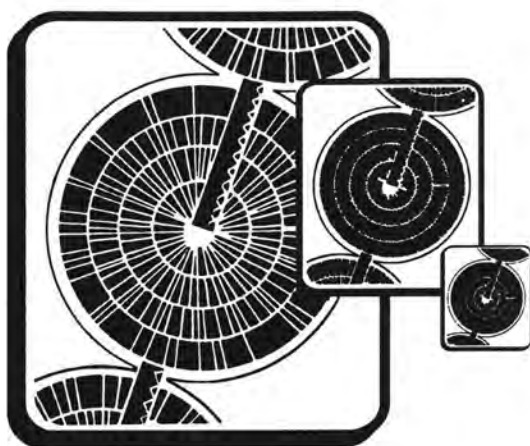


Photovoltaic System Design



Course Manual

FSEC-GP-31-86

Revised April 1996

Florida Solar Energy Center[®]
Cocoa, Florida

Prepared with assistance from the NASA Lewis Research Center

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Photovoltaic System Design

Course Objectives

- 1) *Design and size stand-alone photovoltaic (PV) systems utilizing battery storage.*
- 2) *Produce component and system specifications to be used in the design and procurement process.*
- 3) *Compare the economics of various types of stand-alone electric generation systems.*
- 4) *Compare and contrast utility-interactive PV systems and stand-alone PV systems.*
- 5) *Apply key PV definitions and concepts to the PV system design process.*

Approach to the Course

- 1) *Emphasis is placed on real world industry design practices. Device physics, mathematical modelling and theory are kept to a minimum.*
- 2) *Familiarity with and use of actual system designs and product specifications are stressed.*
- 3) *For utility-interactive systems, the focus is on residential applications and establishing reasonable interconnection requirements.*



Introduction

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Introduction

1

Objectives

- 1) *Identify PV system design requirements.*
- 2) *List stand-alone and utility-interactive photovoltaic applications.*

Key Words

Stand-alone photovoltaic system

Hybrid system

Utility-interactive photovoltaic system

1.1 Introduction and Overview

The objectives of this photovoltaic system design manual are to:

- develop an understanding of photovoltaic fundamentals
- develop the ability to design stand-alone photovoltaic systems
- develop the ability to analyze the economics of photovoltaic vs alternative systems.

The manual and associated course were developed primarily for designers of photovoltaic systems. However, this information should be of value to all those who sell, install, operate, maintain and monitor photovoltaic systems, as well as those who select and procure photovoltaic systems.

1.1.1 Establish PV System Design Requirements

Let's organize our thinking about photovoltaics and PV system design. The five major elements to consider when properly designing a photovoltaic system are:

- the energy source (i.e., the sun)
- the energy conversion process (which takes place in the photovoltaic array)
- energy distribution (i.e., the proper flow of electricity through wires and other components)
- energy storage (typically as chemical bonds in batteries)
- energy use (by electrical appliances or loads).

Major tasks in the design process are:

- assessing customer needs
- establishing design requirements
- sizing batteries and arrays
- producing electrical and mechanical designs
- documenting the final design.

The first steps in photovoltaic design are assisting the customer in clearly defining what they want and what they need and then providing a preliminary assessment of the feasibility and practicality of using photovoltaics to meet these needs.

Following completion of these preliminary assessments, design requirements must be established by:

- performing a site survey and analysis

- specifying the primary functional requirements
- specifying the primary operational requirements
- identifying constraints

Performing a site survey and analysis involves the following:

- determining the amount of variability of solar insolation at the site, and ensuring sufficient access to the sunlight (i.e., no severe shading problems)
- determining weather and environmental conditions and the variability throughout the year
- identifying the size and location of existing structures and planned structures that may limit solar access for certain times of the year
- assessing alternative sources of electricity that may be appropriate for the site and application
- considering the social environment in the vicinity of the site and attitudes concerning the installation of a photovoltaic system

A critical early step in the design process is specifying the primary function requirements in terms of performance output, including the quantity and/or quality of the desired output. For example, the desired output may be expressed in gallons of water per day for a pumping system, or a desired range of temperatures for a vaccine refrigeration system. The primary operational requirements include such things as:

- ease of operation and scheduled maintenance
- reliability
- duty cycle
- operation under expected environmental conditions and for extended periods of low solar insolation
- component and system lifetime
- risk of vandalism, theft and personal injury

Design constraints to consider are cost, schedule, location (insolation, solar access, weather), codes and other restrictions. Design tradeoffs typically involve compromising in the areas of performance (quality and/or quantity), duty cycle, system autonomy and availability, cost, conservation, and/or alternative energy.

A comprehensive photovoltaic system design consists of:

- system drawings and a site layout
- system specifications, including electrical and mechanical specifications
- parts, materials and source lists
- installation and checkout procedures

- operation and maintenance manuals
- training courseware (if applicable, depending on the size and complexity of the system or project)

Design and sizing procedures are developed for three major types of systems: 1) stand-alone systems with battery storage, 2) hybrid systems which use a combination of a photovoltaic array and an engine generator set (i.e., an engine genset) with battery storage and 3) water pumping without battery storage. Emphasis in the course is on stand-alone systems. The design of utility-interactive residential systems is also considered, but detailed sizing procedures are omitted.

For typical stand-alone systems with storage, battery subsystems are treated in depth, including battery types, characteristics, selection criteria and detailed specification.

For hybrid systems, design criteria are discussed and comparisons are made between: photovoltaic stand-alone, engine generator set stand-alone, and photovoltaic-engine genset hybrid. Both performance and economic tradeoffs are investigated.

For water pumping applications, optional configurations discussed include: a fixed orientation array directly coupled to the pump motor and a tracking array directly coupled to the pump motor.

Detailed sizing calculations are performed for the three major types of systems.

Lab exercises include measuring current-voltage (I-V) characteristics of modules and arrays using: a) variable resistive loads, b) a variable power supply and c) capacitor charging. I-V characteristics are also measured for pumps, and array shading experiments are conducted. Voltage regulators are tested for their on-off characteristics, load shedding ability and temperature compensation. For inverters, efficiency curves are developed, signal quality is analyzed, and surge response is investigated.

Lab exercises also include assembly of a complete stand-alone system with battery storage and a thorough demonstration of system monitoring, diagnostics and data acquisition.

Emphasis in the course and manual is placed on working with current product specifications and becoming familiar with actual working hardware and measurement equipment. Device physics and mathematics are kept to a minimum.

There are many reasons to be interested in photovoltaic systems, including the following:

- Photovoltaic systems are reliable, modular, portable, environmentally benign, and

have a strong technology base.

- Over two billion people in the world do not have reliable, on-demand electricity to meet their basic needs.
- Electricity is a versatile, high quality form of energy that can significantly improve the quality of life.
- There is a growing market for PV systems in developing countries, in developed countries, and associated business opportunities.
- The cost of PV systems is coming down. The U.S. goal is to make the technology an attractive alternative to conventional generation using fossil or nuclear power.

1.1.2 Manual Overview

The course manual is divided into 11 sections beginning with an introduction and overview:

Section 1: Introduction and Overview provides an introduction and overview of both the Photovoltaic System Design Workshop and the course manual. Stand-alone and utility-interactive photovoltaic system applications are introduced, and current uses of photovoltaic systems are presented.

Section 2: Solar Radiation introduces those solar resource concepts that are prerequisite to proper system design and sizing.

Section 2a: Electrical Fundamentals defines basic electrical properties and components, and their application in electrical circuits for the design and operation of photovoltaic systems.

Section 3: Photovoltaic Cells explains the response of a photovoltaic cell to sunlight, temperature and electrical load, and describes cell manufacturing processes.

Section 4: Modules, Panels and Arrays discusses the wiring of photovoltaic cells, modules and panels to achieve desired array current and voltage outputs. Module performance specification and reliability are also discussed.

Section 5: Photovoltaic System Components presents the components that make up a photovoltaic system. Electrical loads, arrays, battery storage devices, charge controllers, voltage regulators, inverters and other balance-of-system components are discussed.

Section 6: *Stand-Alone System Sizing Procedures* explains by example the procedures for sizing four different types of photovoltaic systems: 1) stand-alone photovoltaic systems with battery storage, 2) stand-alone engine generator systems, 3) photovoltaic/engine genset hybrid systems and 4) water pumping systems without battery storage.

Section 7: *Electrical Design* discusses electrical design guidelines including wiring, terminations, sizing conductors, over-current protection, grounding, disconnect requirements, protection diodes, lightning protection and instrumentation.

Section 8: *Mechanical Design and Building Integration* presents design guidelines for the array structure, mounting hardware and other nonelectrical aspects of system design.

Section 9: *Maintenance and Troubleshooting* provides guidelines for conducting maintenance inspections and troubleshooting diagnostics.

Section 10: *Economic Analysis* provides procedures for determining life-cycle costs for photovoltaic, engine genset and hybrid stand-alone systems.

Section 10a: *Photovoltaic Lighting Systems* presents an overview of PV lighting systems and considerations for the sizing, design and selection of system components.

Section 11: *Utility Interconnection Considerations* introduces utility interconnection methods, metering options, planning and issues. Utility-interactive inverters are also described.

1.2 Photovoltaic System Applications

There are two general types of photovoltaic systems: stand-alone and utility-interactive. Stand-alone systems do just what their name suggests: they provide power without the help of an outside power source. They are self-reliant. Stand-alone systems usually have some form of storage and/or backup energy supply. Battery or water storage is most common for smaller systems, and diesel generators often provide backup for larger stand-alone systems.

In contrast to stand-alone systems, which are often in remote locations that make it impractical or uneconomical to tie into the utility grid, utility-interactive systems combine the power production of photovoltaics with the convenience of the utility grid as a backup power source. On an economic level, utility-interactive systems must compete directly with conventionally produced electricity.

1.2.1 Stand-Alone Systems

This section provides a fairly comprehensive list of stand-alone photovoltaic system applications. The list begins with those applications that involve basic human needs, such as medical care and adequate water supply. One of the largest and most suitable areas for photovoltaics is the field of telecommunications. Many other appropriate applications and potential markets are presented.

Medical and Health Care

- Power for rural and remote medical clinics
- Refrigerators and freezers for vaccines and medical supplies
- Sterilization and purification equipment
- Improved lighting
- Backup power and emergency communications

Water Delivery Systems

- Water for human consumption (pumping from groundwater wells, desalination and purification)
- Water for livestock and animals
- Irrigation systems for agriculture
- Circulation pumps for solar domestic water and pool heating systems
- Other pumping applications

Telecommunications

- Earth-orbiting satellites
- Microwave repeaters
- UHF/VHF radio and television repeaters
- UHF/VHF mobile radios and televisions
- Radio telephones
- Central telephone exchanges
- Satellite ground stations
- Telemetry
- Portable military communication units

Lighting

- Indoor lighting
- Outdoor lighting

Cathodic (Corrosion) Protection

- Transmission towers
- Bridges
- Pipelines

Wells and wellheads

Navigational Aids

- Beacons
- Buoys
- Lighthouses
- Nav aids for offshore rigs

Battery Charging

Remote Traffic and Transportation Aids

- Highway signs and warnings
- Railroad crossings and track circuits
- Traffic signals and counters
- Call boxes and emergency communications

Aviation Aids

- Radar and airport beacons
- Anemometers and wind shear monitors
- Airport meteorological stations

Residential Electricity

- Remote cabins, cottages and vacation homes
- Mobile homes
- Hybrid systems (with wind turbines or engine generators)

Space Conditioning

- Air conditioners and heat pumps
- Fans and ventilation equipment

Village and Rural Community Power

- Parks and forest ranger facilities
- Stand-alone or hybrid systems (with wind turbines, engine generators or hydroelectricity)

Security Systems

- Intrusion detectors/inhibitors
- Entry monitors
- Electric fences
- Improved lighting

Environmental Sensors

- Radiation samplers
- Noise monitors
- Meteorological stations

Consumer Electronic Products

- Calculators
- Watches and clocks
- Portable radios, televisions and recorders
- Cameras and other electronic devices

Recreational Uses

- Recreation vehicles
- Boats
- Portable power supplies for campers
- Other recreational, entertainment and leisure devices (e.g., battery chargers, golf carts, cars and light aircraft)

Power for Orbiting Satellites

1.2.2 Utility-Interactive Systems

Utility-interactive systems use the utility company as a backup power source. At nighttime, or when the electric demand exceeds the photovoltaic system output, the utility supplies the required energy.

On the other hand, if the photovoltaic system produces more energy than is required at a given time, the excess electricity is fed into the grid.

Under usual customer billing practices, the credit for photovoltaic generated electricity returned to the utility will be less than the retail customer rate for purchased electricity. Consequently, the more cost effective utility-interactive systems will be those that use higher percentages of photovoltaic electricity on site. Utility-interactive photovoltaic system applications include:

Distributed Residential Systems

- With storage
- Without storage

Distributed Commercial and Industrial Systems

- With storage
- Without storage

Centralized Systems

- Residential and neighborhood communities
- Shopping and commercial centers
- Office buildings
- Industrial and research parks
- Central station electric utility power

New markets are opening as the cost of photovoltaic technology comes down and there are new business and job opportunities for widespread applications.

References:

Maycock, Paul D., *Photovoltaics: Sunlight into Electricity in One Step*, Andover, MA: Brick House Publishing Co., 1981, pp. 68-85.

Ventre, Gerard G., *Photovoltaic System Design: A New Workshop at the Florida Solar Energy Center*, Cape Canaveral, FL: Florida Solar Energy Center, 1986.

Exercises

1. Two general types of photovoltaic systems are introduced in Section 1: stand-alone and utility-interactive. For each general type of system, state what you consider to be a major advantage and a major disadvantage compared to the other type.
2. In many photovoltaic system applications, it is necessary to specify the desired output both quantitatively and qualitatively. For example, for an outdoor lighting system, we may specify the required minimum illumination in footcandles over a given area, as well as the color of the light. These are called functional (or performance) requirements. For each of the following applications, state at least one functional requirement:
 - a) water pumping
 - b) vaccine refrigeration
 - c) ventilation
3. It is often necessary to specify the desired operational requirements for a photovoltaic system design. Operational requirements affect the users of the system. An example of an operational requirement is ready access to the batteries so the electrolyte levels can be easily checked and water added as necessary. For each of the following applications, state at least one operational requirement:
 - a) outdoor lighting
 - b) vaccine refrigeration
 - c) emergency communications
4. An important early step in designing photovoltaic systems is establishing the design requirements, which includes:
 - performing a site survey and analysis
 - specifying the primary functional requirements
 - specifying the primary operational requirements
 - identifying constraints
 - identifying tradeoffs.

Assuming the site survey indicates year-round access to sunlight, present at least one statement for each of the other four categories above for photovoltaic-powered railroad crossing warning lights.



Solar Radiation

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Solar Radiation

2

Objectives

- 1) *Determine the average daily solar insolation and monthly variations at given sites.*
- 2) *Determine temperatures and monthly variations at given sites.*
- 3) *Assess shading conditions and potential problems for different times of the year.*
- 4) *For a given application, specify a flat-plate or concentrating array and the preferred orientation or tracking mode.*
- 5) *Apply the concepts in this section to the PV system design process.*

Key Words

<i>Energy</i>	<i>Air mass zero</i>
<i>Power</i>	<i>Angle of incidence</i>
<i>Watts</i>	<i>Solar spectrum</i>
<i>Irradiance (radiant-flux density)</i>	<i>Ultraviolet radiation</i>
<i>Azimuth</i>	<i>Visible radiation</i>
<i>Solar constant</i>	<i>Infrared radiation</i>
<i>Normal incidence</i>	<i>Flat-plate array</i>
<i>Solar power density</i>	<i>Sun-tracking</i>
<i>Solar window</i>	<i>Passive tracking</i>
<i>Orientation</i>	<i>Two-axis tracking</i>
<i>Insolation</i>	<i>Adjustable tilt array</i>
<i>Fixed-orientation</i>	<i>Concentrating array</i>
<i>Direct radiation</i>	<i>Peak sun hours</i>
<i>Diffuse radiation</i>	<i>Typical meteorological year (TMY)</i>
<i>Air mass</i>	

2.1 Basic Concepts

The following ideas are fundamental to the photovoltaic process.

