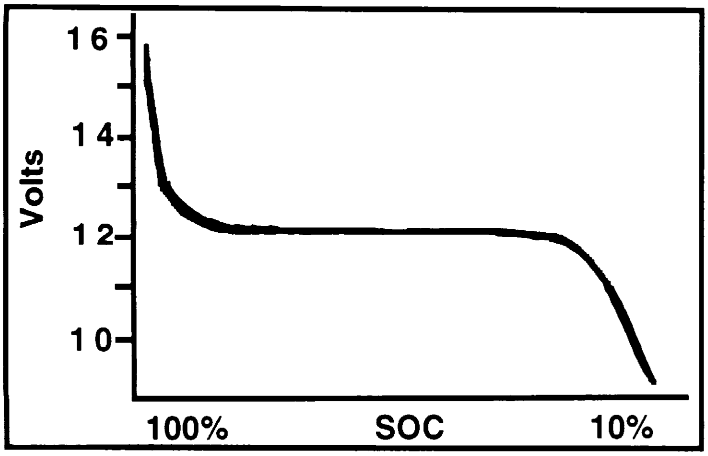


Figure 13. Typical Battery State-of-Charge Curve.

Similarly, when the voltage reaches about 11.5 the load is disconnected and not re-connected until the voltage reaches about 12.4 volts. On some controllers these connect/disconnect voltages may be adjusted in the field. This is a good feature if you have ready access to your system and can monitor battery performance. Otherwise, ask your battery manufacturer what controllers have been used successfully with your type of batteries.

A worksheet to help you specify a controller for your system is given in Appendix B. The controller voltage must be compatible with the nominal system voltage and it must be capable of handling the maximum current produced by the PV array. Multiply the array short-circuit current by at least 1.25 to allow for short periods of high irradiance produced by momentary cloud enhancement. (The document *Stand-Alone Photovoltaic Systems and the National Electrical Code* presents an argument for a conservative 1.56 multiplier.) This maximum current value and the system voltage are the minimum information needed to order a controller. Other features to specify are

- Efficiency (tare loss),
- Temperature compensation,
- Reverse current protection,
- Display meters or status lights
- Adjustable setpoints,
  - High voltage disconnect
  - High voltage re-connect
  - Low voltage disconnect
  - Low voltage re-connect
- Low voltage warning,
- Maximum power tracking

Reverse current protection is the prevention of current flow through the controller from the batteries to the PV array at night. Most controllers include a blocking diode or other mechanism that prevents this unwanted current. Also, most small controllers include built-in LVD capability to switch off the loads, activate lights or buzzers to alert users that action is required, or turn on a standby power supply.

The cost of the controller increases rapidly as the current requirement increases. Controllers for 12-volt and 24-volt systems with currents up to 30 amperes are available at a reasonable cost. Controllers with 30-100 amperes are available but 2-5 times more expensive. Controllers that will switch currents over 100 amperes are usually custom designed for the application. One way to work with currents over 100 amperes is to connect controllers in parallel. It is often less expensive to use five 20-ampere rated controllers in parallel than one 100-ampere unit. However, the array must be electrically divided and each controller wired separately with the controller outputs recombined before connecting to the battery. The activation levels of individual controllers will be slightly different but this presents no problem. All possible array current will be used to charge the batteries until the lowest activation voltage is reached; one controller will then shut off and the other controller(s) will allow current passage until the battery voltage exceeds their threshold.

TYPE

There are two basic types of controllers used for small PV systems. A shunt controller redirects or shunts the charging current away from the battery. These controllers require a large heat sink to dissipate the excess current. Most shunt controllers are designed for smaller systems producing 30 amperes or less. A series controller interrupts the charging current by open-circuiting the PV array. This switching controller is thus limited by the current handling capability of the components used to switch the dc current. There are many variations of both series and shunt controllers. Both types can be designed as single-stage or multistage. Single-stage controllers disconnect the array when the battery voltage reaches the high voltage level. Multistage controllers allow different charging currents as the battery nears full state-of-charge. This technique also provides a more efficient method of charging the battery. As the battery nears full SOC, its internal resistance increases and using a lower charging current wastes less energy. As the size and complexity of the system increase, the need for expert advice on controllers becomes greater. Check with your battery supplier about charge controllers and what features they should have. Most solar system dealers sell both batteries and charge controllers and will have determined the ones that work best together.

More systems have had problems caused by a poor control scheme than any other cause.

INSTALLATION

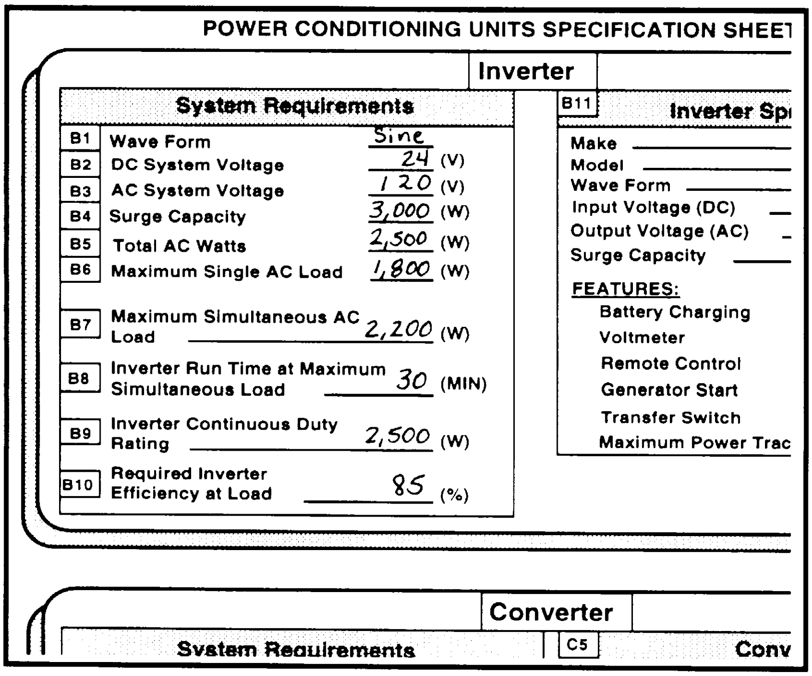
The controller must be installed in a weather resistant junction box and can be located with other components such as diodes, fuses, and switches. Excessive heat will shorten controller lifetime so the junction box should be installed in a shaded area and venting provided if possible. Controllers should not be mounted in the same enclosure with batteries. The batteries produce a corrosive environment that may cause failure of electronic components.

INVERTERS

What features do I need?	*Do I need a sine wave output?*	*Where should the PCS be installed?*

SPECIFICATIONS

Power conditioning units, commonly called inverters, are necessary in any stand-alone PV system with ac loads. The choice of inverter will be a key factor in setting the dc operating voltage of your system. When specifying an inverter, it is necessary to consider requirements of both the dc input and the ac output. All requirements that the ac load will place on the inverter should be considered--not only how much power but what variation in voltage, frequency, and waveform can be tolerated. On the input side, the dc voltage, surge capacity, and acceptable voltage variation must be specified. Selecting "the best inverter" for your application requires a study of many parameters listed by various inverter manufacturers. Some parameters are listed on the specification sheet provided, a portion of which is shown in the inset. This sheet, located in Appendix B, also includes the specification for a dc to dc converter if one is needed to supply dc loads operating at different voltages.


POWER CONDITIONING UNITS SPECIFICATION SHEET

Inverter

	System Requirements		
B1	Wave Form	Sine	
B2	DC System Voltage	24	(V)
B3	AC System Voltage	120	(V)
B4	Surge Capacity	3,000	(W)
B5	Total AC Watts	2,500	(W)
B6	Maximum Single AC Load	1,800	(W)
B7	Maximum Simultaneous AC Load	2,200	(W)
B8	Inverter Run Time at Maximum Simultaneous Load	30	(MIN)
B9	Inverter Continuous Duty Rating	2,500	(W)
B10	Required Inverter Efficiency at Load	85	(%)

B11 Inverter Sp

Make
Model
Wave Form
Input Voltage (DC)
Output Voltage (AC)
Surge Capacity

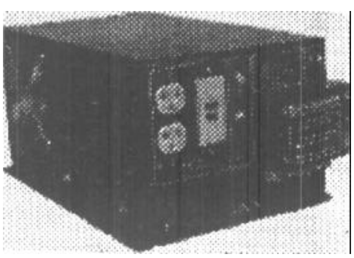
FEATURES:
Battery Charging
Voltmeter
Remote Control
Generator Start
Transfer Switch
Maximum Power Trac

Converter

System Requirements | C5 | Conv

The choice of inverter will affect the performance, reliability, and cost of your PV system. Usually, it is the third most expensive component after the array and battery. Fortunately in 1994, there is a good selection of inverters for stand-alone PV systems in the United States. Characteristics that should be considered are

- output waveform,
- power conversion efficiency,
- rated power,
- duty rating,
- input voltage,
- voltage regulation,
- voltage protection,
- frequency,
- modularity,
- power factor,
- idle current,
- size and weight,
- audio and RF noise,
- meters and switches.



Added features available with some inverters are

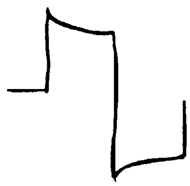
- battery charging capability,
- remote control operation,
- load transfer switch,
- capability for parallel operation.

CHARACTERISTICS

Stand-alone inverters typically operate at 12, 24, 48 or 120 volts dc input and create 120 or 240 volts ac at 50 or 60 hertz. The selection of the inverter input voltage is an important decision because it often dictates the system dc voltage; see the discussion of system voltage selection on page 12.

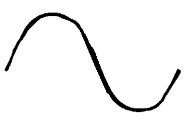
The shape of the output waveform is an important parameter. Inverters are often categorized according to the type of waveform produced; 1) square wave, 2) modified sine wave, and 3) sine wave. The output waveform depends on the conversion method and the filtering used on the output waveform to eliminate spikes and unwanted frequencies that result when the switching occurs.