2.1.1 Energy and Power. Energy is the capacity for doing work. Power is the rate of doing work or expending energy.

Energy

- Capacity for doing work
- Symbol: E
- Units: kWh

Power

- Rate of doing work
- Symbol: P
- Units: kW, or watts

$$\text{Power} = \frac{\text{Energy}}{\text{Time}}$$

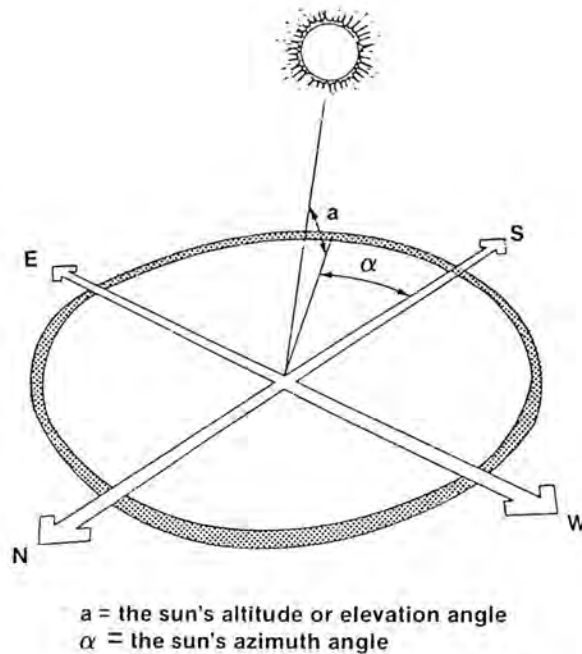
Light drives the photovoltaic process and provides the energy that is converted into electricity. The total amount of solar power striking the earth's surface at any given time is about 1.2×10^{17} watts.

2.1.2 Irradiance. The amount of solar power available per unit area is known as irradiance.

Irradiance, or Radiant-flux density

- Radiant power per unit area
- Symbol: H
- Units: kW/m², or watts/m², or mW/cm²
- Measuring device: Pyranometer (e.g., Eppley PSP), Reference (solar) cells
- Peak value (used in rating): 1 kW/m² (1000 watts/m², 100 mW/cm²)
- Nominal value: 0.8 kW/m² (800 watts/m², 80 mW/cm²)

Irradiance fluctuates according to the weather and the sun's location in the sky. This location constantly changes throughout the day due to changes in both the sun's altitude (or elevation) angle and its azimuth (or compass) angle. Figure 2.1 shows the two angles (the sun's altitude or elevation angle and the sun's azimuth or compass angle) used to specify the sun's location in the sky.



Source: Buresch

Figure 2.1 Sun's location in the sky

2.1.3 Solar Constant. Although photovoltaic devices can be powered by artificial light, their value lies in their ability to use free and renewable sunlight. A photovoltaic device that is outside the earth's atmosphere and that maintains normal incidence to the sun's rays receives a nearly constant rate of energy. This amount, called the solar constant, is approximately 1.36 kW/m^2 . The solar constant and the associated solar spectrum immediately outside the earth's atmosphere are determined solely by the nature of the radiating source (i.e., the sun) and the distance between the earth and the sun.

$$\text{Solar constant} = 1.36 \text{ kW/m}^2$$

Whereas the solar constant is a measurement of solar power density outside of the earth's atmosphere, terrestrial applications of photovoltaic (or any solar) devices are complicated by, and must take into consideration, two variables: 1) geometric effects, including the earth's rotation about its tilted axis and its orbital revolution about the sun, and 2) atmospheric effects.

2.2 Geometric Effects

2.2.1 Hourly and Seasonal Variations. The earth's rotation about its axis produces hourly variations in power intensities at a given location on the ground during the day-time and results in complete shading during the nighttime. In addition, a device located in the northern hemisphere receives more energy during the summer than in winter, thus giving rise to seasonal variations in power intensities. Figure 2.2 illustrates the earth's orbit and seasons of the year.

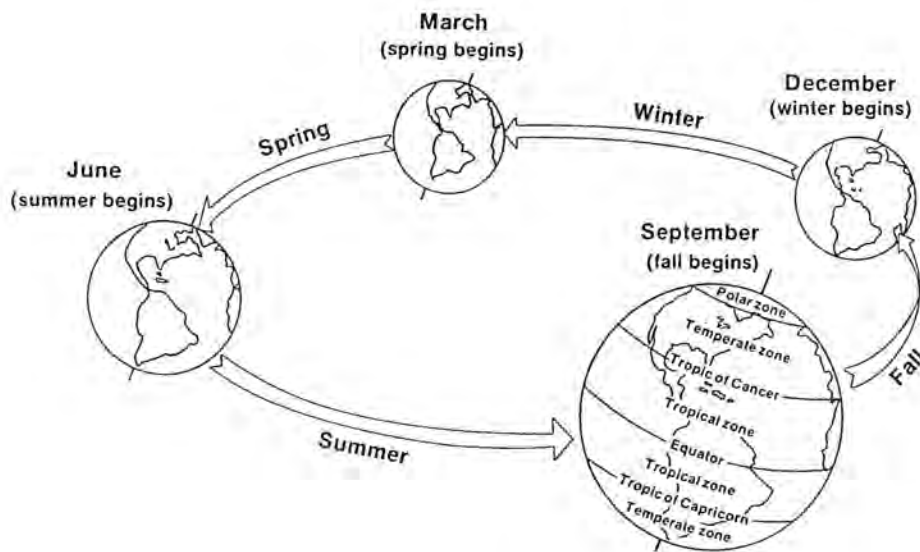


Figure 2.2 Earth's orbit and seasons of the year

Figure 2.3 illustrates the seasonal changes in the sun's path for a given location. This example, for 28° north latitude, shows that in the winter the sun rises in the Southeast, sets in the Southwest, has a relatively short path and rises to a shallow angle above the horizon at noon. In the summertime, the sun rises in the Northeast, sets in the Northwest, has a longer path and rises to a much higher angle above the horizon at noon.

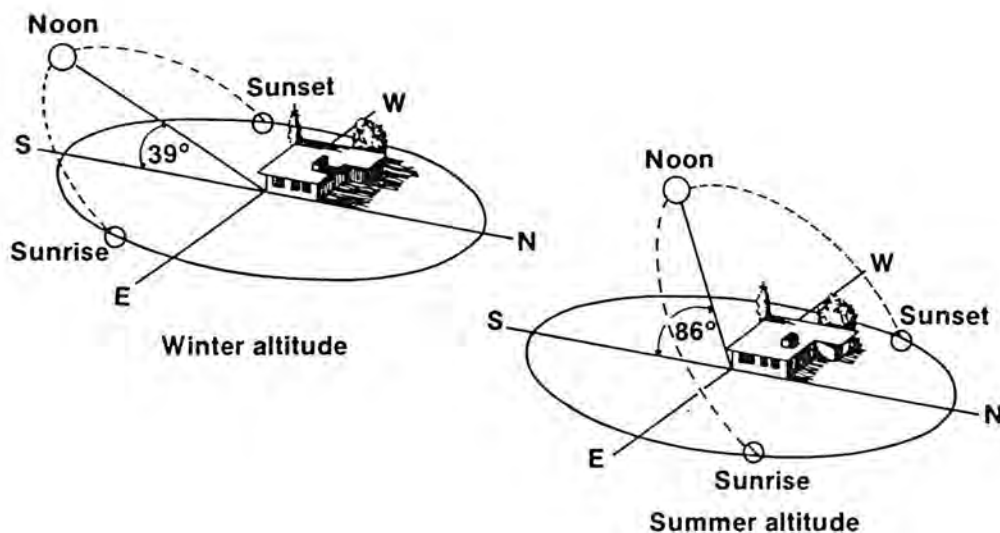


Figure 2.3 Sun paths for 28° N. latitude

2.2.2 Solar Window. The solar window represents the effective area through which useful levels of sunlight pass throughout the year for a specific location. The solar window is used to determine potential shading problems when designing a photovoltaic system as illustrated in figure 2.4.

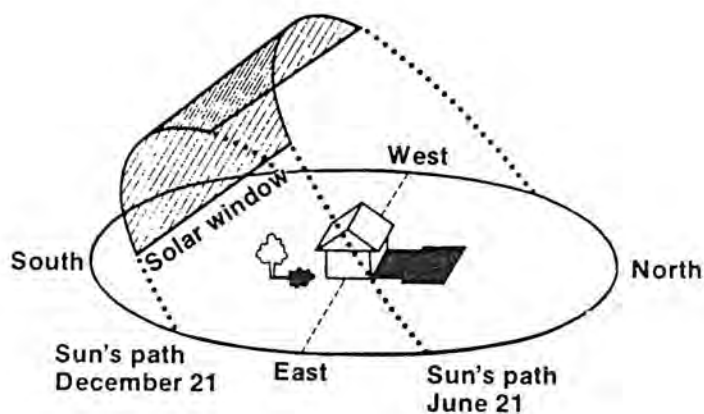


Figure 2.4 The solar window

2.2.3 Receiver Orientation and Relationship to Application. Specifying the receiver orientation is an important step in the design process and depends not only upon location, but also the type of system (e.g., stand-alone or utility-interactive) and the application.

If the demand for electricity is relatively constant throughout the year, receiver orientation for a stand-alone system is usually based on a “worst month” or “worst season” level of insolation. If electric demand varies significantly, the receiver should be tilted to maximize the solar energy collected when it is most needed. Figure 2.5 shows that the optimum array tilt during the summer months is nearly horizontal, whereas the optimum array tilt in the winter is at a much steeper angle.

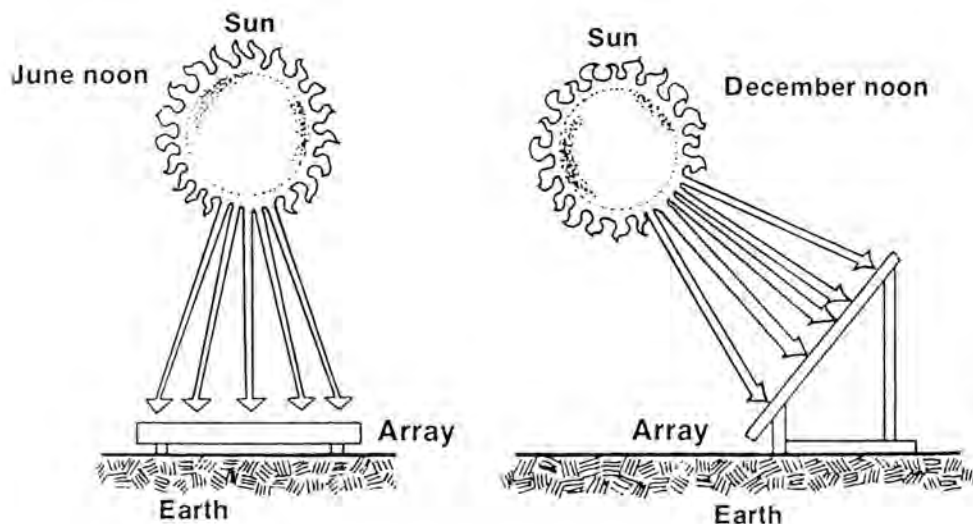


Figure 2.5 Optimum array tilt for June and December

The receiver for utility-interactive systems should be tilted to maximize annual energy production. For fixed orientation systems, this tilt angle (between the collector surface and the horizontal) is approximately equal to 90% of the local latitude. Receivers in the northern hemisphere should be south facing, while those in the southern hemisphere should be north facing. Figure 2.6 shows the two angles, β and γ , that must be given to specify the orientation of a flat-plate array surface. For a sun-tracking device, one or both of these angles will vary with time.

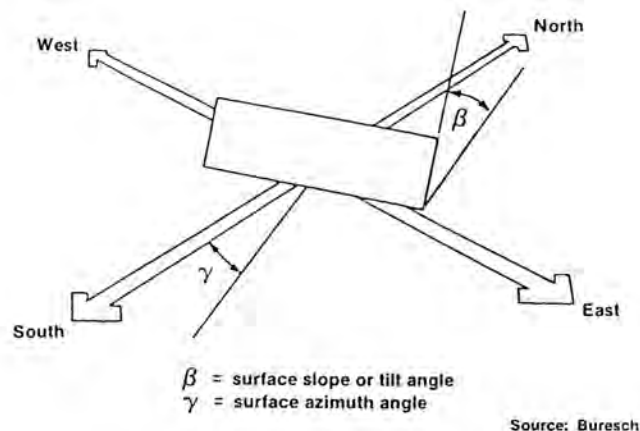


Figure 2.6 Orientation of array surface

2.3 Atmospheric Effects

The presence of the atmosphere and associated climatic effects both attenuate and change the nature of the solar energy resource. The combination of reflection, absorption (filtering), refraction and scattering result in highly dynamic radiation levels at any given location on the earth's surface. Because of cloud cover and scattering of sunlight, the radiation received at a point is both direct (or beam) and diffuse (or scattered). Figure 2.7 illustrates the atmospheric effects on solar energy reaching the earth.

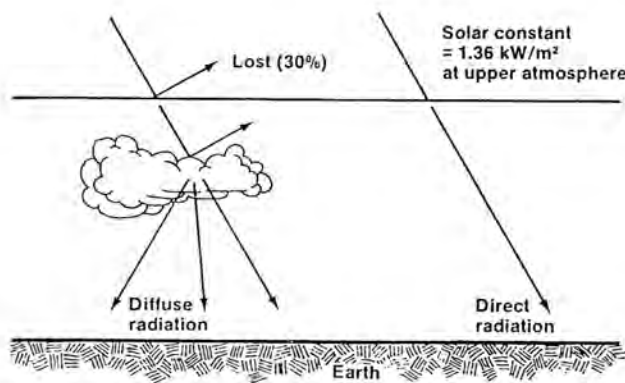


Figure 2.7 Atmospheric effects

Air mass, defined as $1/\cos \theta$ (where θ is the angle between the sun and directly overhead), is a useful quantity in dealing with atmospheric effects. Air mass indicates the relative distance that light must travel through the atmosphere to a given location. Because there are no effects due to air attenuation immediately outside the earth's atmosphere, this condition is referred to as air mass zero (AMO). Air mass one (AM1) corresponds to the sun being directly overhead. Air mass 1.5 (AM1.5), however, is considered more representative of average terrestrial conditions and is commonly used as a reference condition in rating photovoltaic modules and arrays. Figure 2.8 shows the relative distance through the earth's atmosphere that the sun's rays must pass at two times during the day.

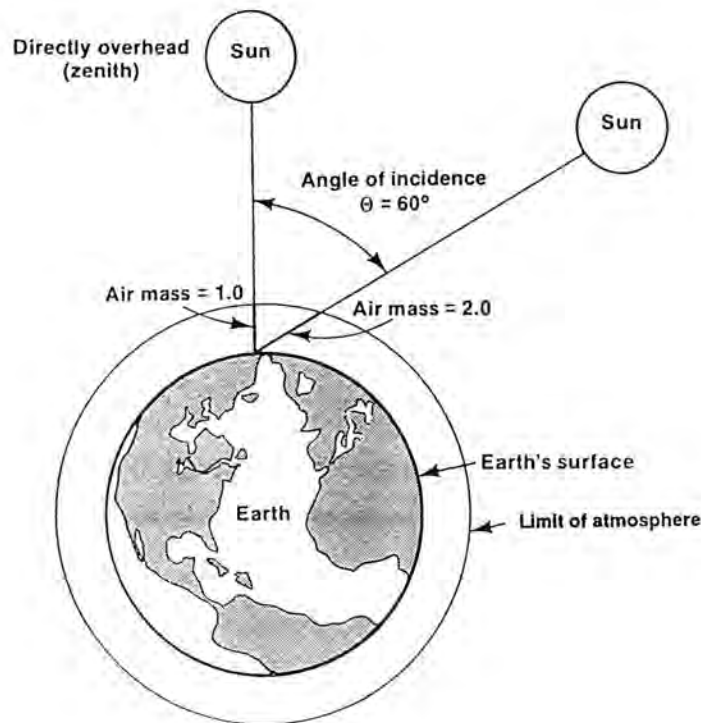


Figure 2.8 Sun's angle of incidence versus distance through atmosphere

The value of air mass at any given time and location can be easily computed using the relations shown in figure 2.9. The higher the value of air mass, the greater the attenuating effect of the atmosphere.

$$\text{Air mass} = \frac{1}{\cos \theta}$$

$$\text{Air mass} = \sqrt{1 + \left(\frac{s}{h}\right)^2}$$

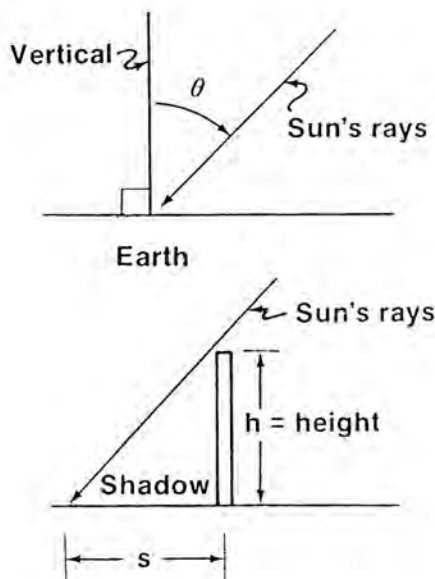


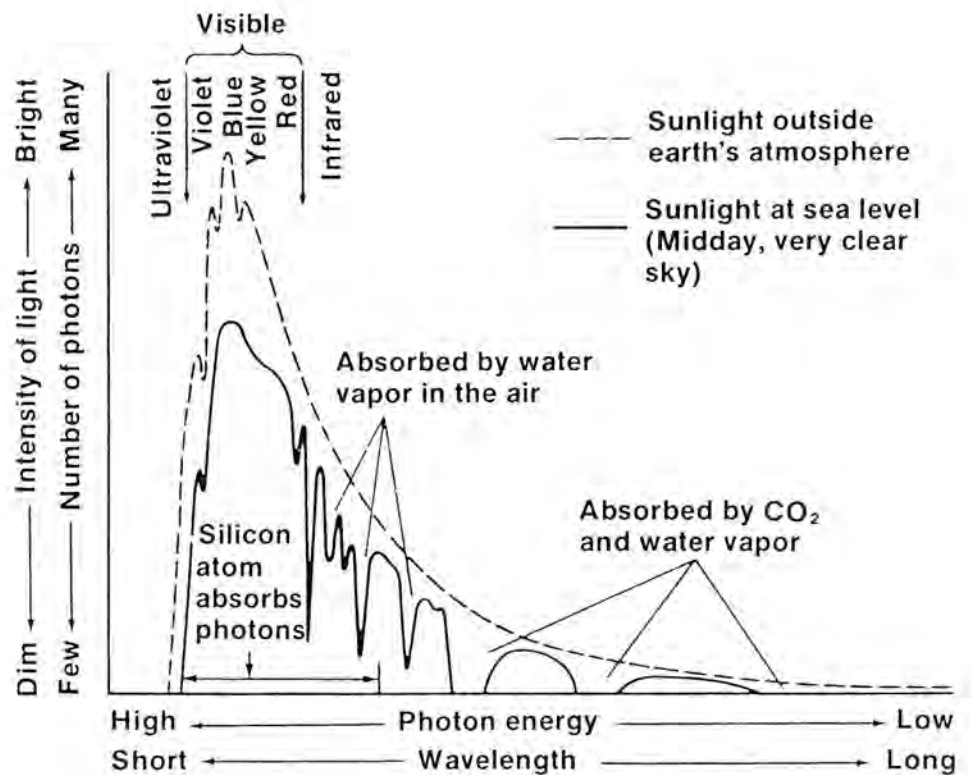
Figure 2.9 Air mass formulas

2.4 Solar Spectrum

The sun radiates power over a continuous band, or spectrum, of electromagnetic wavelengths. Power levels for the various wavelengths in the solar spectrum are not the same.

2.4.1 Ultraviolet, Visible and Infrared Radiation. The sun's total energy is composed of 7% ultraviolet radiation, 47% visible radiation and 46% infrared (heat) radiation. Ultraviolet (UV) radiation causes many materials to degrade and is significantly filtered out by the layer of ozone in the upper atmosphere.

Photovoltaic cells primarily use visible radiation. The distribution of colors within light is important because a photovoltaic cell will produce different amounts of current depending on the various colors shining on it. Figure 2.10 illustrates the relative amounts of power in the various wavelengths of the solar spectrum.



Source: Maycock

Figure 2.10 The solar spectrum

Infrared radiation contributes to the production of electricity from crystalline silicon and some other materials. In most cases, however, infrared radiation is not as important as the visible portion of the solar spectrum.

2.4.2 Effect of the Atmosphere on Spectral Energy Distribution. The atmosphere absorbs certain wavelengths of light more than others. The exact spectral distribution of light reaching the earth's surface depends on how much atmosphere the light passes through, as well as the makeup of the atmosphere. In the morning and evening, the sun is low in the sky and lightwaves pass through more atmosphere than at noon. The same is true for winter versus summer.

Different latitudes on the earth have different average "thicknesses" of atmosphere that sunlight must penetrate. An average value of 1.5 air masses (or AM1.5) has been chosen as a standard atmosphere, which in turn determines a certain spectral distribution to be used for specifying module output.

The spectral distribution of sunlight can be plotted for various air mass values, thus providing a useful indication of atmospheric attenuation effects. Figure 2.11 shows the spectral distribution for AM1.5 in relation to AM0 and a radiating black body at the same temperature as the surface of the sun.

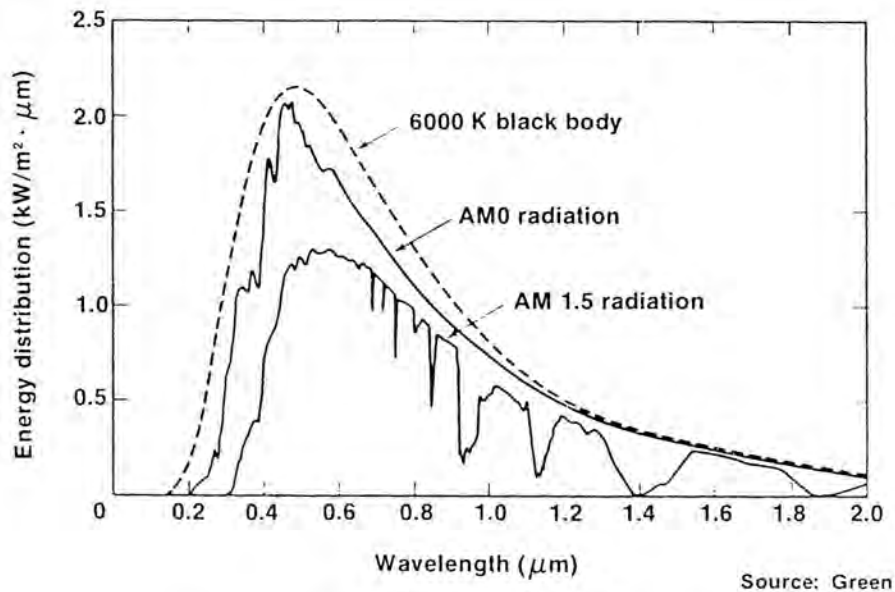


Figure 2.11 Power distribution in sunlight

2.4.3 Sensitivity of Photovoltaic Materials to Various Wavelengths. The spectral distribution of power is important because different photovoltaic cell materials are stimulated by different portions of the solar spectrum. For example, crystalline silicon responds fairly evenly to most of the visible wavelengths and the near infrared wavelengths up to about 1.1 microns, whereas thin-film silicon favors the blue end of the visible spectrum. (See figures 2.10 and 2.11.) Photovoltaic cell research involves developing materials or combinations of materials which better utilize the power within the solar spectrum.

2.5 Receiver Types

2.5.1 Flat-Plate Arrays. Flat-plate arrays use both diffuse and direct sunlight and can operate in either a fixed orientation or in a sun-tracking mode. For most applications, flat-plate arrays are fixed in orientation. However, with the advent of low-cost passive sun-trackers, flat-plate tracking arrays are becoming more popular.

2.5.2 Fixed versus Tracking Arrays. For flat-plate arrays, sun-tracking can increase annual energy output by 20% to 40%, depending on location and the type of tracking used. Two-axis tracking allows the array to continuously face directly at the sun and provides the maximum energy output. There are, however, a variety of single-axis tracking modes that may be more cost effective than two-axis tracking for flat-plate arrays. A compromise between fixed and tracking arrays is the adjustable tilt array, whereby the array tilt angle is adjusted periodically (usually seasonally) to increase the output of the array.

2.5.3 Concentrator Arrays. Concentrator arrays use optical lenses and mirrors to focus sunlight onto high-efficiency cells. Figure 2.12 shows three forms of concentrator devices. The major advantage of concentrating devices is that they use relatively small areas of expensive photovoltaic material. The larger aperture areas are made up of much less expensive plastic lenses or other materials.

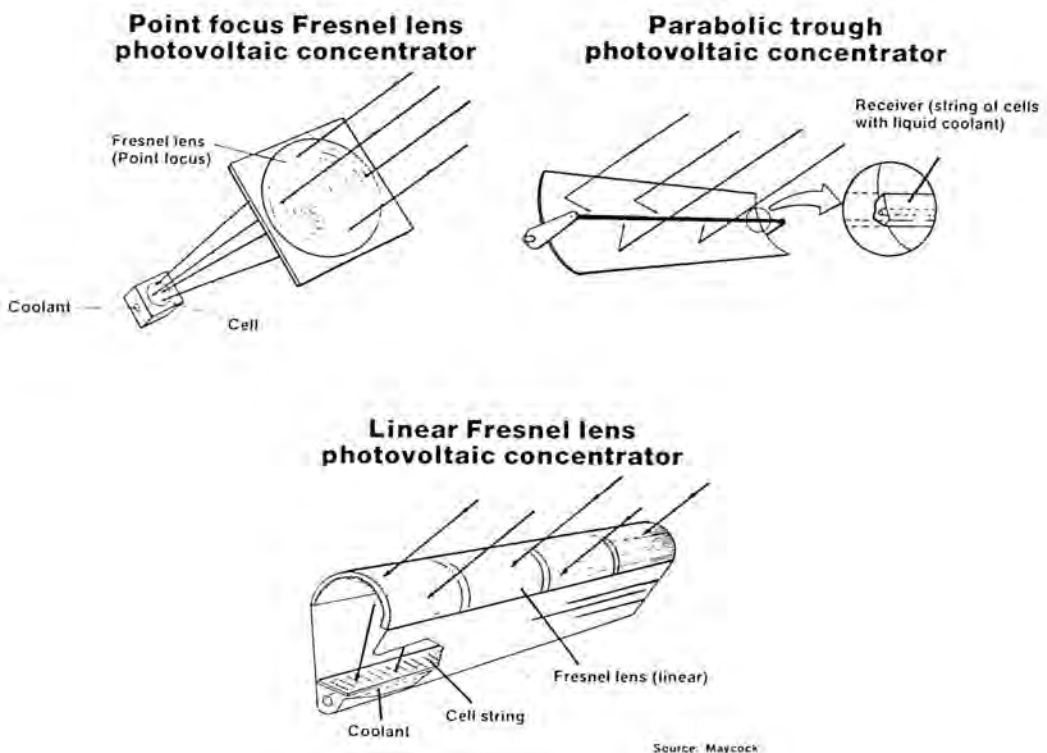


Figure 2.12 Concentrator arrays

Because they rely on their ability to focus direct sunlight, concentrator arrays must track the sun and are best used in areas with high components of direct radiation. There is a considerable regional variation in the amount of direct radiation received in the U.S., with the desert Southwest receiving the most. Consequently, many of the initial applications of concentrating and tracking flat-plate devices have been located in California, Arizona and New Mexico.

2.6 Solar Insolation

The results of the earth's motion and atmospheric effects at various locations have led to essentially two types of solar insolation data: average daily and hourly.

Unlike irradiance, which is power per unit area, solar insolation is radiant energy per unit area. Solar insolation is determined by summing solar irradiance over time and it is usually expressed in units of kWh/m² per day.

2.6.1 Average Daily Solar Radiation Data for Each of the 12 Months. To provide long-term average daily solar radiation data, daily solar radiation for each month is averaged over past years (typically 30 years). These data are useful both in predicting long-term performance and in analyzing the economics of solar energy systems. The actual average daily solar radiation for a given month may vary significantly from the long-term average for that month.

Average daily solar radiation can be obtained from various sources, one of which is the Solar Energy Research Institute's Insolation Data Manual. Data from one source may differ somewhat from another.

2.6.2 Peak Sun Hours. The number of peak sun hours per day at a given location is the equivalent time (in hours) at peak sun condition (i.e., at 1 kW/m²) that yields the same total insolation. Figure 2.13 shows how peak sun hours are determined by constructing a graph having the same area as that for the actual irradiance versus time.

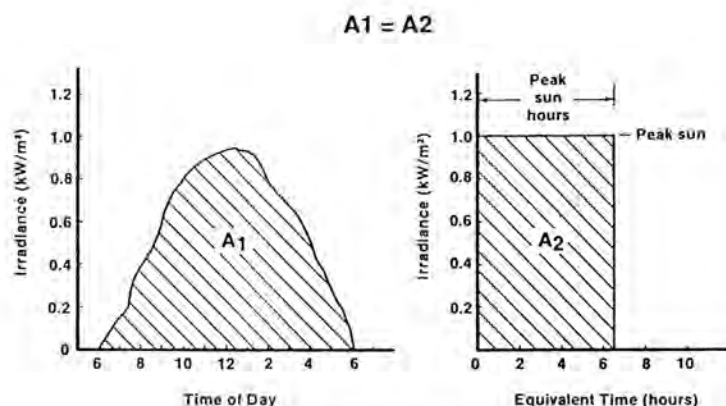


Figure 2.13 Peak sun hours

2.6.3 Hourly Solar Radiation Data for Each of the 12 Months for a Typical Year.

Typical meteorological year (TMY) data are the result of statistical analysis of SOLMET (i.e., solar and meteorological) rehabilitated weather data for past years. The TMY consists of 12 months, with each month selected so that it best represents the average of that particular month over past years. Therefore, the typical meteorological year is a composite year with representative months selected from different years.

To select a representative month such as January, each month of January for past years is compared with the average January of all of the years and the one closest to the average is used. The selection is weighted 50% on solar radiation and 25% each on ambient temperature and wind speed. TMY data are good for photovoltaic system analysis.

TMY data are available for 26 cities from the National Climatic Data Center in Asheville, NC. Less reliable ERSATZ-TMY data (constructed data) are available for an additional 209 U.S. cities.

References:

- ARCO Solar Training Manual, Vol 1., Woodland Hills, CA: ARCO Solar Inc., 1984, p. M-54.
- Khattar, Mukesh, "Solar Radiation Data," *Fundamentals and Applications of Photovoltaics*, Cape Canaveral, FL: Florida Solar Energy Center, 1983, pp. 2-9 through 2-10.
- Ventre, Gerard G., "Introduction and Overview," *Fundamentals and Applications of Photovoltaics*, Cape Canaveral, FL: Florida Solar Energy Center, 1983, pp. 1-1 through 1-3.

Exercises

1. Solar radiation that reaches the Earth's surface is made up of two components. What are they?
2. What are the two major effects that influence the amount and type of radiation that reaches a given point on Earth?
3. Why is the spectral distribution of solar power of interest to photovoltaic system designers?
4. Name a device that is used to measure solar irradiance and/or insolation.
5. Using Appendix A of the laboratory manual, compare the solar insolation for three cities: Orlando, Florida (28.55° north latitude), Tonopah, Nevada (38.07° north latitude), and Spokane, Washington (47.63° north latitude).
 - a) What is the annual horizontal solar insolation (in $\text{kWh}/\text{m}^2\text{-day}$) for each of the three cities?
 - b) What is the maximum annual insolation and the corresponding tilt angle for each of the three cities?
 - c) For what month of the year can the maximum amount of average daily solar insolation be collected for each of the three cities? What are these amounts and what are the corresponding tilt angles?
 - d) What is the worst month of the year for collecting solar insolation for each of the three cities? For the worst month of the year for each city, what tilt angles should be used to collect the maximum amount of solar energy?
6. Based on the results of exercise 1, does the southern-most city receive the most solar energy during the summer? during the winter? on an annual basis? Explain.
7. In which of the above three cities would a concentrating collector that tracks the sun work best? Explain.
8. In which of the three cities would an obstruction, of a given height and located due south of the collector, be more likely to cause a shading problem?
9. For the majority of stand-alone photovoltaic system applications, the desired collector tilt angle is the one which results in the maximum solar insolation during the worst insolation month of the year. For Fort Smith, Arkansas, and for the data given, what is the worst insolation month, collector tilt angle, and corresponding average daily solar insolation in $\text{kWh}/(\text{m}^2\text{-day})$?



Electrical Fundamentals

2a

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Electrical Fundamentals

2a

Objectives

- 1) *Define basic electrical properties including voltage, current, resistance, power and energy.*
- 2) *Express Ohm's law mathematically and apply it to simple direct current circuits.*
- 3) *State Kirchhoff's first and second laws.*
- 4) *Specify the mathematical relationships between voltage, current and resistance in series and parallel circuits.*
- 5) *List common electrical components and their functional properties.*
- 6) *Describe basic meters and instrumentation used to measure electrical properties.*
- 7) *Apply the concepts in this section to the PV system design process.*

Key Words

Voltage

Current

Resistance

Conductance

Charge

Capacitance

Inductance

Energy

Power

Efficiency

Ampere-hour

Direct current

Alternating current

Cycle

Period

Frequency

Waveform

Sine wave

Phase

Power factor

Ohm's law

Kirchhoff's laws

Series circuits

Parallel circuits

2a.1 Introduction

It is essential to have a basic understanding of electrical properties, components and their application in electrical circuits, for designing and operating photovoltaic systems. This section provides basic definitions of electrical properties and their relationships with one another; analysis of simple circuits using Ohm's and Kirchhoff's laws; and a discussion of meters and instrumentation used for measuring electrical parameters.

2a.2 Definitions

Voltage (E) - The unit of electro-motive force (emf), electrical pressure or potential difference, is the volt (V). By definition, one volt is the potential difference required to produce a current of one amp through a conductor with a resistance of one ohm.

Current (I) - The basic unit of electrical current is the ampere or amp (A). By definition, one amp is the current flowing in a conductor having resistance of one ohm and a potential difference of one volt between its ends. One ampere is equivalent to the flow of one coulomb of charge per second.

Resistance (R) - The unit of electrical resistance commonly expressed in units of ohms (Ω). By definition, one ohm is the resistance that results in a potential difference of one volt when the current is one amp.