Square wave inverters are relatively inexpensive, have efficiencies above 90 percent, high harmonic frequency content, and little output voltage regulation. They are suitable for resistive loads and incandescent lamps. Modified sine wave inverters offer improved voltage regulation by varying the duration of the pulse width in their output. Efficiencies can reach 90 percent. This type of inverter can be used to operate a wider variety of loads including lights, electronic equipment, and most motors. However, these inverters will not operate a motor as efficiently as a sine wave inverter because the energy in the additional harmonics is dissipated in the motor windings. Sine wave inverters produce an ac waveform as good as that from most electric utilities. They can operate any ac appliance or motor within their power rating. In general, any inverter should be oversized 25 percent or more to increase reliability and lifetime. This also allows for modest growth in load demand. The efficiency of all inverters is lowest for small load demand and reach their nominal efficiency (around 90 percent) when the load demand is greater than about 50 percent of rated load.

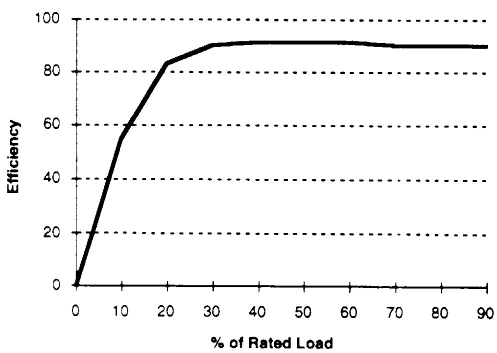


Square Wave

Modified Sine Wave



Sine Wave

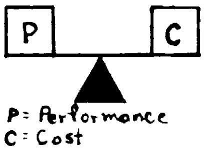


Some appliances do not work with a square wave input.

The manufacturers' specification sheets will list some of the following parameters.

- **Power Conversion Efficiency** - This value gives the ratio of output power to input power of the inverter. Efficiency of stand-alone inverters will vary significantly with the load. Values found in manufacturers' specifications are the maximum that can be expected.

- **Rated Power** - Rated power of the inverter. However, some units can not produce rated power continuously. See duty rating. Choose an inverter that will provide at least 125 percent of simultaneous peak load requirements (Block 11B, Worksheet 1) to allow for some growth in load demand.



- **Duty Rating** - This rating gives the amount of time the inverter can supply its rated power. Some inverters can operate at their rated power for only a short time without overheating. Exceeding this time may cause hardware failure.

The efficiency of inverters can be less than half of that claimed when they are used with certain loads.

- **Input Voltage** - This is determined by the total power required by the ac loads and the voltage of any dc loads. Generally, the larger the load, the higher the inverter input voltage. This keeps the current at levels where switches and other components are readily available.

- **Surge Capacity** - Most inverters can exceed their rated power for limited periods of time (seconds). Surge requirements of specific loads should be determined or measured. Some transformers and ac motors require starting currents several times their operating level for several seconds.

- **Standby Current** - This is the amount of current (power) used by the inverter when no load is active (power loss). This is an important parameter if the inverter will be left on for long periods of time to supply small loads. The inverter efficiency is lowest when load demand is low.

- **Voltage Regulation** - This indicates the variability in the output voltage. Better units will produce a nearly constant root-mean-square (RMS) output voltage for a wide range of loads.

- **Voltage Protection** - The inverter can be damaged if dc input voltage levels are exceeded. Remember, battery voltage can far exceed nominal if the battery is overcharged. A 12-volt battery may reach 16 volts or more and this could damage some inverters. Many inverters have sensing circuits that will disconnect the unit from the battery if specified voltage limits are exceeded.

- **Frequency** - Most loads in the United States require 60 Hz. High-quality equipment requires precise frequency regulation--variations can cause poor performance of clocks and electronic timers.

- **Modularity** - In some systems it is advantageous to use multiple inverters. These can be connected in parallel to service different loads.

Manual load switching is sometimes provided to allow one inverter to meet critical loads in case of failure. This added redundancy increases system reliability.

• Power Factor - The cosine of the angle between the current and voltage waveforms produced by the inverter is the power factor. For resistive loads, the power factor will be 1.0 but for inductive loads, the most common load in residential systems, the power factor will drop, sometimes as low as 0.5. Power factor is determined by the load, not the inverter.

INSTALLATION

An inverter should be installed in a controlled environment because high temperatures and excessive dust will reduce lifetime and may cause failure. The inverter should not be installed in the same enclosure with the batteries because the corrosive gassing of the batteries can damage the electronics and the switching in the inverter might cause an explosion. However, the inverter should be installed near the batteries to keep resistive losses in the wires to a minimum. After conversion to ac power, the wire size can be reduced because the ac voltage is usually higher than the dc voltage. This means the ac current is lower than the dc current for a equivalent power load. All wiring and installation procedures described in Article 300 of the National Electrical Code (NEC) should be followed.

Protect the inverter circuits with fuses on both input and output.

Both the input and output circuits of the inverter should be protected with fuses or circuit breakers. These safety devices should be accessible and clearly labelled. Using a surge protection device on the inverter input to protect against nearby lightning strikes is recommended for most areas. A component such as a movistor shunts surge current to ground. If a nearby lightning strike occurs, this may destroy the movistor, but its destruction might prevent expensive inverter repair bills.

THE BROWN FAMILY SELECT AN INVERTER

QUESTIONS ABOUT INVERTERS

Power Factor?
Waveform?
Rated Efficiency?
Duty Rating?
Surge Capability?
Voltage Protection?
Input?
Output?
Safety Features?
Operator Alarm?
Meters?

The Brown Family chose a 2.5-kilowatt inverter that operated at 24 volts dc and provided 120 volts ac single-phase sine wave output. This unit was adequate for their 1,800 watt domestic household loads, but it would not be large enough to run their water pump and washing machine simultaneously. This problem was avoided by installing a water storage tank on the hill behind their house and using a gravity-feed system for their domestic water system. This water storage would give them independence for several cloudy days and they could use the inverter to run the pump and fill the tank at night or at times when other household demands were low. This allowed the single 2.5-kilowatt inverter to meet all their needs. Before buying the inverter, they visited the local distributor and asked for a demonstration using both resistive and motor loads such as an electric blender. Also, they wanted to hear the unit operating and to know how much current the inverter used when it was in standby. They were concerned about audible noise levels because they planned to put their inverter on the wall in Mr. Brown's workshop. They asked questions about the technical performance of inverters and also questioned the dealer about the service policy and the warranty on the unit.

INTERCONNECTING THE SYSTEM

Where should I put the switches and fuses?

How do I select the wire type and size?

Now that the major components have been sized and selected, it is time to consider how to interconnect everything as a working system. It is important to select wire, connectors, and protection components such as switches and fuses that will last for twenty years or more. To obtain this long life, they must be sized correctly, rated for the application, and installed carefully. Connections are particularly prone to failure unless they are made carefully and correctly. Obtain a quality crimp tool and ask an experienced electrician for advice on ways to make and protect long lasting connections. Remember the performance and reliability of the entire system depends on each connection.

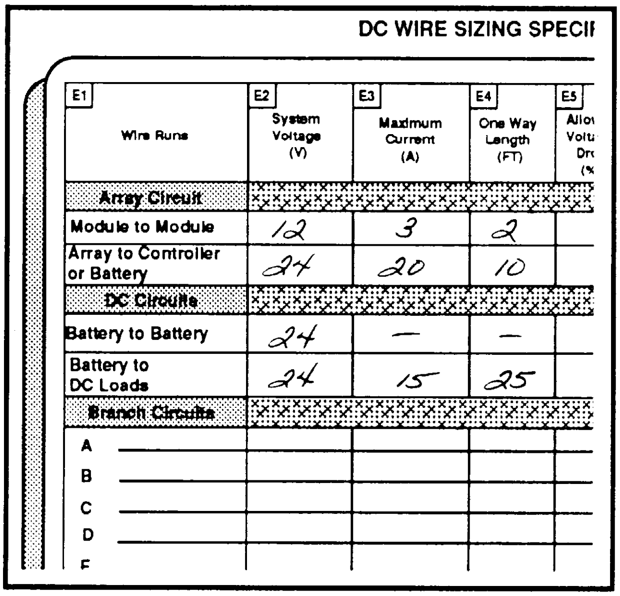
Use switches and fuses for safety of components and personnel.

Selecting wire for your application may seem confusing because there are so many types of wire and insulation available. However, only a few types are popular with PV system installers. In most cases you don't need special (and therefore expensive) wire. Talk to a local electrician or a wire supplier and describe how and where the wire will be used. Ask for recommendations.

WIRE TYPE AND SIZE

Consult Article 310 of the NEC for a discussion of wire types and sizes.

In the United States, the size of wire is categorized by the American Wire Gage (AWG) scale. The AWG scale rates wires from No. 18 (40 mil diameter) to No. 0000 (460 mil diameter). Multiple conductors are commonly enclosed in an insulated sheath for wires smaller than No. 8. The conductor may be solid or stranded. Stranded wire is easier to work with particularly for sizes larger than No. 8. Copper conductors are recommended. Aluminum wire is less expensive, but can cause problems if used incorrectly.* Many different materials are used to make the sheath that covers the conductors.



DC WIRE SIZING SPECI

E1 Wire Runs	E2 System Voltage (V)	E3 Maximum Current (A)	E4 One Way Length (FT)	E5 Allo Volt Dro (%
Array Circuit				
Module to Module	12	3	2	
Array to Controller or Battery	24	20	10	
DC Circuits				
Battery to Battery	24	—	—	
Battery to DC Loads	24	15	25	
Branch Circuits				
A				
B				
C				
D				
E				

* Aluminum is sometimes specified for applications requiring long wire runs, for instance, from array to controller. If aluminum is used, terminations must be made with connectors suitable for use with aluminum wire. These connectors will be stamped AL. Do not splice aluminum to copper wire.

You must select a wire with a covering that will withstand the worst-case conditions. It is mandatory that sunlight resistant wire be specified if the wire is to be exposed to the sun. If the wire is to be buried without conduit it must be rated for direct burial. For applications such as wiring to a submersible pump or for battery interconnections, ask the component dealer for recommendations. Often the dealer or manufacturer will supply appropriate wire and connectors.

Some wire types commonly used in the United States are listed below.

- **Underground Feeder (UF)** - may be used for interconnecting balance-of-systems (BOS) but not recommended for use within battery enclosures; single conductor UF wire may be used to interconnect modules in the array but this type of wire is not widely available.

- **Tray Cable (TC)** - multiconductor TC wire may be used for interconnecting BOS; TC has good resistance to sunlight but may not be marked as such.

- **Service Entrance (SE)** - may be used for interconnecting BOS

- **Underground Service Entrance (USE)** - may be used for interconnecting modules or BOS; may be used within battery enclosures,

- **THHN** - indicates wire with heat resistant thermoplastic sheathing; it may be used for interconnecting BOS but must be installed in conduit--either buried or above ground. It is resistant to moisture but should not be used in wet locations.