Conductance (G) - Conductance is the reciprocal of resistance and is expressed in units of mhos ($\mathcal{U}$), now called siemens (S).

Charge (Q) - The practical unit of electrical charge is the coulomb. One coulomb is the quantity of electrical charge that passes a point in an electrical circuit in one second, when the current is one ampere.

Capacitance (C) - Capacitance is the property of a system of conductors and dielectrics that permits the storage of electrical charge when a potential difference exists between the conductors. The unit of capacitance is the farad (F). By definition, a capacitance of one farad will result in the potential difference being raised by one volt, by the addition of a charge of one coulomb.

Inductance (L) - Inductance is the property of an electric circuit that determines the emf induced for a given rate of current change in the circuit. The common unit of inductance is the henry. An electric circuit has inductance of one henry when a rate of change of one ampere per second will induce an emf of one volt.

Power (P) - Power is the time rate of transferring (transforming) energy and is expressed in units of watts (W). By definition, one watt is the power produced when one ampere flows under a potential difference of one volt. Commonly, power is expressed in kilowatts (kW), equaling 1000 watts. Photovoltaic modules and arrays are often represented by their peak

power rating at a standard test condition.

Energy (W) - Energy is the capacity for doing work and is expressed in units of joules (J), watt-hours (Wh), or kilowatt-hours (kWh). Utility customers are billed based on their energy usage, or kWh consumption.

Efficiency (η) - Efficiency is used to express the ratio of output to input for a particular quantity, usually power or energy. Efficiency is generally expressed as a percentage. For example, PV module efficiency is determined by the ratio of the power output to the solar radiation incident on the module surface. Inverter efficiency is expressed by the ratio of power output to power input. Pump efficiency may be represented by the ratio of the hydraulic power output to mechanical power input.

Ampere-hour (Ah) - In dc electrical circuits such as photovoltaic systems, ampere-hours are often used instead of energy (Wh) to express time-integrated current flows and battery storage capacity. For example, a PV module producing three amps over a four hour period generates 12 ampere-hours. Similarly, an electrical load using two amps over a four hour period consumes 8 ampere-hours.

Direct Current (dc) - A uni-directional current or signal in an electrical circuit, usually represented with a positive/negative polarity. Photovoltaic cells and batteries are direct current devices.

Alternating Current (ac) - A regular, bi-directional current or signal in an electric circuit, oscillating with a periodic frequency. Alternating current is the common mode for the generation, transmission and distribution of electrical power in the U.S.

Cycle - A complete, recurring set of positive and negative values of an alternating current waveform.

Period (T) - The time period for an alternating current signal to complete one cycle. For a 60-hertz alternating current signal, the period for one cycle is equal to 1/60 second, or 16.67 milliseconds.

Frequency (f) - The number of alternating current cycles per second. By definition, one cycle per second equals one hertz (Hz). The common frequency for alternating current in the U.S. is 60 hertz, while 50 hertz is common throughout Europe and in other countries.

Waveform - Alternating current signals are typically described in terms of their waveform. A common waveform is the sine wave, represented mathematically by a sinusoidal function. The power generated by electric utilities and generators has a sine waveform. Other waveforms include square wave and quasi-sine wave patterns. These waveforms have several higher-order components of the typical 60-hertz fundamental frequency, and often result in audible noise and heating, in induction motors and transformer (coil based) appliances. Many inverters used in stand-alone PV systems have square or quasi-sine wave

output signals.

Phase (θ , ϕ) - The voltage and current waveforms in alternating current circuits are often discussed in terms of their electrical phase angle difference (θ). In a purely resistive circuit, the voltage and current waveforms begin concurrently (at the same time), and are said to be in phase with each other. In an inductive only circuit, the current lags the voltage by 90 electrical degrees, or one-quarter of a complete cycle. With capacitance only in the circuit, the current leads the voltage by 90 electrical degrees. Combinations of resistance and inductance are typical of induction motors and transformer or coil based appliances, and results in the current lagging the voltage by greater than zero, but less than 90 degrees.

Phase (ϕ) is also used to characterize alternating current utility service, typically either single (1ϕ) or three (3ϕ) phase. Residential and small commercial utility service are single phase, while heavy commercial and industrial applications with large induction motors use three phase power. In three phase circuits, the three voltage waveforms vary by an electrical phase angle difference of 120 degrees.

Power Factor (pf): In alternating current circuits the power is expressed by:

$$P = EI \cos \theta$$

Eqn. 2.1

The electrical phase angle difference between E and I is θ . $\cos \theta$ is the power factor of the circuit and varies between 0 and 1, either lagging or leading. In a purely resistive (dc circuit) the voltage and current waveforms are in phase, and θ equals zero, so the power factor equals unity ($\cos 0^\circ = 1$). When a circuit has either inductive or capacitive components, the power factor is less than unity and the product of E and I is greater than the true power in the circuit.

Electric utilities are particularly interested for their customers to maintain high power factor loads, as this minimizes current handling requirements for their transmission and distribution equipment. High power factors are desired when using inverters in stand-alone PV systems, to minimize the current required from the battery bank to supply a given load.

2a.3 Fundamentals of Electrical Circuits

2a.3.1 Ohm's Law

Ohm's law states that for a steady-state current, the current in an electrical circuit is directly proportional to the voltage across the circuit, and inversely proportional to the total resistance of the circuit. The following equations express Ohm's law in various forms:

$$\begin{aligned}E &= IR \\I &= E/R \\R &= E/I\end{aligned}$$

Where: E = potential difference in volts
 I = current in amperes
 R = resistance in ohms

Eqn. 2.2

2a.3.2 Electrical Power

In dc electrical circuits, the electrical power is given by the product of the voltage and current:

$$P = EI \quad \text{Where: } P = \text{power in watts}$$

Eqn. 2.3

By substituting the above in equation 2.2, variations in Ohm's law can be expressed as follows:

$$P = I^2R$$

Eqn. 2.4

or:

$$P = E^2/R$$

Eqn. 2.5

2a.3.3 Kirchhoff's Laws

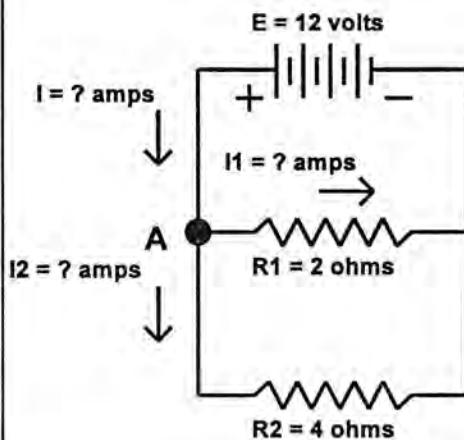
Kirchhoff's laws are derived from Ohm's law and are used to solve for unknown parameters in many electrical circuits.

The *first law* states, the algebraic sum of currents in all wires that meet at a point is zero. The *second law* states, the total change of potential or voltage around any closed circuit is zero. Kirchhoff's laws are based on conservation of energy principles.

In applying Kirchhoff's laws, the polarity of currents flowing into a point are considered positive, while currents flowing away from the point are negative. A rise in potential or voltage (e.g., a battery) is taken as positive, while a drop in potential is taken as negative.

The following example illustrates a simple application of Kirchhoff's and Ohm's laws:

Example 1: Determine I , I_1 and I_2



From Kirchhoff's and Ohm's laws:

$$I = I_1 + I_2 \quad (\text{Kirchhoff's first law at point A})$$

$$E = E_1 = E_2 = 12 \text{ V}$$

$$I_1 = E_1 / R_1 = 12 / 2 = 6 \text{ A} \quad (\text{Ohm's law})$$

$$I_2 = E_2 / R_2 = 12 / 4 = 3 \text{ A}$$

$$\text{Therefore, } I = I_1 + I_2 = 6 + 3 = 9 \text{ A}$$

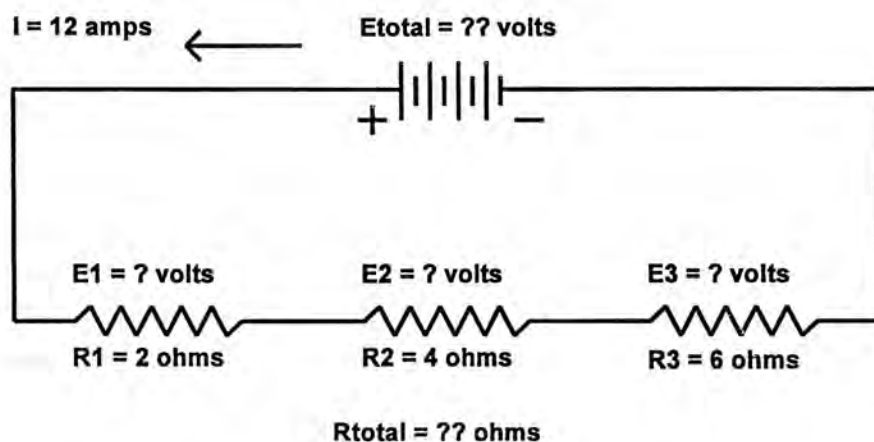
2a.3.4 Series Circuits

The combined resistance of a number of series connected resistors is the sum of the individual resistances:

$$R_{\text{total}} = R_1 + R_2 + \dots R_n \text{ where } n \text{ is the total number of individual resistances}$$

The current in a series circuit is the same at all points. Therefore, based on Ohm's law the voltage drop across each resistance is given by Eqn. 2.2, and the total voltage across the entire series circuit is the sum of voltages across the individual resistances (Kirchhoff's second law).

Example 2: Determine E_{total} , E_1 , E_2 , E_3 and R_{total}



$$E_{R1} = IR_1 = 12 \times 2 = 24 \text{ V (Ohm's law)}$$

$$E_{R2} = IR_2 = 12 \times 4 = 48 \text{ V}$$

$$E_{R3} = IR_3 = 12 \times 6 = 72 \text{ V}$$

$$E_{total} = E_{R1} + E_{R2} + E_{R3} = 24 + 48 + 72 = 144 \text{ V (Kirchhoff's 2nd law)}$$

$$R_{total} = R_1 + R_2 + R_3 = 2 + 4 + 6 = 12 \Omega$$

2a.3.5 Parallel Circuits

The reciprocal of the total resistance of a parallel circuit is the sum of the reciprocals of the individual parallel resistances:

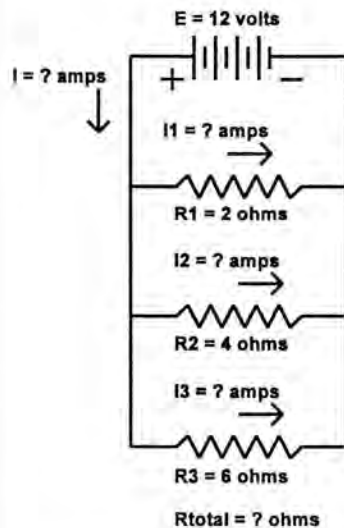
$$1/R_{total} = 1/R_1 + 1/R_2 + 1/R_3 + \dots + 1/R_n$$

Stated in terms of conductance, the total conductance of a parallel circuit is the sum of the individual parallel conductances:

$$G_{total} = G_1 + G_2 + G_3 + \dots + G_n$$

The voltages across each parallel circuit segment are the same. Therefore, based on Ohm's law, the currents through each parallel circuit segment are given by Eqn. 2.2 , and the parallel currents are additive:

Example 3: Determine R_{total} , I_1 , I_2 and I_3



$$\frac{1}{R_{total}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

$$\frac{1}{R_{total}} = \frac{1}{2} + \frac{1}{4} + \frac{1}{6} = \frac{11}{12} \text{ S}$$

$$R_{total} = \frac{12}{11} \text{ ohm} = 1.09 \Omega$$

$$I = \frac{E_{total}}{R_{total}} = \frac{12}{1.09} = 11 \text{ A}$$

$$I_1 = \frac{E_{total}}{R_1} = \frac{12}{2} = 6 \text{ A}$$

$$I_2 = \frac{E_{total}}{R_2} = \frac{12}{4} = 3 \text{ A}$$

$$I_3 = \frac{E_{total}}{R_3} = \frac{12}{6} = 2 \text{ A}$$

$$\text{Therefore: } I = I_1 + I_2 + I_3 = 6 + 3 + 2 = 11 \text{ A}$$

2a.4 Electrical Components

Designers need a basic knowledge of common electrical components and their symbols, so they can understand, interpret and develop electrical schematics for photovoltaic systems. The following section presents the most common electrical/electronic components, a brief description of their function, and the ANSI standard symbol (as commonly represented in electrical diagrams) for each component.

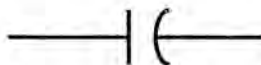
Resistor - A carbon or wire-wound device that creates resistance to the flow of electrical current. Resistors are generally specified in terms of their resistance in ohms (Ω) and their power rating in watts (W).

Electrical symbol:



Capacitor - A device consisting of two conductors separated by a dielectric material. Addition of an electrical charge produces a voltage across the capacitor according to the capacitance value, expressed in units of farads (F) or more commonly micro-farads (μF) which equals 10^{-6} farad. Capacitors are specified in terms of their capacitance and working voltage.

Electrical symbol:



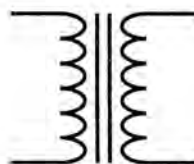
Inductor - A wire-wound coil that induces a voltage as the rate of current changes through the coil. Inductors are generally specified in terms of their inductance (in henrys) and their voltage rating.

Electrical symbol:



Transformer - A device that consists of primary and secondary wire-wound coils around an iron core. Transformers are used to step voltages up or down in alternating current circuits. The ratio of wire turns on the primary and secondary windings dictates the voltage increase or decrease from the primary to secondary terminals.

Electrical symbol:



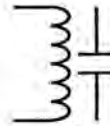
Switch - A device used to open or close a circuit, typically through a mechanically activated contactor. Switches are rated for ac or dc circuits and their voltage and current limits.

Electrical symbol:



Relay - A device that consists of a contactor operated mechanically via coil-induced magnetism, essentially an electrically-operated switch. The contactor may be either a mechanically, or a mercury activated switch. Relays are rated for ac or dc application, and their current and voltage limits. Solid-state transistors or semi-conductor devices are often used instead of relays when high-speed, low-power switching is required.

Electrical symbol:



Diode - A semi-conductor device that limits current flow to only one direction, or a one-way electrical valve. Sometimes called a rectifier, diodes are used to rectify alternating current to direct current. Diodes are commonly used in the array design of photovoltaic systems. Diodes are made from several materials, including silicon and germanium, with germanium having a lower voltage drop. Diodes are rated in terms of their current and voltage ratings.

Electrical symbol:



Battery - An electro-chemical cell used to store direct current electricity, consisting of positive and negative plates immersed in an electrolyte solution. Batteries are usually specified in terms of their voltage and ampere-hour storage capacity. Battery types vary considerably, but the most common type is the lead-acid cell.

Electrical symbol:



Fuse - A fine-wire device used to protect conductors and equipment from excessive current. Fuses are generally one-time devices that open-circuit or blow when their current ratings are exceeded. Fuses come in many physical sizes and are rated for dc or ac currents, voltage, interrupt ampere limit, and response time.

Electrical symbol:



Circuit Breaker - Constructed with a bi-metallic strip that open-circuits a contactor when heated under excessive current flow. Circuit breakers have ratings similar to fuses. Unlike fuses, circuit breakers are resettable after tripping to open-circuit.

Electrical symbol:



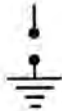
Ground - A direct electrical connection to earth potential from an electrical circuit, usually by a copper clad, steel ground rod. Grounding is used to protect equipment, as well as, to provide personnel safety in the event of equipment short-circuits or leakage currents. In photovoltaic systems operating above 50 volts, grounding is required.

Electrical symbol:



Lightning Arrester - A semi-conductor device, such as a metal oxide varistor (MOV), designed to remain open-circuit under normal operating conditions. When a high-voltage surge is induced in the circuit, the lightning arrester short-circuits and directs the excess energy away from sensitive circuit components, usually to ground. MOV lightning arresters are commonly used in PV systems and are rated in terms of voltage and energy capacity.

Electrical symbol:



2a.5 Meters and Instruments

Following is a brief description of common meters and instruments used to measure electrical properties:

Voltmeter - A meter used to measure the potential difference or voltage between two points in an electrical circuit. Voltmeters typically have settings for voltage ranges and ac and dc operation.

Electrical symbol:



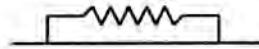
Ammeter - A meter used to measure the current flow or amperes through an electric circuit, typically requiring that the circuit be broken for the ammeter to be installed in series. Current may also be measured with current shunts or hall effect clamp-on transducers.

Electrical symbol:



Current Shunt - A precision calibrated metal strip or resistor, designed to give a voltage drop across the shunt that is proportional to the current flowing through it. The voltage drop is measured with a voltmeter and converted to the current using the shunt resistance and Ohm's law.

Electrical symbol:



Ohmmeter - A meter used to measure the resistance in ohms between two points in an electrical circuit. Most ohmmeters operate by sending a small current through the circuit and by measuring the voltage drops, determine the resistance via Ohm's law. The voltage drops can be calculated (if the currents are known) by measuring the resistance of electrical circuits.

Oscilloscope - An oscilloscope is a voltmeter that measures and displays a voltage signal with respect to time, and is particularly useful for examining alternating current waveforms.

Watt-Hour Meter - These meters record energy flows over time. For dc circuits, watt-hours can be recorded by integrating the product of the voltage and current over time. Power analyzers or watt-meters can generally be used to measure both ac and dc power.

The induction watt-hour meter is the common instrument used to measure utility-supplied ac energy to residential and commercial utility customers. The induction watt-hour meter operates by the torque created by the alternating magnetic flux, produced by the potential and by the load current. This driving torque creates rotation of an aluminum disk, which activates mechanical or electro-mechanical counters. The disk revolution rate is proportional to the power through the meter.



Photovoltaic Cells

3

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Photovoltaic Cells

3

Objectives

- 1) *Describe the photovoltaic effect, i.e., the energy conversion process that occurs when solar radiation strikes light sensitive materials.*
- 2) *Sketch the current-voltage characteristic for a PV cell and identify the important parameters: I_{sc} , V_{oc} , P_{max} , I_{mp} and V_{mp} .*
- 3) *Graphically show the changes in the current-voltage characteristics corresponding to changes in irradiance and temperature.*
- 4) *Compare the various methods of manufacturing PV cells.*
- 5) *Define cell efficiency and fill factor.*
- 6) *Apply the concepts in this section to the PV system design process.*

Key Words

Photovoltaic cell

p-n junction

Photons

Potential energy

Holes

Voltage

Current

Current-Voltage (I-V) characteristic or curve

Resistive load

Resistance

Open circuit

Short circuit

Maximum power point (P_{max})

Maximum power current (I_{mp})

Maximum power voltage (V_{mp})

Load

Cell efficiency

Nominal operating cell temperature

Temperature correction factor

Semiconductor materials

Thick materials

Fill factor

3.1 Photovoltaic Cell Response

Photovoltaic cells are devices that convert light into electricity. Because the source of light (or radiation) is usually the sun, they are often referred to as solar cells. The word photovoltaic comes from “photo,” meaning light, and “voltaic,” for voltage. The output of a photovoltaic cell (or a connected array of cells) is direct-current (dc) electricity.

3.1.1 Photovoltaic Effect. A typical photovoltaic cell is a thin rectangular or circular wafer of phosphorous-doped silicon adjacent to boron-doped silicon. The region in which these two layers are in contact, called the p-n (i.e., positive-negative) junction, sets up a permanent electric field. It is this electric field that gives direction to the light-stimulated electrons and allows direct-current electricity to flow.

Light can be thought of as small bullets of pure energy called photons. These photons actually penetrate into the cell, knocking loose electrons that were bound to atoms. When bound electrons are hit by photons and dislodged from their crystal atoms, they gain potential energy and are in a position to move and do useful work before they settle back into a bound state somewhere.

The positions vacated by the electrons, called holes, act in a similar manner to the electrons, but with an associated positive charge. The electric field of the p-n junction acts as a broom, sweeping the free electrons with potential energy in one direction, and the holes in the other. This flow of charge is electric current and the potential energy is called voltage. Common mechanical analogies to these electric quantities are:

voltage = electrical pressure = force = push

current = electrical flow = motion + volume = volume rate of flow

power = rate of doing work = rate of energy gain or loss

energy = work = (power x time) added up

3.1.2 The Current-Voltage (I-V) Characteristic. The most important performance descriptor for a photovoltaic cell, module or array is its current-voltage, or I-V, characteristic (I represents current and V represents voltage). For given irradiance, temperature and area, the operating voltage and current vary with load. By varying the load (say, for example, with a variable resistance) one can measure corresponding values of current and voltage and thus generate an I-V curve.

Current will vary from zero (corresponding to infinite resistance or open circuit) to a maximum, called short-circuit current, or I_{sc} (corresponding to zero resistance).

The maximum or open circuit voltage, V_{oc} , corresponds to the infinite resistance condition. Voltage is zero at the short-circuit condition. Thus, I_{sc} and V_{oc} are two limiting parameters that are used to characterize a photovoltaic cell, module or array for given irradiance, operating temperature and area. In figure 3.1 each point on the I-V curve represents a possible operating point for given irradiance, cell temperature and cell area. The actual operating point is determined by the battery voltage, the load or the voltage control electronics package to which the array is connected.

I_{sc} = Short-circuit current
Zero load
• maximum current
• zero voltage

V_{oc} = Open-circuit voltage
Infinite load
• zero current
• maximum voltage

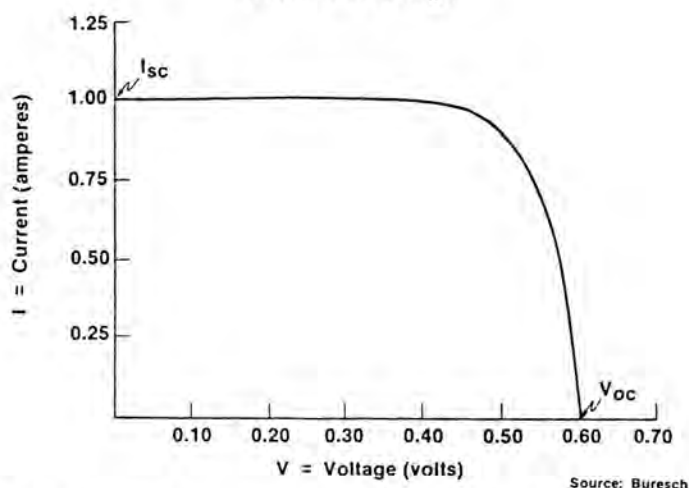
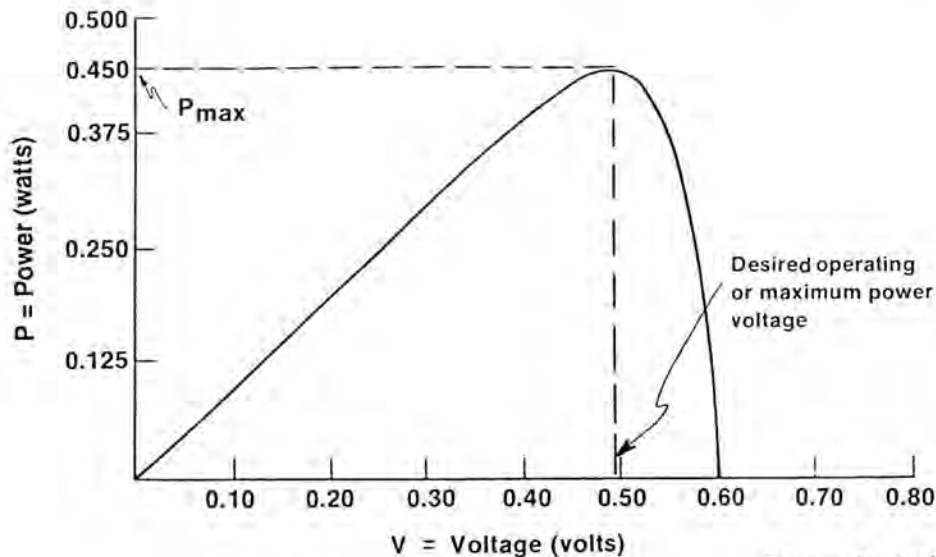


Figure 3.1 Current-voltage (I-V) characteristic for a photovoltaic cell

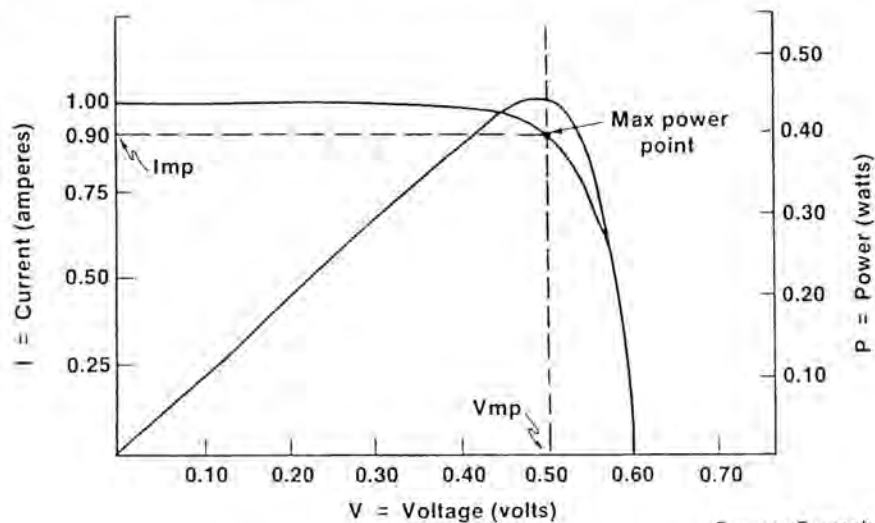
For each point on an I-V curve, the product of the current and voltage represents the power output for that operating condition. By calculating power (current x voltage) for a sufficient number of points, power can be plotted versus voltage (or current, if desired). The voltage at which maximum power is extracted is the desired operating voltage (or maximum power voltage) for a photovoltaic cell, module or array. The photovoltaic cell must be operated at this point to attain maximum efficiency. Figure 3.2 shows that of all the possible operating points for a photovoltaic cell, there is only one voltage (and corresponding current) for which maximum power can be extracted. Note that no power is extracted at open-circuit and short-circuit conditions since the current and voltage are zero, respectively.



Source: Buresch

Figure 3.2 Power versus voltage for a photovoltaic cell

The current corresponding to the maximum power voltage, V_{mp} , is called the maximum power current, I_{mp} . The maximum power point (P_{max}) is the point on the I-V curve for which maximum power is extracted. The quantities, P_{max} , I_{mp} and V_{mp} , together with I_{sc} and V_{oc} , are the five parameters that manufacturers use to specify their product's power output under given conditions of irradiance, operating temperature and air mass. Figure 3.3 shows an overlay of the power versus voltage curve and the I-V curve.



Source: Buresch

Figure 3.3 Maximum power parameters

3.1.3 Response to Load. If an irradiated photovoltaic cell is connected directly to an electrical device (or load), it is the load that determines the cell's operating point. To find that point, the I-V curve for the cell is superimposed over the I-V curve for the load. For a simple resistive load, the I-V curve for the resistor is just a straight line. Figure 3.4 shows that the operating point for the photovoltaic cell lies at the intersection of the cell's I-V curve and I-V straight line for the resistance. Note that different resistances result in different operating points for the cell and that there is only one resistance at which maximum power can be extracted.

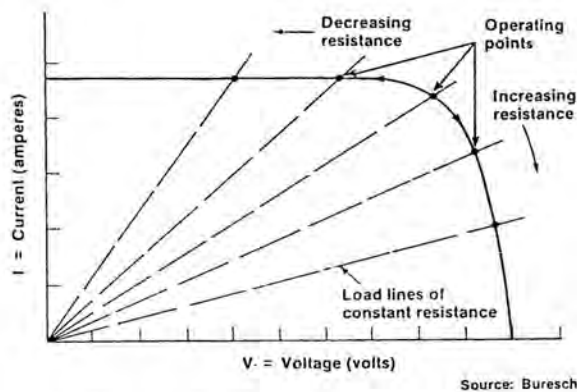


Figure 3.4 Effect of resistive load on cell operating point

3.1.4 Response to Irradiance. Changes in irradiance level significantly affect output current, but have a much smaller effect on voltage. Figure 3.5 shows the significant effect of the sunlight level on current and the rather small effect on voltage. It is this latter phenomenon that makes photovoltaic devices especially attractive for charging batteries.

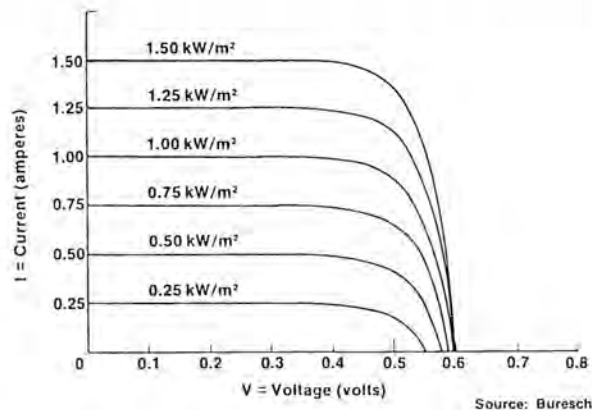


Figure 3.5 Effect of irradiance on cell response

Short-circuit current is directly proportional to the amount of available sunlight. Open-circuit voltage, on the other hand, increases dramatically at low light levels and then increases only slightly with increased sunlight. Figure 3.6 shows that short-circuit current is directly proportional to irradiance, whereas the open-circuit voltage changes very little for irradiance levels above 0.2 kW/m².

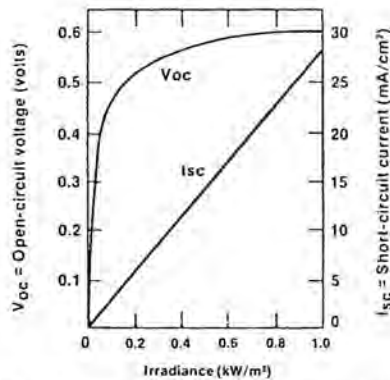
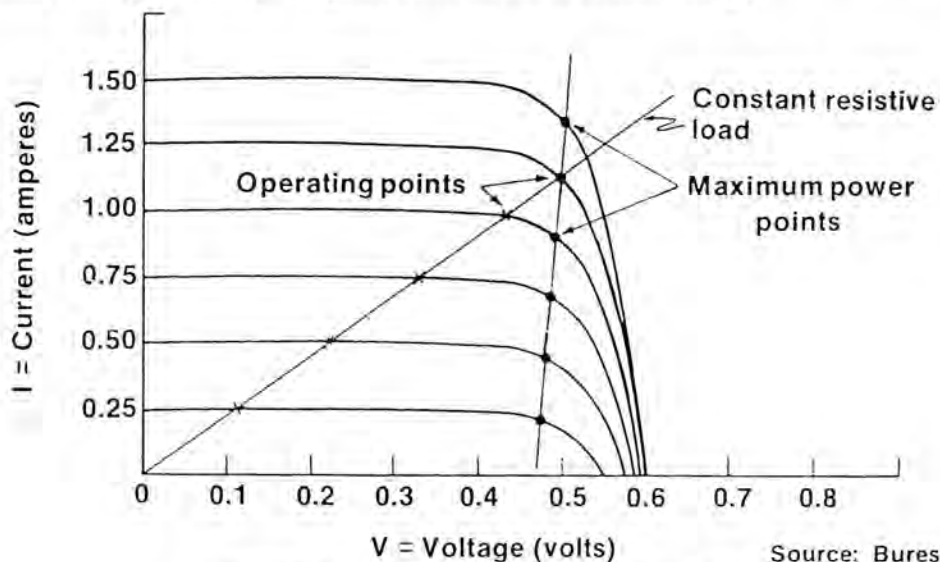


Figure 3.6 Effect of irradiance on cell voltage and current

Figure 3.7 shows the effect of changes in irradiance on the operating points of the cell for a constant resistive load. Note that as the sunlight level goes down, the operating points move farther and farther away from the maximum power points. Photovoltaic cells will operate very inefficiently unless some means are employed to keep them operating near their maximum power points. In practice this effect is accomplished by properly sizing battery subsystems or by using electronic means to control voltage.



Source: Buresch

Figure 3.7 Effect of changes in irradiance on cell operating and maximum power points

3.1.5 Response to Temperature. The operating temperatures of solar cells are important in that higher operating temperatures typically result in lower power outputs and efficiencies; they also decrease cell lifetime. As temperature increases, current increases slightly. Voltage, however, decreases significantly with increases in cell temperature, resulting in a net reduction in power. Figure 3.8 shows the effect cell temperature has on cell current and voltage.

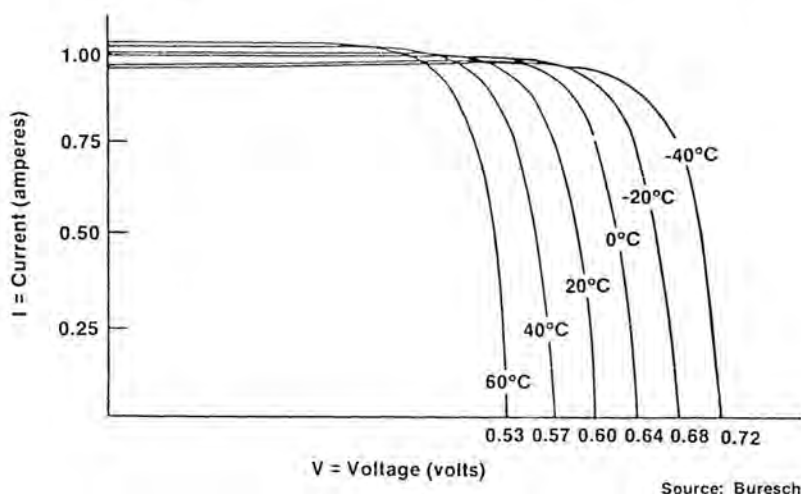


Figure 3.8 Effect of cell temperature on cell current and voltage

3.1.5.1 Nominal Operating Cell Temperature. The nominal operating cell temperature (NOCT) is the temperature at which a cell operates under conditions of 0.8 kW/m² irradiance, 20°C ambient temperature, 1.0 m/sec wind speed and array open-circuit conditions.