Protect the wire from the sun if possible.

- **TW** - refers to moisture resistant thermoplastic sheathing; it may be used for interconnecting BOS but must be installed in conduit. May be used in wet locations.

The use of NMB (Romex) is not recommended except for ac circuits as in typical residential wiring. Although commonly available, it will not withstand moisture or sunlight.

More useful information is contained in the NEC. It is recommended that any designer/installer review Article 300 before proceeding. This article contains a discussion of wiring methods and Table 310-13 gives the characteristics and recommended usage of different wire types. Table 310-16 gives temperature derate factors. Another useful reference available from the PVDAC at Sandia National Laboratories is *"Photovoltaic Power Systems and the National Electrical Code, Suggested Practices."*

Selecting the correct size and type of wire for the system will optimize performance and increase reliability. The size of the wire must be capable of carrying the current at the operating temperature without excessive losses. It is important to derate the current carrying capacity of the wire if high temperature operation is expected. A wire may be rated for high temperature installations (60-90°C) but this only means the insulation of the wire can withstand the rated temperature–it does not mean that ampacity is unaffected. The current carrying capability (ampacity) depends on the highest temperature to which the wires will be exposed when it is carrying the current. According to Table 310-16 in the NEC, a UF type wire operating at 55°C can safely carry only 40 percent of the current it can carry at 30°C–a significant derate. If the ampacity of the wire is exceeded, overheating, insulation break-down, and fires may occur. Properly sized fuses are used to protect the conductors and prevent this kind of damage.

Loss in a dc circuit is equal to I^2R where I is the current and R is the resistance of the wire. For 100 ampere current this means 10,000 times the loss in the circuit. It is easy to see why resistance must be kept small. Also, the voltage drop in the circuit is equal to IR. Voltage drop can cause problems, particularly in low voltage systems. For a 12-volt system, a one volt drop amounts to over 8 percent of the source voltage. Avoid long wire runs or use larger wire to keep resistance and voltage drop low. For most applications AWG No. 8, No. 10, and No. 12 are used.

The wire sizing worksheets given in Appendix B, a portion of which is shown in the inset, provide a consistent way to record the minimum wire size for different subsystems. Four tables are included that give maximum length for selected wire sizes and currents. The tables are for 12-, 24-, 48-, and 120-volt dc systems and provide the minimum wire size that should be used if the voltage drop is to be limited to 3 percent for any branch circuit. A portion of the 24-volt table is shown in Table 2. (These tables can be adjusted to reflect different voltage drop percentages by using simple ratios. For example, a 2 percent table can be calculated by multiplying the values in Table 2 by 2/3.) The tables are calculated for one-way distance taking into account that the circuit consists of both positive and negative wires. As an example, assume the array is 30 feet from the controller and the maximum current is 10 amperes. Table 2 shows that a No. B-size wire can be used up to a one-way distance of 40 feet (no temperature derate included). While the general rule is to limit the voltage drop for any branch circuit to 3 percent, there may be low-voltage applications where it should be less than 1 percent. For the total wire run on any path from source to load, the loss should be no greater than 5 percent.

Fuses are used to protect the conductors in the system.

The sub-systems must be protected from the high current possible from the battery.

TABLE 2
Portion of 24-V Table

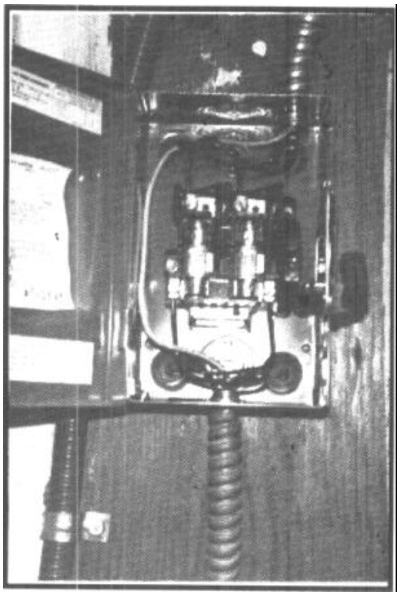
					Maxi
				3% Voltage Drop;	
AWG Wire Size		14	12	10	8
Resistance (Ω/1000 ft.)		2.52500	1.58800	0.99890	0.62820
Amperes	Watts	Distance	Distance	Distance	Distance
0.5	12	570	907		
1	24	285	453	721	
2	48	143	227	360	573
3	72	95	151	240	382
4	96	71	113	180	287
6	144	48	76	120	191
8	192	36	57	90	143
10	240	29	45	72	115
12	288	24	38	60	96
14	336	20	32	51	82

SWITCHES AND FUSES

Install switches in accessible places.

There is a specification sheet provided in Appendix B that can be used to size and record the switches, diodes, and fuses for the system. Switches, circuit breakers, and fuses are used to protect personnel and equipment. The switches provide the capability to manually interrupt power in case of emergency or for scheduled maintenance. The fuses provide overcurrent protection of the conductors in case of system shorting or ground faults. Diodes are used to control the direction of current flow in the system.

These protection components should be located throughout the stand-alone PV system. The designer should ask "What might happen?" and try to guard against reasonable failure scenarios. The largest current source in the system is the battery. A typical battery can provide over 6,000 amperes for a few milliseconds if faults occur and the battery is short-circuited. These levels of current can destroy components and injure personnel so an in-line fuse should be installed in all battery circuits. The fuses must be rated for dc operation and have an amperage interrupt capability (AIC) sufficient for these high currents. The NEC requires that there must be a method of disconnecting power from both sides of any installed fuse. This may require additional switches to be installed. Any switch used in a dc circuit should be specifically rated for dc operation, An ac switch may operate properly a few times, but it will probably fail when it is needed most. DC components are rated for voltage and current. Common voltage levels are 48, 125, 250, and 600 volts dc. Current ratings of 15, 30, 60, 100, and 200 amperes are common. The switch or breaker must be sized to handle the maximum possible current. This is the same current level used to specify the fuses. Fused disconnect switches with both devices incorporated into one assembly may be available. Using these will save on installation costs. DC rated circuit breakers can be used to replace both switches and fuses. They may be more difficult to find but the reliability is high and they are preferred by many system designers.



You can buy switch/fuse assemblies for installation in one box.

The current produced by the PV array is limited, but the array short-circuit current, multiplied by a safety factor of 1.56, is commonly used to specify the size of a slow-blow fuse in the array output circuit. Should a ground fault occur in the array while the controller is engaged, this fuse will protect the array modules and the conductors from high battery current. In the load circuits a fuse or circuit breaker is usually installed for each significant load.

Switches, fuses, blocking diodes, movistors, and any sensors used for data acquisition are normally installed in a centrally located weather-proof junction box (J-box). The controller is often installed in the same J-box which may be referred to as the control center of the system. All negative wires should be attached to the negative buss and a solid copper wire used to connect this buss to the ground lug in the J-box. (The ground lug is connected to the common ground rod of the system). The positive leads are usually connected through a fuse to the positive buss. A surge protection device such as a movistor can be connected from each positive lead to ground. (See the wiring diagrams for the system design examples in this manual.)

CONNECTIONS

Protect all connections. More system failures are caused by poorly made connections than by component failures.

Poorly made connections are the biggest cause of problems in stand-alone PV systems. Making a good connection requires the correct tools and connectors. Do the following:

- Use connectors--do not try to wrap bare wire around a terminal. Make sure the connector size and wire size are compatible.

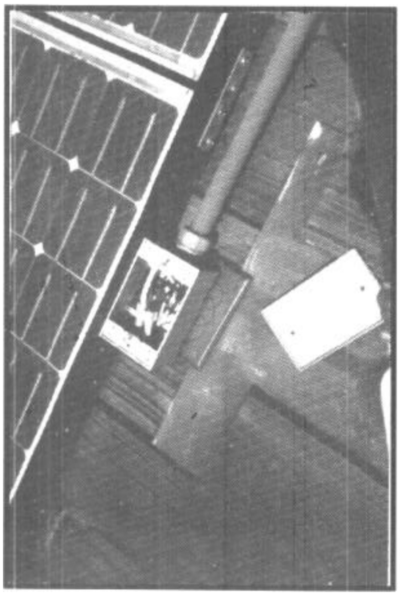
- Strip 3/8 to 1/2 inch of insulation from the wire and clean.

- Use a good quality crimp tool to attach the connector to the wire. A ring-type connector is superior to a spade-type connector because there is no possibility of the wire falling off the terminal.

- Solder the crimped connection. This is particularly important if the installation is in a marine environment or exposed to the weather. However, soldering makes a wire brittle and subject to breaking if the wire is repeatedly flexed near the connection.

- Use weather resistant boxes to make connections between sub-systems. Do not try to make more than two connections to the same terminal. Make sure the terminals and connectors are clean and of the same type of metal. Tighten firmly. Split bolt connectors should be used instead of terminal strips if the wire size is greater than No. 8. If disassembly is not required, soldered connections may also be used but only if the connection is electrically and mechanically sound before the soldering.

- Allow plenty of wire for entry and exit of the boxes. Use boxes with strain relief entrances and tighten the clamps firmly around the wires. After making the connection to the terminal, check each wire for strain relief.



- Test thoroughly after installation. Check the connector attachment--give it a pull test. Look for places where the connections or bare wire might touch the metal box or other metal equipment. Make sure the wires to the terminal strip are neatly aligned and do not overlap. Check entry and exit points for nicks or cuts in the wire insulation.

SYSTEM INSTALLATION

How should the array be grounded?

What about wind damage or lightning?

What kind of battery enclosures are needed?

Stand-alone PV systems will be reliable power producers for more than two decades if properly sized for the application, engineered well, and installed carefully. All electrical wiring should be done in accordance with the NEC and local codes. Some general guidance is given here.

Trying to save $ on installation of system components is false economy.

ARRAYS

PV arrays for stand-alone systems are installed in many unique and innovative ways. However, there are common issues involved in any installation, whether the array is fixed or tracking, mounted at ground level, or on a pole or building. The array orientation and tilt angle considerations are discussed in the section on PV arrays, page 29.

The objective is a solidly mounted PV array that will last for many years and withstand all kinds of weather. Regardless of whether you buy or build the mounting structure make sure it is anchored and the modules are restrained. Many module manufacturers and distributors sell mounting hardware specifically designed for their modules. This hardware is intended for multiple applications and different mounting techniques and considerations like wind loading have been included in the design. Using this mounting hardware is the simplest and often the most cost effective. Customized array mounting structures can be expensive. Consider the characteristics of various mounting materials:

Use materials that will last 20+ years.

- **Aluminum** - lightweight, strong, and resistant to corrosion. Aluminum angle is an easy material to work with, holes can be drilled with commonly available tools, and the material is compatible with many PV module frames. Aluminum is not easy to weld.

- **Angle Iron** - easy to work with but corrodes rapidly. Galvanizing will slow corrosion but mounting brackets and bolts will still rust, particularly in a wet environment. The material is readily available and brackets can be welded easily.

- **Stainless Steel** - expensive and difficult to work with but will last for decades. May be a good investment in salt spray environments.

- **Wood** - inexpensive, available, and easy to work with but may not withstand the weather for many years--even if treated with preservative. Attaching modules to a wooden frame requires battens or clips to hold them in place.

Figure 14 shows one mounting technique that has been used for small PV systems. Aluminum or galvanized angle can be used for the support struts, steel fence posts can be driven into the ground and the cross-beam can be made from treated wood, metal, or concrete. Galvanized U-bolts can be used to hold the cross-beams. Stainless steel bolts and nuts are recommended because they will not rust and portions of the array can be removed if future maintenance is required. The foundation for the array should be designed to meet the wind load requirements of the region. Wind load depends on the size of the array and the tilt angle. Ask a local contractor or your module distributor how to anchor your array to withstand the wind expected in your area.

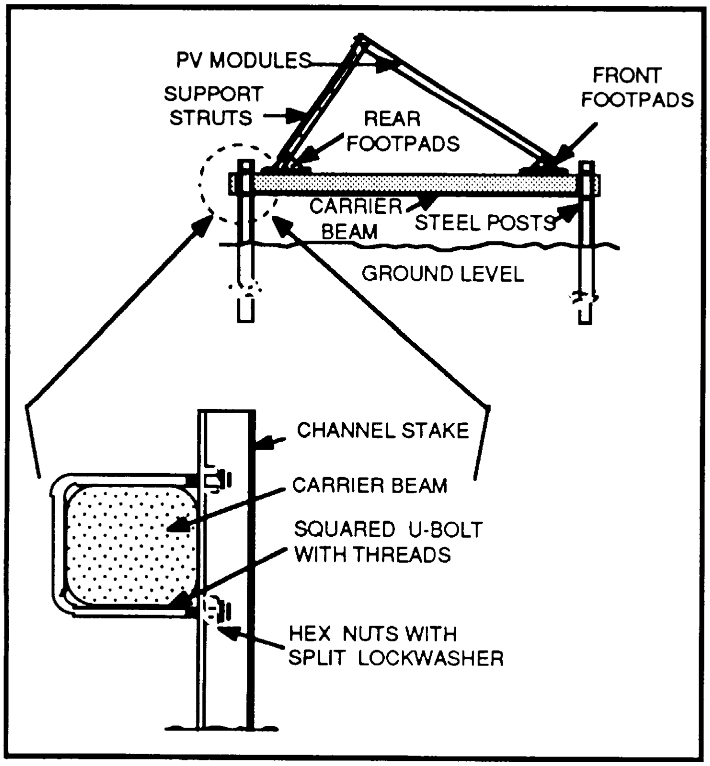


Figure 14. Simple Ground Mount for a PV Array.

Ground mounting of PV arrays is recommended for stand-alone sytems.

Changing the tilt angle of an array to account for seasonal changes in sun altitude is not required. For mid-latitude locations, a tilt angle change every three months is estimated to increase energy production about 5 percent on an annual basis. For most applications, the additional labor and the added complexity of the array mount does not justify the small increase in energy produced.

If tracking of the flat-plate array is desired, the recommended trackers are single axis units that require little control or power; see Figure 15. These are passive trackers driven by a closed Freon system that causes the tracker to follow the sun with adequate accuracy for flat-plate PV modules. In high wind areas a powered tracker may be preferred. Pole mounted trackers that support 4 to 12 PV modules are available and often used for small stand-alone systems, particularly water pumping applications. The tracker manufacturer will provide

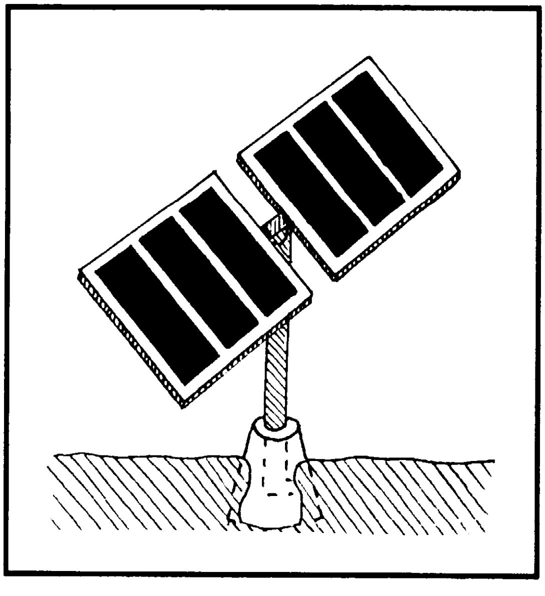


Figure 15. Passive Tracker for a PV Array.

all the array mounting hardware and instructions for securely installing the tracker. The amount and type of foundation for the pole-mounted tracker depends on the size of the array being supported. Reinforced concrete with anchor bolts is recommended. The foundation and frame should be designed to withstand the worst case wind expected in the area. The movement of the array should be checked to make sure the path is clear of obstructions.

Secure the array for worst-case windstorms.

In general, roof mounting of PV modules should be avoided. They are more difficult to install and maintain, particularly if the roof orientation and angle are not compatible with the optimum solar array tilt angle. Penetrating the roof seal is inevitable and leaks may occur. Also, it is important to achieve a firm and secure attachment of the array mounting brackets to the roof. Attaching the mounting brackets to the rafters will provide the best foundation, but this may be difficult because module size and rafter spacing are usually not compatible. If there is access to the underside of the roof, 2 x 6-inch blocks can be inserted between the rafters and the attachment made to the blocks. Attaching the array to the plywood sheathing of the roof may result in roof damage, particularly if high winds are likely.

If a roof mount is required, be sure to allow a clear air flow path up the roof under the array as shown in Figure 16. The array will operate cooler and produce more energy if it stands off the roof at least 3 inches, Flush mounting PV modules to the roof of a building is not recommended. The modules are more difficult to test and replace, and the performance of the array is decreased because of the higher operating temperatures,

BATTERIES

Batteries must be protected from the elements. If freezing temperatures are expected, the batteries can be buried below the frost line in a watertight enclosure or in a building where the temperature will remain above freezing. If the batteries are buried, a well-drained location should be selected and a drainhole provided in the battery enclosure. Batteries should not be set directly on concrete surfaces as self discharge will be increased,

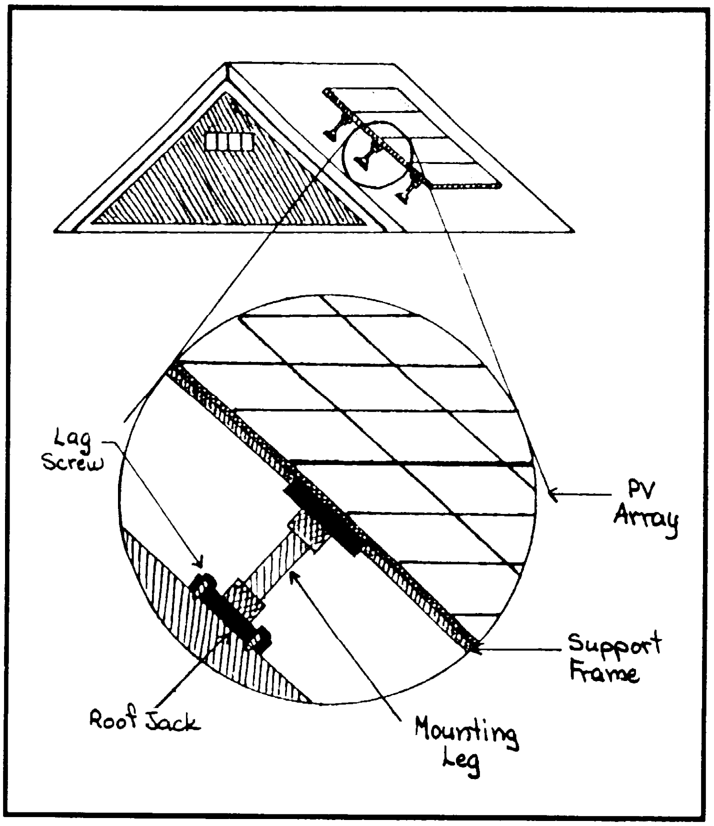


Figure 16. Roof Mount for a PV Array.

particularly if the surface gets damp. Adequate venting must be provided to minimize explosion hazard if open-cell batteries are used. Any battery should be stored in a location where access is limited to knowledgeable personnel. Never allow unsupervised children or pets near batteries.

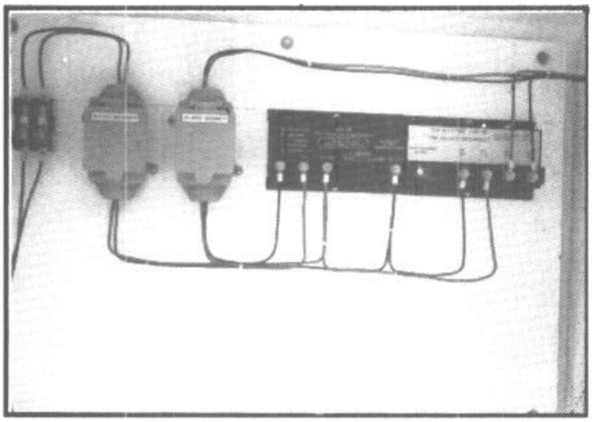
Do not set batteries on cold, damp surfaces.

Commercial battery enclosures may be available but are usually expensive. For small systems, a heavy-duty plastic tub may serve as an inexpensive alternative. Be sure it will withstand direct sunlight if the batteries are to be installed outdoors and above ground.