3.1.5.2 Temperature Correction Factor. Current output, voltage output and consequent power output vary with temperature. If power output for other than a given temperature is desired, a correction factor must be used. The typical correction factor for maximum power is (-0.004/°C) for crystalline silicon cells.

3.1.6 Cell Performance. Cell performance is determined by efficiency and fill factor.

3.1.6.1 Efficiency. Commercially available silicon cells have efficiencies as high as 15%. Laboratory efficiencies of about 20% have been achieved. Considerable research is in progress to improve efficiency, lower production costs and increase durability. Figure 3.9 shows the effects of temperature on efficiency for a typical crystalline silicon solar cell.

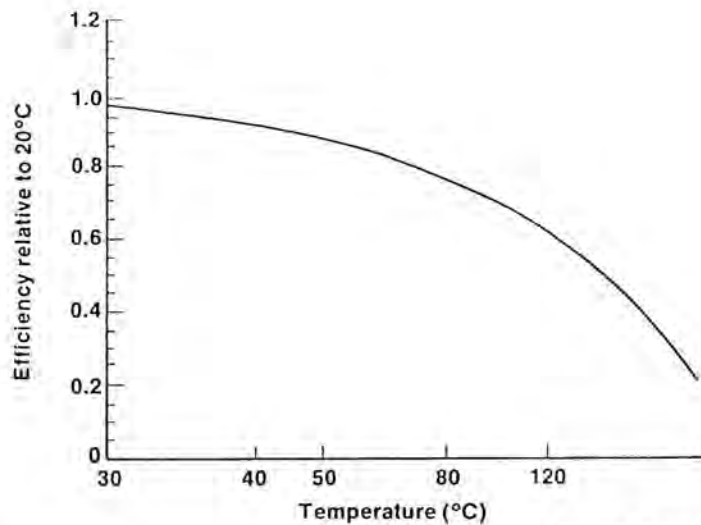


Figure 3.9 Effect of cell temperature on solar cell efficiency

3.1.6.2 Fill Factor. Fill factor, the ratio of the maximum power and the product of I_{sc} and V_{oc} , is an operating characteristic that indicates the performance quality of the cell. Figure 3.10 shows that fill factor graphically is the ratio of the inner rectangular area to the outer rectangular area. Decreases in fill factor over time indicate problems with cells, modules or arrays.

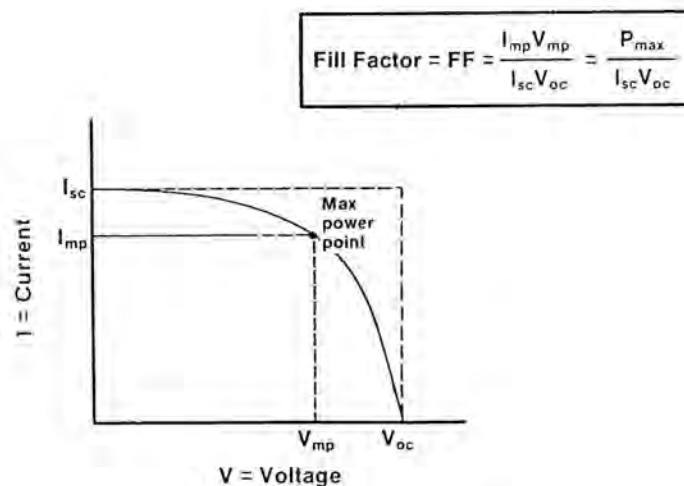


Figure 3.10 Fill factor

3.2 Manufacturing Processes

In 1960, photovoltaic cells were essentially handmade, cost approximately \$1,000 per peak watt of power and were used almost exclusively for space applications. In 1970, cells were manufactured in batch processes, cost approximately \$100 per peak watt and were still used primarily for space applications. It was the oil embargo of 1973, however, that provided the strong impetus for terrestrial photovoltaic applications. In 1980, larger quantities of cells were produced in larger batch processes, cost approximately \$10 per peak watt, saw significant terrestrial applications (primarily stand-alone, remote devices) and began to be investigated for grid-connected residential applications.

Today we are on the threshold of continuous process manufacturing, and large orders of photovoltaic modules are being purchased for less than \$5 per peak watt. There are thousands of stand-alone systems and several megawatt-size central power stations in operation or under development. In addition, there is a substantial market for photovoltaic consumer products (such as watches, calculators, radios, televisions, battery chargers, etc.).

A variety of semiconductor materials are used in fabricating photovoltaic cells and modules. These include single-crystal silicon, polycrystalline silicon, hydrogenated thin-film amorphous silicon and a large number of advanced technology materials, including cadmium telluride, copper indium diselenide and gallium arsenide.

Single-crystal and most polycrystalline silicon cells are referred to as “thick” cells. They come in a range of thicknesses from about four to seventeen mils and, in general, are in a more advanced state of development than their thin-film counterparts. Thin-film materials are typically less than five microns thick and are, therefore, orders of magnitude less material intensive.

3.2.1 Czochralski Process. The standard method of growing single-crystal silicon from a molten bath is called the Czochralski process. A relatively small amount of polysilicon is placed in a crucible in a vacuum furnace to produce a silicon melt. A solid, single-crystal silicon seed is lowered into the bath, rotated slowly and pulled upward. The molten silicon adheres to the seed and solidifies as it is drawn out, forming a cylindrical ingot. The crystalline structure of the grown ingot conforms to that of the single-crystal seed material.

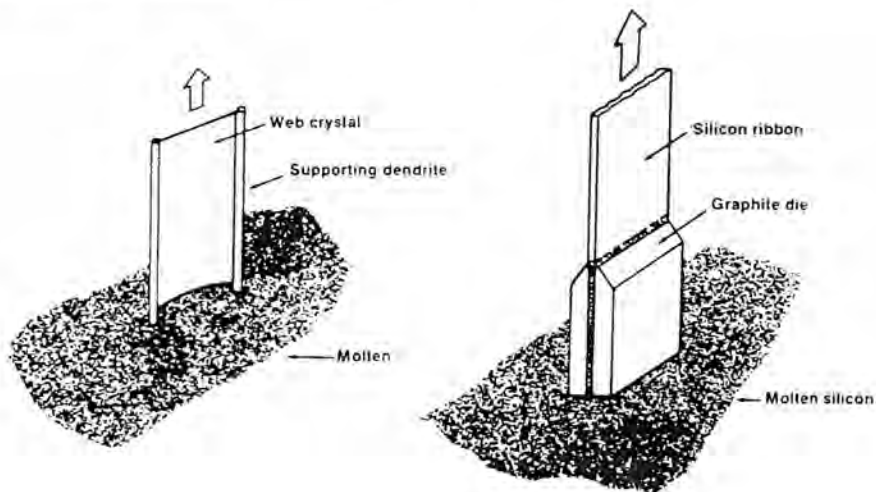
Pure silicon ingots are typically 10 to 15 cm in diameter and 75 to 100 cm in length. The ingots are sliced into very thin wafers, losing about half of the valuable silicon in the process.

To improve the prospects for Czochralski cells, larger ingots need to be grown per unit of time, and improved slicing techniques must be developed. However, the Czochralski process suffers from being both material and energy intensive.

3.2.2 Edge-Defined Film-Fed Growth (EFG) Technique. This process, developed by Mobil Solar Energy Corporation, uses the growth of silicon ribbons to make cells. A die is partially immersed in molten silicon and capillary action causes the silicon to rise and meet a solid ribbon in the die. The molten silicon solidifies as it is withdrawn from the die.

In order to increase production rates, manufacturers have developed a machine that produces nine ribbons simultaneously. The resultant product is called a nonagon because its cross-section is a nine-sided polygon. Ribbons have the advantage of not wasting material in the slicing process. They also enable a more dense packing of the rectangular module than circular cells.

3.2.3 Dendritic Web Process. Specific manufacturers have developed relatively high efficiency silicon cells (i.e., 16% and higher) using a ribbon process that uses surface tension properties rather than capillarity. Two-edge dendrites are formed in the molten silicon and, as they are withdrawn, a superior ribbon material with controllable thickness and uniformity is produced.



Larger ingots possessing more than 90% single-crystal material must be produced in the future in order to lower costs. Solarex Corporation has also developed an ingot casting process, known as Semix, which uses a different cooling rate than the HEM process and produces a high quality polycrystalline cell with an efficiency comparable to single-crystal cells.

3.2.5 Thin-Film Devices. Considerable research is in progress with many different materials to develop low cost photovoltaic devices. The most common of these is hydrogenated thin-film amorphous silicon. Unlike crystalline silicon, in which the molecular alignment is ordered, the molecular alignment in amorphous silicon is random. The efficiency of thin-film materials is relatively low and is subject to degradation. However, efficiencies can be improved by using multiple layers of compatible materials, and progress in minimizing the effects of degradation is being made. Flat-plate module efficiencies are typically 2% to 5% for single junction devices, and can exceed 6% for multiple junction devices. Improvements in manufacturing processes may yield thin-film module efficiencies comparable to those for thick cell devices.

Most thin-film manufacturing processes involve some type of vapor deposition in an electric field environment. The most common is referred to as the glow-discharge process.

3.3 World Module Shipments

The photovoltaics industry is international. Table 3.1 presents 1989 world module shipments by module type.

Table 3.1 1995 world photovoltaic module shipments by cell type (MW)

Module type	U.S.	Japan	Europe	R.O.W.*	Total	%Percent
Single crystal, flat-plate	22.00	4.50	14.35	5.85	46.70	57.4
Polycrystal silicon	9.00	6.50	4.55	0.00	20.05	24.6
Amorphous silicon	1.25	7.00	2.20	0.50	10.95	13.5
Crystal concentrators	0.30	—	—	—	0.30	0.4
Ribbon (silicon)	2.00	—	—	—	2.00	2.5
Cadmium telluride	0.10	1.20	—	—	1.30	1.6
Si on low-cost substrate	0.10	—	—	—	0.10	0.1
Totals	34.75	19.20	21.10	6.35	81.40	100.0

* Rest-of-world

Source: P. Maycock

Table 3.2 presents world module shipments by country.

Table 3.2 1989 - 1995 world PV module shipments

Country	1989	1990	1991	1992	1993	1994	1995
United States	14.10	14.80	17.10	18.10	22.44	25.64	34.75
Japan	14.20	16.80	19.90	18.80	16.70	16.50	19.20
Europe	7.90	10.20	13.40	16.40	16.55	21.70	21.10
Rest of World	4.00	4.70	5.00	4.60	4.40	5.60	6.35
Total (MW)	40.20	46.50	55.40	57.90	60.09	69.44	81.40

Source: P. Maycock

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Exercises

1. For a given current-voltage (I-V) characteristic, how many possible operating points are there?
2. Sketch an I-V curve and label the following: I_{sc} , V_{oc} , I_{mp} , V_{mp} , and P_{max} .
3. How does I_{sc} vary with increasing irradiance levels?
4. How does V_{oc} vary with increasing irradiance levels?
5. How does I_{sc} vary with increasing cell temperature?
6. How does V_{oc} vary with increasing cell temperature?
7. Given $I_{sc} = 1.0$ amp, $V_{oc} = 0.6$ volt, $I_{mp} = 0.9$ amp, and $V_{mp} = 0.5$ volt, compute the cell fill factor, FF. Is higher or lower fill factor desirable?
8. Comparing single-crystal silicon, polycrystalline silicon, and thin-film amorphous silicon, which cell material gives the highest efficiency? Which material is least stable?



Modules, Panels and Arrays

4

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Modules, Panels and Arrays

4

Objectives

- 1) *Sketch the current-voltage characteristics (i.e., I-V curves) for PV devices connected in series and in parallel.*
- 2) *Explain how photovoltaic cells are connected and configured to build strings, blocks, modules, panels and arrays.*
- 3) *Explain the functions of blocking and shunt diodes.*
- 4) *Specify the various rating conditions for modules.*
- 5) *For a given application, list three independent descriptors that can be used in a procurement specification for a PV array.*
- 6) *Apply the concepts in this section to the PV system design process.*

Key Words

Positive terminal
Negative terminal
Series connected
Unmatched devices
Parallel connected
Array
Module
String

Block
Panels
Blocking diode (series diode, isolation diode)
Bypass diode (shunt diode)
Standard test conditions (STC)
Standard operating conditions (SOC)
Nominal operating conditions (NOC)

4.1 Connecting Photovoltaic Devices in Series

Connecting photovoltaic devices in series involves connecting the positive terminal of one to the negative terminal of another.

4.1.1 Similar Devices. When similar or matched devices (i.e., identical cells, modules, panels) are connected in series, as in figure 4.1, the voltages add and the current is unaffected.

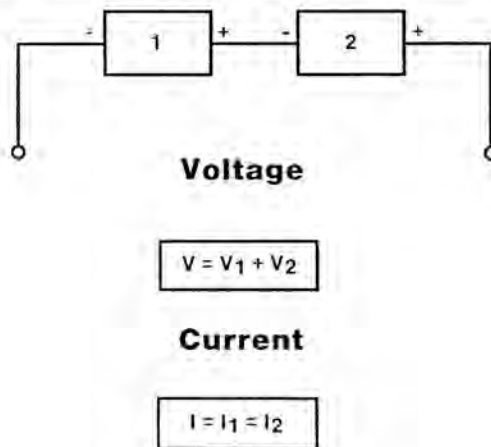


Figure 4.1 Two similar series-connected photovoltaic devices

The effect of connecting similar devices in series is illustrated in figure 4.2 by an I-V curve.

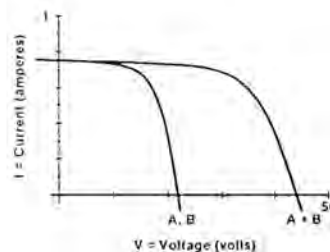


Figure 4.2 I-V curves for two similar series-connected photovoltaic devices

4.1.2 Dissimilar or Unmatched Devices. When dissimilar or unmatched devices are connected in series, voltages still add but current through the circuit is limited by the worst device in the series. For example, if there is one module in a string with a lower current output than the others, the current through the string will be approximately equal to that of the module with the least current.

Figure 4.3 presents I-V curves for two dissimilar photovoltaic devices connected in series. In this illustration, device A has a higher current and voltage than device B. When connected in series, the total voltage is equal to the voltage of A plus the voltage of B. The resulting current, however, is only slightly higher than the current of device B.

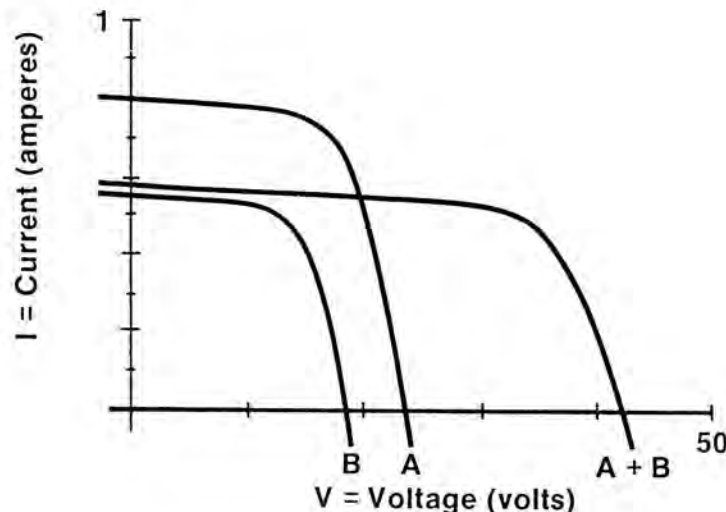
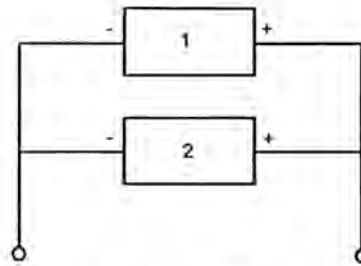


Figure 4.3 I-V curve for two dissimilar series-connected photovoltaic devices

4.2 Connecting Photovoltaic Devices in Parallel

Connecting photovoltaic devices in parallel involves connecting the positive terminals together and the negative terminals together.

4.2.1 Similar Devices. Paralleling similar photovoltaic devices causes the individual currents to add, while the voltage stays the same as shown in figure 4.4.



Voltage

$$V = V_1 = V_2$$

Current

$$I = I_1 + I_2$$

Figure 4.4 Two similar parallel-connected photovoltaic devices

Figure 4.5 illustrates, on an I-V curve, the additive effect of currents for similar devices connected in parallel.