CONTROL CENTER

Electronic controllers, converters, or inverters are often installed in the control center along with switches, fuses, and other BOS. Electronic components must be able to withstand expected temperature extremes in both operating and non-operating states. Any printed circuit boards in these units should be coated or sealed to protect the electronics from humidity and dust. Certified electrical service boxes should be used. Consult any electrical supply company to get advice about the type of box needed for a specific application.

Install all switches, fuses, movistors and electronics in a protected J-box.



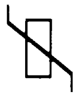
High temperatures will shorten the life of electronic equipment. Try to mount the boxes in a shaded area and/or provide air circulation, particularly for inverters. Dust can be a problem in a well-vented enclosure. Some boxes have filters at the air access points. Filters require regular cleaning. Screen the inlets of the electrical boxes to prevent spiders, wasps, and other insects from setting up residence. Finding wasps in the electrical box may not affect performance, but it will certainly make maintenance more exciting.

GROUNDING

A good ground will provide a well-defined, low-resistance path from the stand-alone PV system to earth ground. This path is expected to carry fault current if system malfunctions occur so the ground wire must be as large as the largest conductor in the system. Two types of grounding are needed in PV systems--system ground and equipment ground. For the system ground, one of the current carrying conductors, usually the negative, is grounded at a single point. This establishes the maximum voltage with respect to ground and also serves to discharge surge currents induced by lightning. Any exposed metal that might be touched by personnel should be grounded. This includes equipment boxes and array frames. This will limit the risk of electrical shock should a ground fault occur.

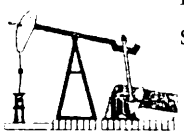
A low-resistance earth ground requires good contact between the ground rod and earth. Subterranean water lowers the resistivity of the contact. If the system is in an area with rocky soil, a good ground may be difficult to achieve. Consult a local electrician for suggestions.

A PV array can attract lightning, especially if located at a high elevation relative to the surrounding terrain. In particular, water pumping systems may draw lightning because of the excellent ground path provided by the well casing. Current surges can be caused by a direct lightning hit or by electromagnetic coupling of energy into the PV system's conductors.



Consider using lightning rods above arrays located on high ground.

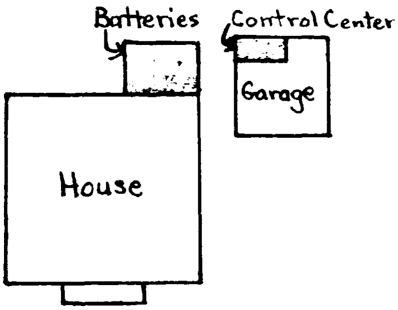
There is little that can be done to protect the PV system equipment from a direct lightning strike. Surges caused by near strikes occur more frequently and the severity of possible damage depends on the distance from the strike to the array. Commercially available surge protection devices (movistors and silicon oxide varistors) are reasonably priced and their use is recommended. They are normally installed in the array output and at the dc input to any electronic device. If an inverter is used, surge protection devices should be installed at the ac output as well as the dc input. Installing the wiring in grounded, buried metallic conduit will decrease susceptibility to lightning.



THE BROWN FAMILY PLAN THEIR SYSTEM INSTALLATION

Each family member was taught safe system operation and how to disconnect array power.

The Browns came to understand that a system is a collection of interactive components, and satisfactory operation is dependent on the reliability of each part. They were told that more system downtime is caused by failure of connections, switches, and fuses than failure of controllers, batteries or modules. These common failures can be avoided, to a large degree, with good installation practices. The Browns intended to supervise the installation of their system, so they studied the codes and regulation for electrical installations in their area. They contacted local authorities and asked what codes applied. They were particularly interested in safety issues, compliance with the NEC, convenience, and ease of maintenance. They carefully selected the location for their array, batteries, and control center. They planned to install the batteries, inverter, controller, and safety switches in a 100 square foot enclosure on the north side of their house. The wire run from batteries to inverter was less than 10 feet. The control/battery room would be attached to the house but could be accessed only from outside through double-wide, lockable doors. They made sure there would be good cross-flow ventilation in the insulated room. The PV array would be installed using the simple ground mounting technique described in this handbook. They would use lag screws to attach the panel frames to a treated wooden 4 x 4 carrier beam. They planned to buy the panel frames, and support hardware from the module manufacturer. By using this hardware, they would also be able to use the manufacturer designed wiring harness to electrically interconnect the PV modules. They would use conduit for all wire runs except the array to battery. For this, they would use No. 6 direct-burial cable. Number 6 wire was larger than required but would keep the voltage drop to just over 1 percent. With components on-hand and planning completed, the Browns started their installation project.



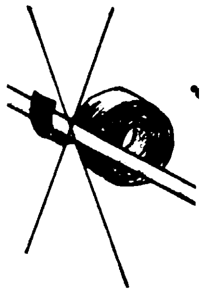
MAINTENANCE

How much maintenance will be required? ***Do I need special equipment or training?***

PERIODIC CHECKS

Preventive maintenance is the best maintenance! Periodic checks are recommended for any stand-alone PV system so that little problems can be found and corrected before they affect system operation. The system should be checked soon after installation when it is presumably operating well. Much of the checking can be done with only a voltmeter, a clamp-on ammeter, and some common sense. Many failures can be avoided if periodic checking is done and corrective action taken before the problems cause system failure. Do these recommended checks regularly:

Preventive maintenance is the best maintenance.



Check systems at least once a year.

- Check the tightness of all connections in the system. Battery connections should be cleaned and sealed with a corrosion inhibitor.

- Check the electrolyte level and add clean (distilled) water as necessary. Do not overfill the batteries. Measure the specific gravity of each cell in the battery every year. The specific gravity is an indicator of the battery state-of-charge but the measurements may be misleading if the electrolyte has stratified. Check specific gravity from different levels in the cell to see if the electrolyte is stratified. If stratification is present, the battery should be charged vigorously to mix the electrolyte. If the specific gravity reading of any cell is different from the others by 0.050 it may indicate a weak cell. Monitor this cell's performance to see if replacement is required.

- With the battery under load, check the voltage of each battery cell and compare it to the average of all cell voltages. If the voltage of any cell differs by 0.05 volts from the others, it indicates a possible problem. Monitor this cell's performance to see if replacement is required.

- Check the system wiring. If any wires are exposed, look for cracking or checking of the insulation. Inspect the entry and exit points from all junction boxes and look for breaks or cracks in the insulation. Replace wires if necessary. Do not rely on common black electrical tape for long-term repair of damaged insulation.

- Check that all junction boxes are closed and sealed. Inspect for water damage or corrosion. If electronic components are mounted in junction boxes, check for ventilation in the box. Change or clean air filters.

- Inspect the array mounting frame or tracking mechanism. Maintain any tie-down anchors.

- Check the operation of switches. Make sure the switch movement is solid. Look for corrosion or charring around contacts. Check fuses with a voltmeter. A good fuse will have almost no voltage drop when current is flowing. Look for discoloration at the fuse ends.

The designer should provide specific instructions for maintaining the system. Following that advice, doing these simple checks, and correcting any visible problem as soon as they appear will increase the system availability and extend its life.

TROUBLESHOOTING

If a known or suspected problem has occurred, it can usually be located by following a logical progression of tests and analyzing the results. Basic tests can be completed with simple tools such as a voltmeter, clamp-on ammeter, hydrometer, pliers, screwdrivers, and crescent wrenches. Gloves, safety glasses, (for working around batteries), and rubber-soled shoes are recommended. Remove jewelry before testing any electrical circuits. Have two people working together to test the system. Before testing, make sure that both persons know where the power disconnect switches are and how to operate them. Safety first! Remember a PV array will produce power any time the sun is shining and any array that contains more than two modules can produce enough electricity to kill a human being under worst-case conditions. Always measure the voltage present before touching a wire or connector and never disconnect a wire before knowing what voltage and current are

Safety first

Figure 17 gives some general guidance for finding problems in stand-alone PV systems with batteries. Check the simple things first. Look for blown fuses, tripped breakers, or bad connections. Repair as necessary. Check the status lights, if any, on the controller. Next, check the loads. The appliances or pumps, etc. may have blown a fuse or failed. Check to see if the correct voltage and current are present at the load input. If you have another load that can be plugged into that circuit see if it will work. If it does, the original appliance is suspect. If the correct voltage is not present, check the battery voltage. If the correct voltage is present at the output, check the circuit between the battery and the load. Recharge the battery if the battery voltage is low. You can also check the voltage and specific gravity of each cell and look for weak cells. If the battery voltage is low (less than 11.0 volts on a 12 volt system) the problem may be with the controller. (Has the weather been cloudy for a long period--if so, there may be no system problem.) Check the input voltage at the controller, Is it equal to the battery voltage? If so, the controller has the array connected to the battery, Is a charging current flowing from the array? If yes, you may want to disconnect the load(s) and let the array charge the battery. If no current is flowing or if the voltage at the controller input equals the open-circuit voltage of the array, the controller may have failed. If the

Check the simple things first.

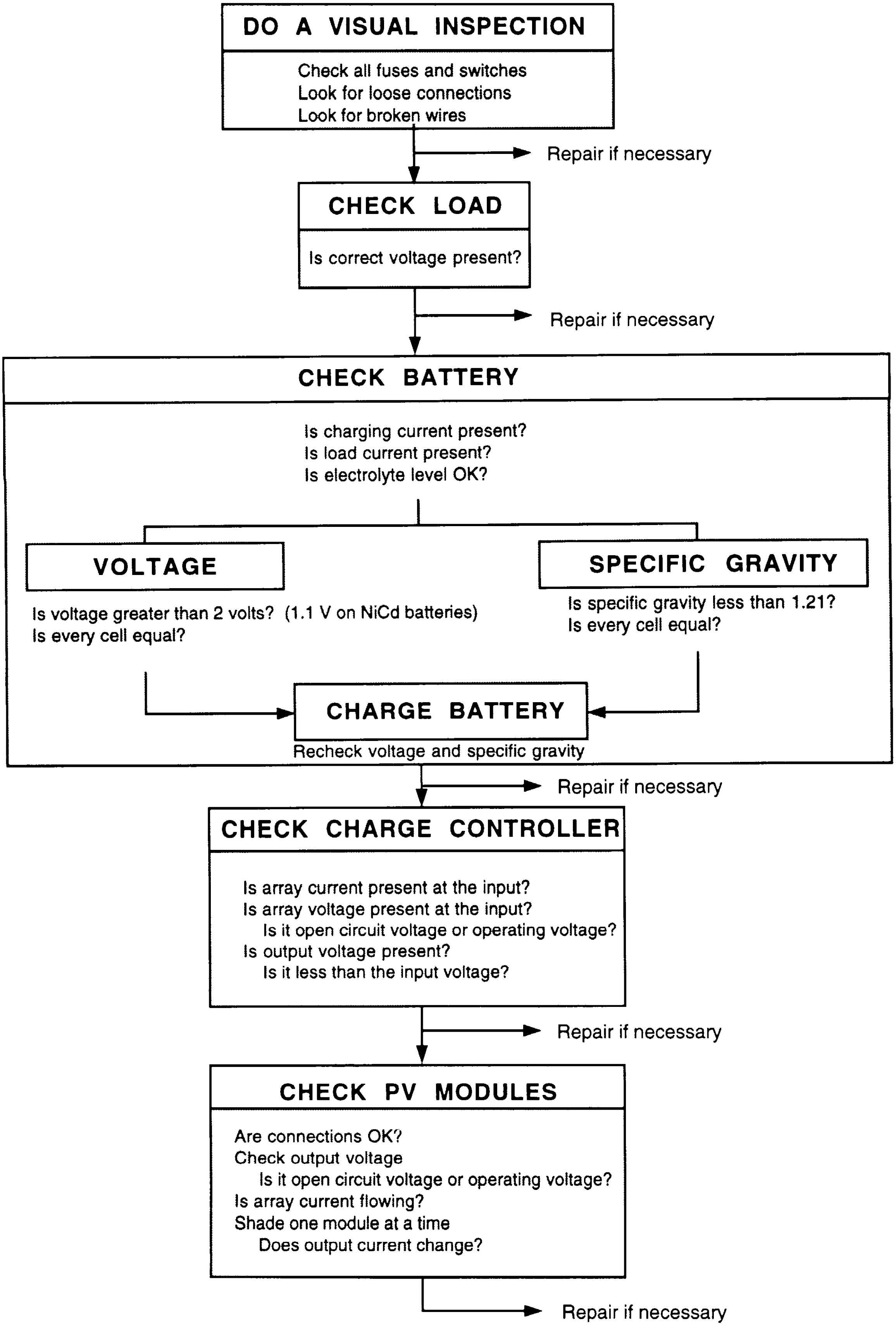
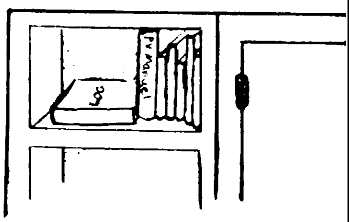


Figure 17. Troubleshooting Guide.

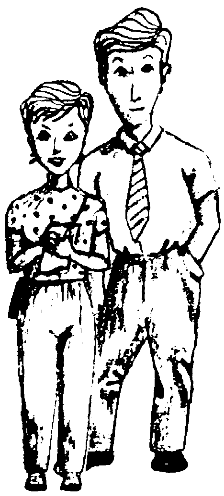
controller is okay, test the array. Measure the voltage at the output. You may want to bypass the controller and connect the array directly to the battery-check for current. Shade each module in turn and see if the current changes. Be sure to return the system to its original configuration when you have finished troubleshooting.

If the loads operate sometimes and you suspect the quantity of power being produced, the problem may be more difficult to locate. The power output of a stand-alone PV system varies with conditions, and checking the system performance requires simultaneous measurement of the existing solar conditions, the temperature, and the power output from the system. This may require specific test equipment and expertise that is not widely available. Contact your system designer or installer if you suspect a decrease in system performance but you can locate no problems.

THE BROWN FAMILY DEVELOP A MAINTENANCE PLAN



The Browns bought a notebook and recorded all system data in it.



The Browns wanted their PV system to include sensors and meters so they could monitor system performance and be alert to potential trouble. They took photographs as their system was installed and included this photographic record in a log book they planned to keep as a record of all system events. They put this and all other system documentation on a shelf near the control center.

They ordered an operations manual complete with all system schematics, component specifications, warranties, preventive maintenance procedures, and a troubleshooting guide. They spent several hours studying the system documentation, and each family member was taught how to disconnect the array power and electrically isolate the battery bank. They put a sign over the array disconnect switch that reminded them that the dc side of the disconnect would have voltage present anytime the sun was shining.

They plan to inspect the system every month for the first year and every three months thereafter. They plan to tighten connections, clean equipment boxes, and look for corrosion. They will check the level on the battery electrolyte and correct the little things that may save them money over the long term. The system should serve them well--if they take care of it, it will take care of them.

ECONOMICS: LIFE-CYCLE COST

How do I compare the cost of alternative systems?

DESCRIPTION

Doing a life-cycle cost analysis (LCC) gives you the total cost of your PV system--including all expenses incurred over the life of the system. There are two reasons to do an LCC analysis: 1) to compare different power options, and 2) to determine the most cost-effective system designs. For some applications there are no options to small PV systems so comparison of other power supplies is not an issue. The PV system produces power where there was no power before. For these applications the initial cost of the system is the main concern. However, even if PV power is the only option, a life-cycle cost (LCC) analysis can be helpful for comparing costs of different designs and/or determining whether a hybrid system would be a cost-effective option. An LCC analysis allows the designer to study the effect of using different components with different reliabilities and lifetimes. For instance, a less expensive battery might be expected to last 4 years while a more expensive battery might last 7 years. Which battery is the best buy? This type of question can be answered with an LCC analysis.

Some agencies might want to compare the cost of different power supply options such as photovoltaics, fueled generators, or extending utility power lines. The initial costs of these options will be different as will the costs of operation, maintenance, and repair or replacement. A LCC analysis can help compare the power supply options. The LCC analysis consists of finding the present worth of any expense expected to occur over the reasonable life of the system. To be included in the LCC analysis, any item must be assigned a cost, even though there are considerations to which a monetary value is not easily attached. For instance, the cost of a gallon of diesel fuel may be known; the cost of storing the fuel at the site may be estimated with reasonable confidence; but, the cost of pollution caused by the generator may require an educated guess. Also, the competing power systems will differ in performance and reliability. To obtain a good comparison, the reliability and performance must be the same. This can be done by upgrading the design of the least reliable system to match the power availability of the best. In some cases, you may have to include the cost of redundant components to make the reliability of the two systems equal. For instance, if it takes one month to completely rebuild a diesel generator, you should include the cost of a replacement unit in the LCC calculation. A meaningful LCC comparison can only be made if each system can perform the same work with the same reliability.

LCC analysis is a tool to compare the cost of alternative systems.

LCC analysis can be used to study the effect of changing economic variables.

LCC CALCULATION

The life-cycle cost of a project can be calculated using the formula:

$$LCC = C + M_{pw} + E_{pw} + R_{pw} - S_{pw}.$$

where the pw subscript indicates the present worth of each factor.

The capital cost (C) of a project includes the initial capital expense for equipment, the system design, engineering, and installation. This cost is always considered as a single payment occurring in the initial year of the project, regardless of how the project is financed.

Maintenance (M) is the sum of all yearly scheduled operation and maintenance (O&M) costs. Fuel or equipment replacement costs are not included. O&M costs include such items as an operator's salary, inspections, insurance, property tax, and all scheduled maintenance.

The energy cost (E) of a system is the sum of the yearly fuel cost. Energy cost is calculated separately from operation and maintenance costs, so that differential fuel inflation rates may be used.

Replacement cost (R) is the sum of all repair and equipment replacement cost anticipated over the life of the system. The replacement of a battery is a good example of such a cost that may occur once or twice during the life of a PV system. Normally, these costs occur in specific years and the entire cost is included in those years.

Convert all values to their present worth.

Salvage value is usually 10 to 20 percent of original cost.

The salvage value (S) of a system is its net worth in the final year of the life-cycle period. It is common practice to assign a salvage value of 20 percent of original cost for mechanical equipment that can be moved. This rate can be modified depending on other factors such as obsolescence and condition of equipment.

Future costs must be discounted because of the time value of money. One dollar received today is worth more than the promise of $1 next year, because the $1 today can be invested and earn interest. Future sums of money must also be discounted because of the inherent risk of future events not occurring as planned. Several factors should be considered when the period for an LCC analysis is chosen. First is the life span of the equipment. PV modules should operate for 20 years or more without failure. To analyze a PV system over a 5-year period would not give due credit to its durability and reliability. Twenty years is the normal period chosen to evaluate PV projects. However, most engine generators won't last 20 years so replacement costs for this option must be factored into the calculation if a comparison is to be made.

To discount future costs, the multipliers presented in Tables 3 and 4 can be used. Table 3 lists Single Present Worth factors. These are used to discount a cost expected to occur in a specific year, such as a battery replacement in year 10 of a project. Table 4 lists Uniform Present Worth factors. These are used to discount annually recurring costs, such as the annual fuel cost of a generator. To use the tables, simply select the column under the appropriate discount rate and read the multiplier opposite the correct year or span of years.

The discount rate used has a large effect on LCC results.

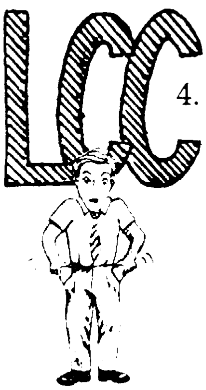
The discount rate selected for an LCC analysis has a large effect on the final results. It should reflect the potential earnings rate of the system owner. Whether the owner is a national government, small village, or an individual, money spent on a project could have been invested elsewhere and earned a certain rate of return. The nominal investment rate, however, is not an investor's real rate of return on money invested. Inflation, the tendency of prices to rise over time, will make future earnings worth less. Thus, inflation must be subtracted from an investor's nominal rate of return to get the net discount rate (or real opportunity cost of capital). For example, if the nominal investment rate was 7 percent, and general inflation was assumed to be 2 percent over the LCC period, the net discount rate that should be used would be 5 percent.

Use 20-30 years for a PV system evaluation.

A low discount rate increases future cost--a high discount rate emphasizes initial costs.

Different discount rates can be used for different commodities. For instance, fuel prices may be expected to rise faster than general inflation. In this case, a lower discount rate would be used when dealing with future fuel costs. In the example above the net discount rate was assumed to be 5 percent. If the cost of diesel fuel was expected to rise 1 percent faster than the general inflation rate, then a discount rate of 4 percent would be used for calculating the present worth of future fuel costs. Check with your local bank for their guess about future inflation rates for various goods and services. You have to make an estimate about future rates, realizing that an error in your guess can have a large affect on the LCC analysis results. If you use a discount rate that is too low, the future costs will be exaggerated; using a high discount rate does just the opposite, emphasizing initial costs over future costs. You may want to perform an LCC analysis with "high, low and medium" estimates on future rates to put bounds on the life-cycle cost of alternative systems.