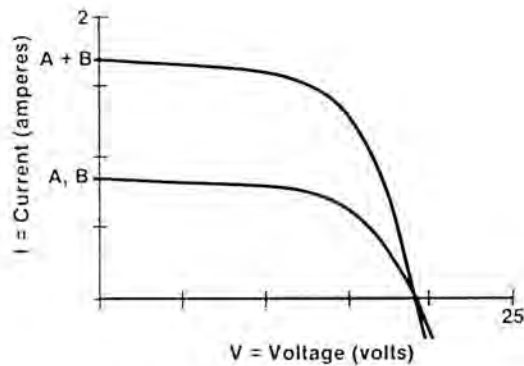


Figure 4.5 I-V curves for two similar parallel-connected photovoltaic devices

4.2.2 Dissimilar or Unmatched Devices. Figure 4.6 shows the I-V curves for two dissimilar photovoltaic devices connected in parallel. The two devices, A and B, each have different I-V characteristics. When connected in parallel, the current of device A and device B are added together to get the total current. The open-circuit voltage is approximately equal to the average of the open-circuit voltages of the two devices.

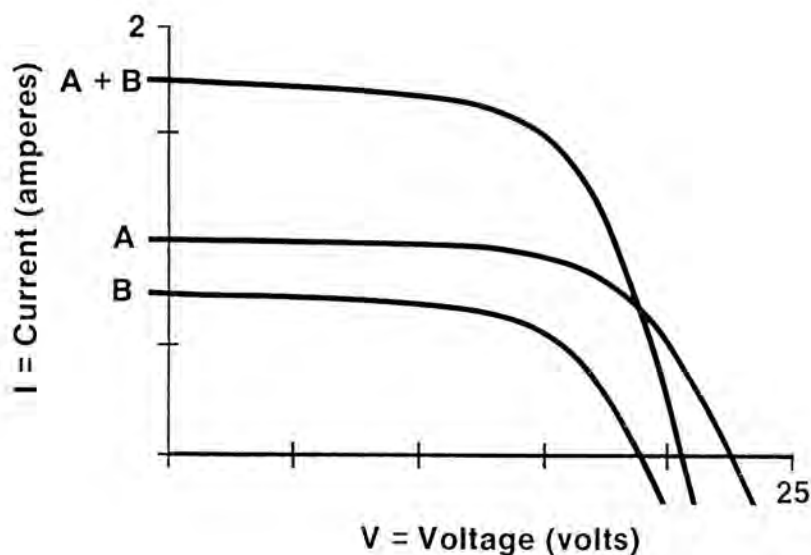


Figure 4.6 I-V curves for two dissimilar parallel-connected photovoltaic devices

4.3 Building a Photovoltaic Array

Photovoltaic arrays are designed to meet an electrical need. By connecting modules in series and in parallel, a desired voltage and current output can be obtained.

The cell is the basic building block of a photovoltaic module. Groups of cells connected in series are called strings. Figure 4.7 shows two strings connected in parallel and the associated I-V curves. Each of the strings contains five cells. The two parallel strings are connected to form a series block.

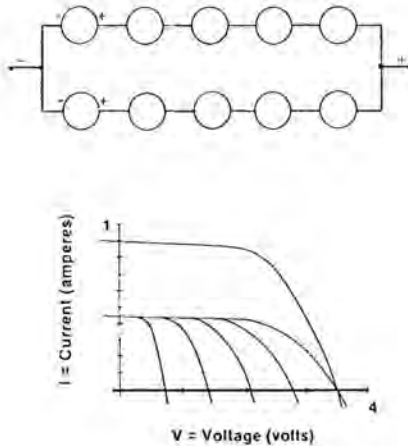


Figure 4.7 Two parallel strings, one series block, five cells per substring

Figure 4.8 shows the same number of cells wired differently. There are still two strings in parallel, but cross connections form five series blocks with one cell per substring. Note that the resulting I-V curve is the same as for figure 4.7. (The I-V curves would have been somewhat different if the cells were not matched.)

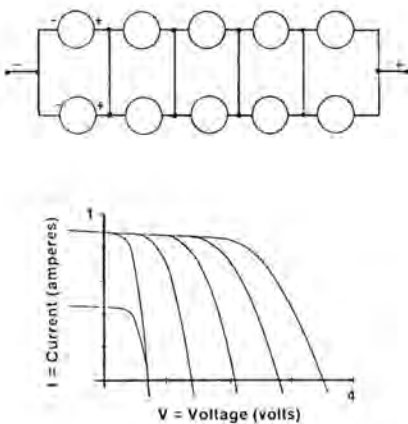


Figure 4.8 Two parallel strings, five series blocks, one cell per substring

Wiring of a sample module is illustrated in figure 4.9. The purpose of the bypass diodes shown in the figure will be discussed later.

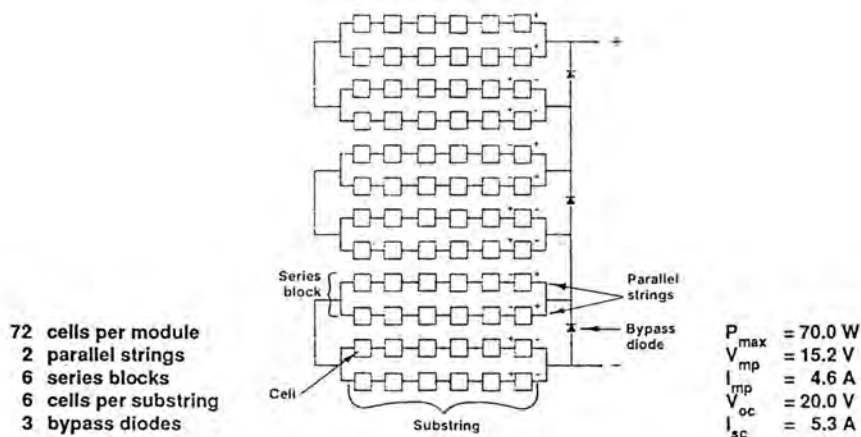


Figure 4.9 Sample module

Modules such as this are wired to other modules to form panels, and panels are wired together to form an array. Figure 4.10 is a diagram of an array of modules and the resulting I-V characteristics.

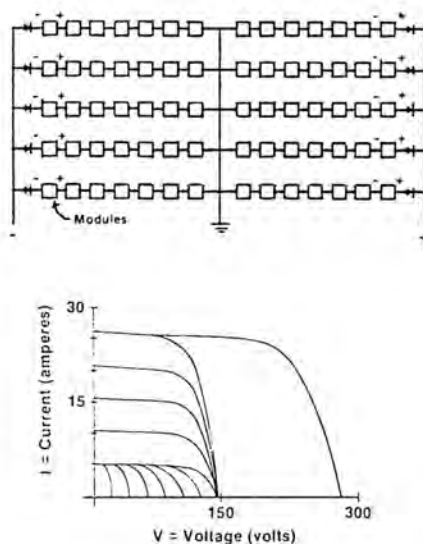


Figure 4.10 Sample array

4.4 Protection Diodes

Diodes are semiconductors that allow current to flow in only one direction. Diodes are used in two ways in a photovoltaic array: as blocking diodes and as bypass diodes. Each of these functions is of fundamental importance in minimizing system power loss.

4.4.1 Blocking Diodes. Blocking diodes (also known as series or isolation diodes) are placed in series with a module, or string of series-wired modules, to prevent current from flowing “backwards” through the modules. Figure 4.11 illustrates a blocking diode.

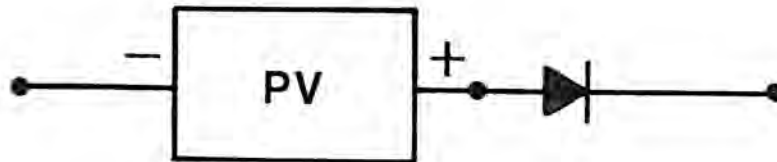
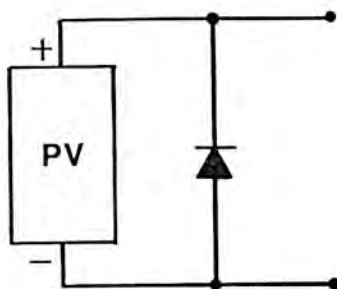


Figure 4.11 Blocking diode

Blocking diodes conduct current during normal system operation and, for stand-alone systems, prevent discharge of batteries at night.

4.4.2 Bypass Diodes. When a string of cells in series contains one bad cell or one cell shaded from the sun, an open circuit can exist in which there is no current flow.

Bypass (or shunt) diodes are used to shunt current around rather than through a group of cells or modules whenever necessary. The bypass diode “bridges the gap” so that the other cells and modules continue to produce power in the photovoltaic array. Figure 4.12 shows the advantage of having multiple bypass diodes in a series string. The more bypass diodes in this illustration, the less the effect of one shaded or bad cell.



Effect on performance by the addition of bypass diodes for one-cell shadowing

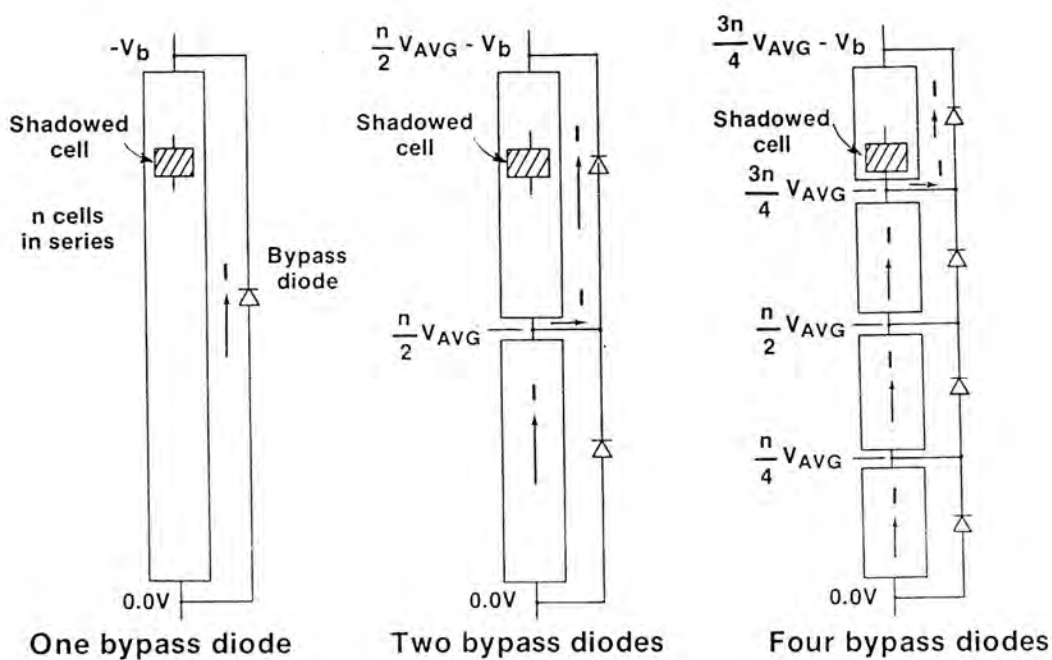


Figure 4.12 Bypass diode(s) and effect

4.5 Module Performance Specifications

Module output parameters (e.g., V_{oc} , I_{sc} , V_{mp} , I_{mp} , P_{max}) only have meaning when the rating conditions under which these outputs occur are specified.

4.5.1 Rating Conditions

Standard Test Conditions (STC)

- Irradiance = 1000 watts/m²
- Cell temperature = 25°C
- Air mass = 1.5

Standard Operating Conditions (SOC)

- Irradiance = 1000 watts/m²
- Cell temperature = NOCT
- Air Mass = 1.5

Nominal Operating Conditions (NOC)

- Irradiance = 800 watts/m²
- Cell temperature = NOCT
- Air mass = 1.5

Nominal Operating Cell Temperature (NOCT) is measured under the following conditions:

- Irradiance on surface of array = 800 watts/m²
- Ambient air temperature = 20°C
- Photovoltaic array electrically open-circuit
- Wind speed = 1.0 m/sec

4.5.2 Manufacturers' Performance Data. Manufacturers' specification sheets usually provide output under standard test conditions. Output under other conditions of irradiance and temperature is sometimes provided, but not always.

4.6 Module Reliability

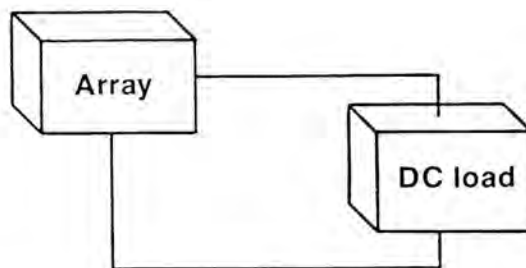
Since the mid-1970s, the Jet Propulsion Laboratory (JPL) has been tasked with the responsibility of improving the reliability of flat-plate modules. Significant reliability improvements have been accomplished for crystalline silicon modules through considerable research, development and testing by JPL, the photovoltaics industry and other research organizations. JPL has established design specifications for modules and associated qualification testing to ensure that the modules meet reliability goals.

Qualification tests for Block V rating were developed to achieve 30-year module lifetimes. Some of the specific JPL Block V test requirements are as follows:

- **Thermal Cycling** – The module is subjected to 200 thermal cycles of -40°C to $+90^{\circ}\text{C}$ to verify its ability to withstand thermal stress caused by diurnal and climatic variations.
- **Humidity-Freezing** – The module is subjected to $+85^{\circ}\text{C}$ @ 85% relative humidity and then dropped to -40°C once a day for a total of 10 days to verify its ability to tolerate exposure to moisture during service.
- **Cyclic Pressure Loading** – The module is subjected to 10,000 pressure cycles of -50 psf to $+50$ psf to verify its ability to withstand variable pressure loads caused by gusting winds.
- **Twisted Mounting Surface Requirement** – The module surface is twisted 20 mm per meter of length to ensure that it can function under sustained distortion caused by mounting on a nonplanar structure.

Modules must pass several other electrical and mechanical tests to meet JPL Block V specifications. Modules that pass JPL Block V testing should prove to be extremely reliable in the field.

4.7 Selecting Arrays



The size of the photovoltaic array is determined by considering electrical loads, available solar insolation, tilt of the array and characteristics of the individual photovoltaic modules that make up the array.

4.7.1 Selection Criteria. Selection criteria for the array are established by the designer and typically vary from one application to another. When choosing a specific photovoltaic module with which to build an array, the following factors should be considered:

- Voltage-current characteristics of the module
- Long-term reliability of the modules
- Power output density
- Suitability for high-temperature operation
- Suitability for self-regulated operation
- Material and performance stability over time
- Laminate construction
- Dimensions and weight
- Junction box/wiring configuration
- Framing materials: strength and corrosion resistance
- Bypass diode arrangement
- Availability of auxiliary hardware
- Reputation of manufacturer
- Cost and warranty.

4.7.2 Procurement Specifications. Procurement specifications for modules and arrays can be either very simple and brief, or much more detailed. One or more of the following module specifications may be selected:

- Module manufacturer and model number
- Module dimensions
- Number and wiring arrangement of cells in the module
- Junction box configuration
- Module bypass diode arrangement

- Module maximum power, maximum power current, maximum power voltage, short-circuit current, open-circuit voltage and associated rating conditions
- Module current and voltage temperature coefficients
- Module laminate materials
- Module framing materials.

To adequately describe an array and accessory components in a procurement specification, the following items should be considered, although not all of them are normally required:

- Number and wiring arrangement of modules in the array
- Total number of modules in array
- Total array area
- Array dimensions
- Array bypass diode arrangement
- Array-source circuit-disconnect arrangement
- Overcurrent protection
- Surge protection
- Number and arrangement of blocking diodes
- Intermodule and array wiring specification
- Power, current and voltage ratings at standard operating conditions
- Array circuit grounding arrangement
- Mounting type, materials and structural specification
- Fastener specification
- Module framing and array mounting hardware grounding arrangement
- Instrumentation and provisions for diagnostics.

References:

Russell, Miles, **Residential Photovoltaic System Handbook**, Reading, MA: Sundance Publications, 1984, pp. 128-9.

Ross, Ronald G., Jr., **Photovoltaic Module and Array Design**, Las Vegas, NV: 18th IEEE Photovoltaic Specialists Conference, 1985, pp. 107-130.

Exercises

1. A photovoltaic module has $I_{sc}=3.0$ amps, $V_{oc}=22.0$ volts, $I_{mp}=2.7$ amps, and $V_{mp}=17.0$ volts at standard test conditions (STC). Sketch the I-V curve and:
 - a) Compute the maximum power output, P_{max} , at STC.
 - b) Compute the module fill factor, FF.
2. If the module of problem 1 is directly connected to a 6-ohm resistor, what is the approximate operating voltage?
3. At an irradiance level of 640 W/m^2 and cell temperature of 35°C , the following current-voltage (I-V) measurements were made:

Current (amps)	Voltage (volts)
0.41	0
0.41	6
0.41	8
0.41	10
0.41	13
0.39	16
0.35	18
0.26	20
0	22

- a) What is the approximate value of P_{max} ?
 - b) What is the approximate value of P_{max} at 1000 W/m^2 irradiance?
 - c) What would be the approximate value of P_{max} at 500 W/m^2 irradiance?
4. If the module of problem 3 is connected directly to a 12-volt battery, determine the approximate module operating current, voltage and power.