LCC can be used to analyze investment decisions.



TECHNICAL NOTES

1. The formula for the single present worth (P) of a future sum of money (F) in a given year (N) at a given discount rate (I) is

$$P = F/(1 + I)^N.$$

2. The formula for the uniform present worth (P) of an annual sum (A) received over a period of years (N) at a given discount rate (I) is

$$P = A[1 - (1 + I)^{-N}]/I.$$

3. The formula for the modified uniform present worth of an annual sum (A) that escalates at a rate (E) over a period of years (N) at a given discount rate (I) is

4. The formula for the annual payment (A) on a loan whose principal is (P) at an interest rate (I) for a given period of years (N) is

$$A = P\{I/[1 - (1 + I)^{-N}]\}.$$

TABLE 3
Single Present Worth Factors

Net Discount Rate

Year	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.10	0.11	0.12
1	0.990	0.980	0.971	0.962	0.952	0.943	0.935	0.926	0.917	0.909	0.901	0.893
2	0.980	0.961	0.943	0.925	0.907	0.890	0.873	0.857	0.842	0.826	0.812	0.797
3	0.971	0.942	0.915	0.889	0.864	0.840	0.816	0.794	0.772	0.751	0.731	0.712
4	0.961	0.924	0.888	0.855	0.823	0.792	0.763	0.735	0.708	0.683	0.659	0.636
5	0.951	0.906	0.863	0.822	0.784	0.747	0.713	0.681	0.650	0.621	0.593	0.567
6	0.942	0.888	0.837	0.790	0.746	0.705	0.666	0.630	0.596	0.564	0.535	0.507
7	0.933	0.871	0.813	0.760	0.711	0.665	0.623	0.583	0.547	0.513	0.482	0.452
8	0.923	0.853	0.789	0.731	0.677	0.627	0.582	0.540	0.502	0.467	0.434	0.404
9	0.914	0.837	0.766	0.703	0.645	0.592	0.544	0.500	0.460	0.424	0.391	0.361
10	0.905	0.820	0.744	0.676	0.614	0.558	0.508	0.463	0.422	0.386	0.352	0.322
11	0.896	0.804	0.722	0.650	0.585	0.527	0.475	0.429	0.388	0.350	0.317	0.287
12	0.887	0.788	0.701	0.625	0.557	0.497	0.444	0.397	0.356	0.319	0.286	0.257
13	0.879	0.773	0.681	0.601	0.530	0.469	0.415	0.368	0.326	0.290	0.258	0.229
14	0.870	0.758	0.661	0.577	0.505	0.442	0.388	0.340	0.299	0.263	0.232	0.205
15	0.861	0.743	0.642	0.555	0.481	0.417	0.362	0.315	0.275	0.239	0.209	0.183
16	0.853	0.728	0.623	0.534	0.458	0.394	0.339	0.292	0.252	0.218	0.188	0.163
17	0.844	0.714	0.605	0.513	0.436	0.371	0.317	0.270	0.231	0.198	0.170	0.146
18	0.836	0.700	0.587	0.494	0.416	0.350	0.296	0.250	0.212	0.180	0.153	0.130
19	0.828	0.686	0.570	0.475	0.396	0.331	0.277	0.232	0.194	0.164	0.138	0.116
20	0.820	0.673	0.554	0.456	0.377	0.312	0.258	0.215	0.178	0.149	0.124	0.104
21	0.811	0.660	0.538	0.439	0.359	0.294	0.242	0.199	0.164	0.135	0.112	0.093
22	0.803	0.647	0.522	0.422	0.342	0.278	0.226	0.184	0.150	0.123	0.101	0.083
23	0.795	0.634	0.507	0.406	0.326	0.262	0.211	0.170	0.138	0.112	0.091	0.074
24	0.788	0.622	0.492	0.390	0.310	0.247	0.197	0.158	0.126	0.102	0.082	0.066
25	0.780	0.610	0.478	0.375	0.295	0.233	0.184	0.146	0.116	0.092	0.074	0.059
26	0.772	0.598	0.464	0.361	0.281	0.220	0.172	0.135	0.106	0.084	0.066	0.053
27	0.764	0.586	0.450	0.347	0.268	0.207	0.161	0.125	0.098	0.076	0.060	0.047
28	0.757	0.574	0.437	0.333	0.255	0.196	0.150	0.116	0.090	0.069	0.054	0.042
29	0.749	0.563	0.424	0.321	0.243	0.185	0.141	0.107	0.082	0.063	0.048	0.037
30	0.742	0.552	0.412	0.308	0.231	0.174	0.131	0.099	0.075	0.057	0.044	0.033
35	0.706	0.500	0.355	0.253	0.181	0.130	0.094	0.068	0.049	0.036	0.026	0.019
40	0.672	0.453	0.307	0.208	0.142	0.097	0.067	0.046	0.032	0.022	0.015	0.011
45	0.639	0.410	0.264	0.171	0.111	0.073	0.048	0.031	0.021	0.014	0.009	0.006
50	0.608	0.372	0.228	0.141	0.087	0.054	0.034	0.021	0.013	0.009	0.005	0.003
55	0.579	0.337	0.197	0.116	0.068	0.041	0.024	0.015	0.009	0.005	0.003	0.002
60	0.550	0.305	0.170	0.095	0.054	0.030	0.017	0.010	0.006	0.003	0.002	0.001
65	0.524	0.276	0.146	0.078	0.042	0.023	0.012	0.007	0.004	0.002	0.001	0.001
70	0.498	0.250	0.126	0.064	0.033	0.017	0.009	0.005	0.002	0.001	0.001	0.000
75	0.474	0.226	0.109	0.053	0.026	0.013	0.006	0.003	0.002	0.001	0.000	0.000

TABLE 4
Uniform Present Worth Factors

Net Discount Rate

Year	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.10	0.11	0.12
1	0.990	0.980	0.971	0.962	0.952	0.943	0.935	0.926	0.917	0.909	0.901	0.893
2	1.970	1.942	1.913	1.886	1.859	1.833	1.808	1.783	1.759	1.736	1.713	1.690
3	2.941	2.884	2.829	2.775	2.723	2.673	2.624	2.577	2.531	2.487	2.444	2.402
4	3.902	3.808	3.717	3.630	3.546	3.465	3.387	3.312	3.240	3.170	3.102	3.037
5	4.853	4.713	4.580	4.452	4.329	4.212	4.100	3.993	3.890	3.791	3.696	3.605
6	5.795	5.601	5.417	5.242	5.076	4.917	4.767	4.623	4.486	4.355	4.231	4.111
7	6.728	6.472	6.230	6.002	5.786	5.582	5.389	5.206	5.033	4.868	4.712	4.564
8	7.652	7.325	7.020	6.733	6.463	6.210	5.971	5.747	5.535	5.335	5.146	4.968
9	8.566	8.162	7.786	7.435	7.108	6.802	6.515	6.247	5.995	5.759	5.537	5.328
10	9.471	8.983	8.530	8.111	7.722	7.360	7.024	6.710	6.418	6.145	5.889	5.650
11	10.368	9.787	9.253	8.760	8.306	7.887	7.499	7.139	6.805	6.495	6.207	5.938
12	11.255	10.575	9.954	9.385	8.863	8.384	7.943	7.536	7.161	6.814	6.492	6.194
13	12.134	11.348	10.635	9.986	9.394	8.853	8.358	7.904	7.487	7.103	6.750	6.424
14	13.004	12.106	11.296	10.563	9.899	9.295	8.745	8.244	7.786	7.367	6.982	6.628
15	13.865	12.849	11.938	11.118	10.380	9.712	9.108	8.559	8.061	7.606	7.191	6.811
16	14.718	13.578	12.561	11.652	10.838	10.106	9.447	8.851	8.313	7.824	7.379	6.974
17	15.562	14.292	13.166	12.166	11.274	10.477	9.7.63	9.122	8.544	8.022	7.549	7.120
18	16.398	14.992	13.754	12.659	11.690	10.828	10.059	9.372	8.756	8.201	7.702	7.250
19	17.226	15.678	14.324	13.134	12.085	11.158	10.336	9.604	8.950	8.365	7.839	7.366
20	18.046	16.351	14.877	13.590	12.462	11.470	10.594	9.818	9.129	8.514	7.963	7.469
21	18.857	17.011	15.415	14.029	12.821	11.764	10.836	10.017	9.292	8.649	8.075	7.562
22	19.660	17.658	15.937	14.451	13.163	12.042	11.061	10.201	9.442	8.772	8.176	7.645
23	20.456	18.292	16.444	14.857	13.489	12.303	11.272	10.371	9.580	8.883	8.266	7.718
24	21.243	18.914	16.936	15.247	13.799	12.550	11.469	10.529	9.707	8.985	8.348	7.784
25	22.023	19.523	17.413	15.622	14.094	12.783	11.654	10.675	9.823	9.077	8.422	7.843
26	22.795	20.121	17.877	15.983	14.375	13.003	11.826	10.810	9.929	9.161	8.488	7.896
27	23.560	20.707	18.327	16.330	14.643	13.211	11.987	10.935	10.027	9.237	8.548	7.943
28	24.316	21.281	18.764	16.663	14.898	13.406	12.137	11.051	10.116	9.307	8.602	7.984
29	25.066	21.844	19.188	16.984	15.141	13.591	12.278	11.158	10.198	9.370	8.650	8.022
30	25.808	22.396	19.600	17.292	15.372	13.765	12.409	11.258	10.274	9.427	8.694	8.055
35	29.409	24.999	21.487	18.665	16.374	14.498	12.948	11.655	10.567	9.644	8.855	8.176
40	32.835	27.355	23.115	19.793	17.159	15.046	13.332	11.925	10.757	9.779	8.951	8.244
45	36.095	29.490	24.519	20.720	17.774	15.456	13.606	12.108	10.881	9.863	9.008	8.283
50	39.196	31.424	25.730	21.482	18.256	15.762	13.801	12.233	10.962	9.915	9.042	8.304
55	42.147	33.175	26.774	22.109	18.633	15.991	13.904	12.319	11.014	9.947	9.062	8.317
60	44.955	34.761	27.676	22.623	18.929	16.161	14.039	12.377	11.048	9.967	9.074	8.324
65	47.627	36.197	28.453	23.047	19.161	16.289	14.110	12.416	11.070	9.980	9.081	8.328
70	50.169	37.499	29.123	23.395	19.343	16.385	14.160	12.443	11.084	9.987	9.085	8.330
75	52.587	38.677	29.702	23.680	19.485	16.456	14.196	12.461	11.094	9.992	9.087	8.332

TABLE 5
Yearly Principal and Interest Per $1,000 Loan

Loan Rate		5-Year Loan	10-Year Loan	15-Year Loan	20-Year Loan	25-Year Loan
0.05		$230.97	$129.50	$96.34	$80.24	$70.95
0.0525		$232.57	$131.08	$97.98	$81.95	$72.74
0.055		$234.18	$132.67	$99.63	$83.68	$74.55
0.0575		$235.78	$134.26	$101.29	$85.42	$76.38
0.06		$237.40	$135.87	$102.96	$87.18	$78.23
0.0625		$239.01	$137.48	$104.65	$88.96	$80.09
0.065		$240.63	$139.10	$106.35	$90.76	$81.98
0.0675		$242.26	$140.74	$108.07	$92.57	$83.89
0.07		$243.89	$142.38	$109.79	$94.39	$85.81
0.0725		$245.53	$144.03	$111.53	$96.23	$87.75
0.075		$247.16	$145.69	$113.29	$98.09	$89.71
0.0775		$248.81	$147.35	$115.05	$99.96	$91.69
0.08		$250.46	$149.03	$116.83	$101.85	$93.68
0.0825		$252.11	$150.71	$118.62	$103.75	$95.69
0.085		$253.77	$152.41	$120.42	$105.67	$97.71
0.0875		$255.43	$154.11	$122.23	$107.60	$99.75
0.09		$257.09	$155.82	$124.06	$109.55	$101.81
0.0925		$258.76	$157.54	$125.90	$111.50	$103.88
0.095		$260.44	$159.27	$127.74	$113.48	$105.96
0.0975		$262.11	$161.00	$129.60	$115.46	$108.06
0.1		$263.80	$162.75	$131.47	$117.46	$110.17
0.1025		$265.48	$164.50	$133.36	$119.47	$112.29
0.105		$267.18	$166.26	$135.25	$121.49	$114.43
0.1075		$268.87	$168.03	$137.15	$123.53	$116.58
0.11		$270.57	$169.80	$139.07	$125.58	$118.74
0.1125		$272.27	$171.59	$140.99	$127.63	$120.91
0.115		$273.98	$173.38	$142.92	$129.70	$123.10
0.1175		$275.69	$175.18	$144.87	$131.79	$125.29
0.12		$277.41	$176.98	$146.82	$133.88	$127.50
0.1225		$279.13	$178.80	$148.79	$135.98	$129.72
0.125		$280.85	$180.62	$150.76	$138.10	$131.94
0.1275		$282.58	$182.45	$152.75	$140.22	$134.18

MULTIPLY THE COST PER $1000 BY THE SIZE OF THE LOAN (IN THOUSANDS OF DOLLARS)

THE BROWN FAMILY DOES A LIFE-CYCLE COST ANALYSIS

The Browns used the life-cycle cost worksheet to compare PV and propane systems.

When the Brown Family was planning their home, they considered two options for providing electricity--the use of a diesel generator and the installation of a stand-alone PV system. They considered the reliability and power availability of these two options to be equal if both systems were maintained in good condition throughout their operational life spans. However, they expected to make three replacements (or rebuilds) of the generator over the 20-year period. They performed the following LCC analysis to help them determine the total cost the two options. They used the LCC Worksheet in Appendix B for eachexample.

LIFE-CYCLE COST ANALYSIS

PROJECT DESCRIPTION: Brown Family/Generator System

ECONOMIC PARAMETERS:

1. Years in Life-Cycle: 20
2. Investment Rate: 7
3. General Inflation Rate: 4
4. Fuel Inflation Rate: 5

Net Discount Rate (2-3) = 3 Differential Fuel Inflation (4-3) = 1

Item	Single Present Worth Year	Uniform Present Worth Years	Dollar Amount		Present Worth Factor (Table 4 or 5)		Present Worth Amount
1. Capital Equipment and installation			7,800	X	1	=	$7,800
2. Operation and Maintenance							
• Labor: Tune-up		20	120	X	14.88	=	1,785
• Yearly Inspection		20	75	X	14.88	=	1,115
• Insurance				X		=	
• Other				X		=	
3. Energy Costs							
• Generator Fuel		20	200	X	18.05	=	3,610
• (Discount Rate = .02)				X		=	
4. Repair and Replacement							
Battery Bank	8		1,500	x	.789	=	1,185
• Battery Bank	16		1,500	X	.623	=	935
• Generator Rebuild	5		1,200	X	.863	=	1,035
• Generator Rebuild	10		1,200	X	.744	=	890
• Generator Rebuild	15		1,200	X	.642	=	770
•				X		=	
5. Salvage							
• 20% Original	20		1,360	X	.258	=	(350)
• Equip. Cost ($6,800)				X		=	
TOTAL LIFE-CYCLE COST	(ITEMS 1 + 2 + 3 + 4 - 5)						$18,775

NOTES

LCC for Generator System

The proposed generator system consisted of a 4-kilowatt generator, a 500 ampere-hour battery bank, and a 2.5-kilowatt inverter. The initial installation cost of this system was calculated to be $7,800 U.S. dollars, including design and engineering. The generator would consume $200 a year in fuel, require annual inspections ($75/year) and tune-ups ($120/year), and have to be rebuilt every 5 years at an estimated cost of $1,200. In addition, the battery bank would have to be replaced every 8 years.

The PV system consisted of a 600-watt array, a 950-ampere-hour battery, and a 2.5-kilowatt inverter. The cost of designing and installing this system was estimated to be $10,800. The only future cost for this system was replacing the batter) bank every 8 years and a yearly inspection at $75 per year.

The life-cycle period was set at 20 years to coincide with the expected life of the PV power system. Mrs. Brown thought the family could earn a 7 percent rate of return on a 20 year fixed investment, and general inflation was assumed to be 4 percent a year. Thus, their net discount rate was set at 3 percent. Fuel inflation was estimated to be 5 percent a year so the differential fuel inflation was set at 1 percent (5 percent fuel inflation minus 4 percent general inflation). Having made the basic assumptions for each system the family filled out the LCC sheet in Appendix B for both alternatives.

LIFE-CYCLE COST ANALYSIS

PROJECT DESCRIPTION: Brown Family/PV System

ECONOMIC PARAMETERS:

1. Years in Life-Cycle: 20
2. Investment Rate: 7
3. General Inflation Rate: 4
4. Fuel Inflation Rate: 5

Net Discount Rate (2-3) = 3

Differential Fuel Inflation (4-3) = 1

Item	Single Present Worth Year	Uniform Present Worth Years	Dollar Amount		Present Worth Factor (Table 4 or 5)		Present Worth Amount
1. Capital Equipment and Installation			10,800	X	1	=	$10,800
2. Operation and Maintenance							
• Labor: Yearly Inspection		20	75	X	14.88	=	1,115
• Materials				X		=	
• Insurance				X		=	
• Other				X		=	
3. Energy Costs							
•				X		=	
•				X		=	
4. Repair and Replacement							
• Battery Bank	8		2,850	X	.789	=	2,250
• Battery Bank	16		2,850	X	.623	=	1,775
•				X		=	
•				X		=	
•				X		=	
•				X		=	
5. Salvage							
• 20% Original Equip. Cost ($10,500)	20		2,160	X	.258	=	(560)
				X		=	
TOTAL LIFE-CYCLE COST	(ITEMS 1 + 2 + 3 + 4 - 5)						$15,380

NOTES:

LCC for PV System

The initial capital cost of each system is treated as a payment that occurs in Year 0 of the life-cycle. Even if the money is borrowed, the initial cost is not discounted because financing costs should not be included in any life-cycle cost analysis.

The yearly tune-up cost is calculated under the maintenance heading. This is an annually recurring cost and is discounted using Table 4 at a 3 percent net discount rate. (For the 20 years the factor is 14.877. The annual inspection cost is multiplied by this factor to obtain the present worth estimate.) Energy cost is also an annual cost and is handled the same way, except the discount rate used is differential fuel inflation rate of 1 percent.

Repair costs are discounted using the 3 percent net discount rate and Table 3. At a 3 percent discount rate, the factor for year 8 is 0.789. The repair cost is multiplied by this factor and entered into the presentworth column. This is done for each individual repair, in this case, two battery replacements and three generator rebuilds.

The final cost factor is salvage. Here, 20 percent of the original value of each system's hardware is entered and discounted in year 20. A 7 percent discount rate is used because inflation is not a factor in the salvage value computation.

The present worth figures can now be added, subtracting the salvage value, to give the life-cycle cost of each system. The generator system cost was $18,775 while the LCC of the PV system was $15,380. Since the PV system costs less and provides silent power reliably, the Brown Family confirmed the economic feasibility of their desire to invest in a PV system.

After deciding on the PV system, the Browns wanted to check the annual financing cost of their PV system so they could estimate their cash flow requirements. Using the loan payment chart given in Table 5, they calculated the principal and interest on the $10,500 initial system cost. The result was $991.09 per year or about $83 per month for 20 years assuming a 7 percent interest rate. The Browns felt the independence provided by their PV system was a big bargain.

LIFE-CYCLE COST COMPARISON

Item	Present Worth Generator System	Present Worth PV System
1. Capital Equipment and Installation	$7,800	$10,800
2. Operation and Maintenance		
• Labor: Tune-up	1,785	1,115
• Yearly Inspection	1,115	
• Insurance		
• Other		
3. Energy Costs		
• Generator Fuel	3,610	–
• (Discount Rate = .02)		
4. Repair and Replacement		
• Battery Bank, yr. 8	1,185	2,250
• Battery Bank, yr. 16	935	1,775
• Generator Rebuild, yr. 5	1,035	
• Generator Rebuild, yr. 10	890	
• Generator Rebuild, yr. 15	770	
5. Salvage		
• 20% Original	(350)	(560)
TOTAL LIFE-CYCLE COST	$18,775	$15,380

NOTES:

Go PV