Exercises (cont.)

5. If the module of problem 3 is connected directly to a 24-volt battery, what would happen? What kind of protection diode should you use to minimize the problem caused by this arrangement? Explain.
6. How does the I-V curve for PV modules connected in series differ from the I-V curve for PV modules connected in parallel? Draw sketches for both cases.
7. For the modules in problem 6, explain what happens if the PV modules are unmatched. Sketch the corresponding I-V curves.



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Photovoltaic System Components

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Objectives

- 1) *Define the two major categories of photovoltaic systems.*
- 2) *Draw block diagrams of stand-alone PV systems.*
- 3) *List the major components in stand-alone PV systems.*
- 4) *Identify selection criteria for electrical loads used in stand-alone PV systems.*
- 5) *Describe the functions of electrical loads, batteries, charge controllers and inverters.*
- 6) *Identify basic battery components and characteristics.*
- 7) *List common types of storage batteries used in stand-alone PV systems.*
- 8) *Apply the concepts in this section to the PV system design process.*

Key Words

<i>Utility-interactive system</i>	<i>Formation</i>	<i>Series circuit</i>
<i>Stand-alone system</i>	<i>Primary battery</i>	<i>Voltage</i>
<i>Direct-coupled system</i>	<i>Secondary battery</i>	<i>Capacity</i>
<i>Hybrid system</i>	<i>SLI battery</i>	<i>Parallel circuit</i>
<i>Electrical loads</i>	<i>Motive power battery</i>	<i>Conductor</i>
<i>Storage batteries</i>	<i>Stationary battery</i>	<i>Overcurrent</i>
<i>Cell</i>	<i>Lead-acid battery</i>	<i>Hydrometer</i>
<i>Plate</i>	<i>Lead-antimony battery</i>	<i>Load tester</i>
<i>Grid</i>	<i>Lead-calcium battery</i>	<i>Specific gravity</i>
<i>Active material</i>	<i>Captive electrolyte battery</i>	<i>Voltage regulator</i>
<i>Separator</i>	<i>Gelled battery</i>	<i>Charge controller</i>
<i>Electrolyte</i>	<i>AGM battery</i>	<i>Set point</i>
<i>Case</i>	<i>Nickel-cadmium battery</i>	<i>Temperature compensation</i>

5.1 Introduction

A photovoltaic (PV) array produces electricity directly from sunlight. However, to be useful this energy must be properly controlled, stored, converted and distributed. Several components, in addition to the PV array, are required to perform these functions. This section provides an overview of the common types and classifications of photovoltaic systems, considerations of electrical loads, and describes the design and performance characteristics of common components such as batteries, battery charge controllers, inverters and other balance of system (BOS) components.

5.1.1 Types of Photovoltaic Systems

Photovoltaic systems are generally divided into two major categories: utility-interactive (grid-connected), and stand-alone, described as follows:

UTILITY-INTERACTIVE SYSTEMS - Sometimes referred to as grid-connected, these systems require an interface with the utility grid to operate. They usually do not have backup or energy storage, and the power produced by the PV system is delivered first to the system loads, with the balance delivered to the utility grid. When the loads exceed the power produced by the PV system (at night and during low insolation periods), the balance of required power is taken from the utility grid. As a result these systems involve a bi-directional flow of energy between the PV system and the utility grid. A primary component of grid-connected PV systems is the power conditioner or inverter that converts the dc energy produced by the PV array to ac energy at the appropriate voltage, phase and frequency. These power conditioners are often referred to as synchronous inverters, because they match or synchronize their output power phase and frequency with the utility grid. Utility-interactive inverters are different from stand-alone inverters, as they can not operate without connection to an energized utility grid.

Compared to common utility energy rates and because of their high life cycle energy costs, grid-connected PV systems have had limited application. Utility-interactive systems, their components and interconnect considerations, are discussed in Section 11 of this manual.

Figure 5.1 is a basic diagram of a utility-interactive PV system.

Utility-Interactive PV System

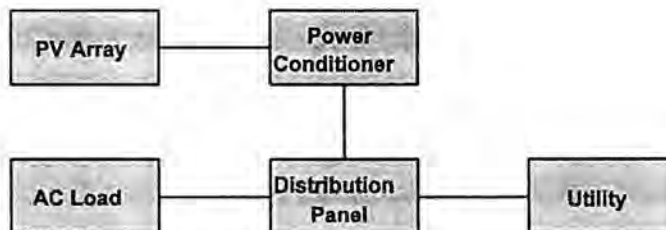


Figure 5.1

STAND-ALONE SYSTEMS - This type of PV system operates autonomously or independently of the electric utility grid. Stand-alone PV systems are a large part of the photovoltaic market because of their practical and cost-effective use in a variety of remote power needs. A few common types of stand-alone PV systems are defined as follows:

Direct-Coupled Systems - This is the simplest type of stand-alone PV system, configured with a dc load directly connected to the positive and negative terminals of a PV module or array. Direct-coupled systems have no electrical storage and can only be used when the load requirements and the power produced by the PV array coincide. Common direct-coupled applications include water pumping/circulation and ventilation fans. DC-powered refrigerators may even be operated directly-coupled to PV arrays, if sufficient thermal storage is available to maintain required temperatures at night and during period of below-average insolation. A critical factor in direct-coupled PV system design is matching the load with the maximum power output of the PV array. (Laboratory 2 in the accompanying laboratory manual for this course investigates the direct-coupling of loads to PV arrays.) Figure 5.2 illustrates a direct-coupled PV system.

Direct-Coupled Stand-Alone PV System



Figure 5.2

Battery Storage Systems: Since the power produced by a PV array can not always be used when it is produced, energy storage in the form of batteries is required in stand-alone PV systems. These types of systems do not use battery charge control and are typically used when the load profile is well defined and the battery is oversized with respect to the PV array, resulting in low charge rates. PV-powered navigational aids designed by the U.S. Coast Guard are typically of this type. Figure 5.3 illustrates a stand-alone PV system with battery storage.

Stand-Alone PV System With Battery Storage



Figure 5.3

Battery Storage with Charge Control: If the load is variable (not well defined), and the battery is marginally or optimally sized with respect to the PV array and load, a battery charge controller is generally required to protect the battery from overcharge and overdischarge. The types and characteristics of battery charge controllers are detailed later in this section. Figure 5.4 illustrates a stand-alone PV system with battery storage and charge control.

Stand-Alone PV System With Battery Storage and Charge Control

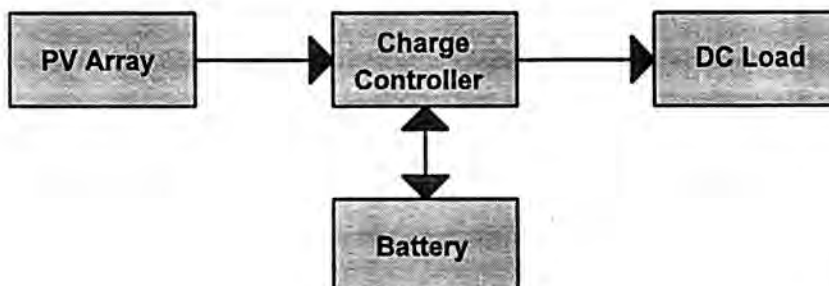


Figure 5.4

Battery Storage With AC and DC Loads: In some cases, it may be required to power both ac and dc electrical loads in stand-alone PV systems. In these cases, an inverter is needed to convert the dc battery energy to ac energy. Figure 5.5 illustrates a stand-alone PV system with battery storage, charge control, and ac and dc electrical loads.

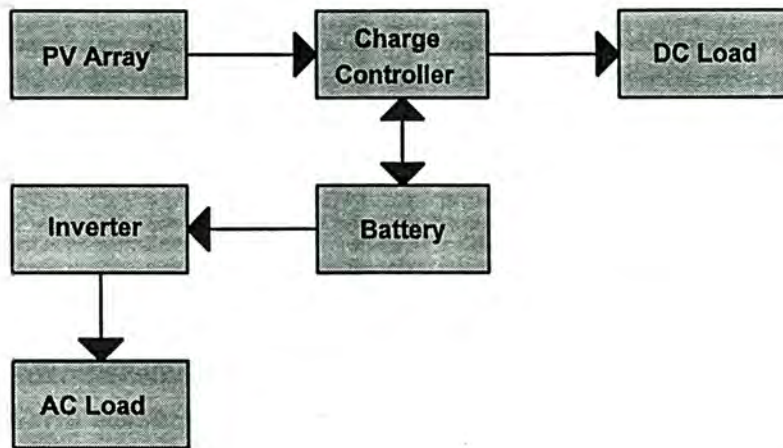
Stand-Alone PV System with DC and AC Loads

Figure 5.5

Hybrid Systems: This is a type of stand-alone PV system with one or more energy sources, in addition to the PV array, that may be used for battery charging. Common energy sources used in PV hybrid systems include wind turbine generators, and diesel or gas fueled engine generator sets. Figure 5.6 illustrates a typical hybrid system.

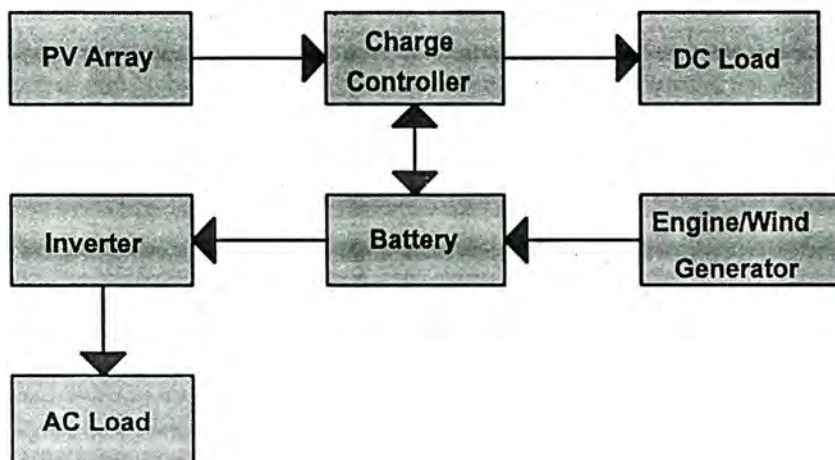
Stand-Alone Hybrid PV System with DC and AC Loads

Figure 5.6

5.1.2 BOS Components

BOS (balance of system) is a term used to classify equipment, materials and hardware in a PV system, other than the PV array. Primary BOS components include batteries, battery charge controllers and inverters. Electrical BOS hardware includes disconnect and overcurrent protection devices, diodes, surge suppressors and grounding equipment. Mechanical BOS hardware includes such items as the array support structure, enclosures, ventilation, etc. An overview of electrical and mechanical BOS components is given in sections 7 and 8 of this manual.

5.2 Electrical Loads

Electrical loads are defined as the end-use appliances, devices or equipment that require electricity to operate. In stand-alone PV systems, electrical loads may include lights, water pumps, refrigerators, fans, telecommunication equipment, common household appliances or any other electrically-operated devices. PV systems can operate any types of electrical loads, so designers should have a good understanding of them and their voltage, current, and power requirements. This is essential knowledge for designing the PV electrical system, and if required, specifying the type of power conditioning equipment.

Quantifying the electrical loads (developing the system load profile) is the first critical step in sizing stand-alone PV systems. The magnitude and duration of the electrical loads determine the type, size and performance requirements of the PV system. Considerable variations exist in the energy consumption and efficiency of electrical loads, making the load selections an important part of the design process. Electrical loads should be as energy efficient as possible, because they dictate the overall size and cost of the PV system.

Many electrical loads require alternating current (ac) electricity, rather than the direct current (dc) available from the photovoltaic array and battery subsystem. Alternating current loads include most common household appliances, power tools, office equipment and other devices or equipment that operate from utility-supplied power. When possible, dc-powered electrical loads should be used in stand-alone PV systems, thereby eliminating the need for an *inverter* and usually resulting in a more energy-efficient, simplified system design. For cases that require ac and dc loads, the designer must carefully consider which loads are best served by using dc versus ac power, as this affects the size and selection of the inverter. (In many cases, dc-powered appliances may be substituted for ac-powered ones.)

5.2.1 Common Types and Characteristics of Electrical Loads

Several varieties of electrical loads can provide the same results. For example, one person might illuminate a walkway with fluorescent fixtures, while another might use standard incandescent bulbs. The most common types of electrical loads and their characteristics are discussed below:

Resistive Loads - Resistive loads are those electrical loads that utilize the flow of current through a filament, wire, coil or other resistive element to produce heat or light. Common examples of resistive loads include incandescent lamps, electric water and space heaters, clothes dryers, electric blankets, toasters and electric ranges. Resistive loads are flexible because they can be operated on either direct or alternating current at their rated voltage. In general, resistive loads are simple, low cost, and widely available. However, they are inefficient and expensive to operate when compared to competing alternatives. For example, fluorescent and high intensity discharge lamps are several times more efficient than resistive incandescent, and propane or natural gas is less expensive than electricity to operate those devices producing heat, such as cooking and space heating appliances. For domestic water heating, solar water heating is generally an economical alternative to electric or gas-fired heaters.

Motor Loads - Electric motors are devices that convert electrical energy into rotational mechanical energy. Generators are essentially motors driven by a rotational force that produces electrical energy. A motor operates by passing a current through a wire loop, or armature in a magnetic field, causing the armature to rotate. Electric motors can be operated with either dc or ac power (i.e., a universal type motor), depending on their design.

Electric motors are used to power pumps, compressors, fans, kitchen appliances, power tools and many commercial and industrial processes. The characteristics of the electrical load created by a motor depends to somewhat on the mechanical load it is powering. This can be seen when operating centrifugal and positive displacement pumps that impose different loading on the motor. The size and performance of electric motors varies widely, depending on the mechanical load or horsepower to be delivered (i.e., the torque and speed).

The common types of electric motors are discussed below:

DC Motors - To maintain the same direction armature rotation in a dc motor, the direction of the current in the armature is switched each half rotation by means of a split-ring commutator and brushes. Permanent magnets are used for the magnetic field in small dc motors, and electromagnets are used in larger designs. Series and shunt are two types of dc motors. The series type is more commonly used because it performs better over a greater speed range than the shunt motor. DC motors are often directly coupled to PV arrays in water pumping systems using water storage, and for an effective pumping system, it is important to match the pump/motor load with the PV array maximum power points.

AC Motors - In an ac motor, current fed into the armature windings cause it to rotate in the magnetic field, thus turning the shaft. Since the ac current switches every half cycle, there is no need for a split-ring commutator, as in the dc motor. A disadvantage of ac motors is that speed control is difficult and must be done by varying the frequency of the input power. Synchronous motors are designed to rotate one revolution every cycle of the alternating current supply (60 Hz ac power results in 60 revolutions per second, or 3600 revolutions per minute). Synchronous motors are used in applications when maintaining exact speed is critical, (i.e., generators). Induction motors constitute the majority of the motors in use today,

because they are simple to build, inexpensive and robust.

5.3 Storage Batteries

In stand-alone photovoltaic systems, the electrical energy produced by the PV array can not always be used immediately. Because the demand for energy does not always coincide with its production, electrical storage batteries are commonly used in PV systems. The primary functions of a storage battery in a PV system are to:

- a) store electrical energy when it is produced by the PV array and supply energy to electrical loads as needed;
- b) supply power to electrical loads at stable voltages, by suppressing or "smoothing out" transient voltages that may occur in PV systems; and
- c) supply surge or high peak operating currents to electrical loads or appliances.

A storage battery is an electrochemical cell that stores energy in chemical bonds. When a battery is connected in a circuit to an electrical load, such as an incandescent light or resistor, the chemical energy within a battery is converted to electrical energy and there is a flow of current through the circuit.

An understanding of storage battery design, terminology and performance characteristics is essential in the design of stand-alone PV systems. The next sections describe basic battery components and terminology including manufacturing, cell design, types and classifications, performance characteristics, charging requirements, and design and selection criteria.

5.3.1 Battery Design and Manufacturing

Battery manufacturing is an intensive, heavy industrial process involving the use of hazardous and toxic materials. Batteries are generally mass produced, combining several sequential and parallel processes to construct a complete battery unit. After production, initial charge and discharge cycles are conducted on batteries before they are shipped to distributors and consumers.

Cell - The basic electrochemical unit in a battery, consisting of a set of positive and negative plates divided by separators, immersed in an electrolyte solution and enclosed in a case. In a typical lead-acid battery each cell has a nominal voltage of 2.1 volts, so there are 6 series cells in a nominal 12-volt battery. Figure 5.7 is a diagram of a basic battery cell.

Battery Cell Composition

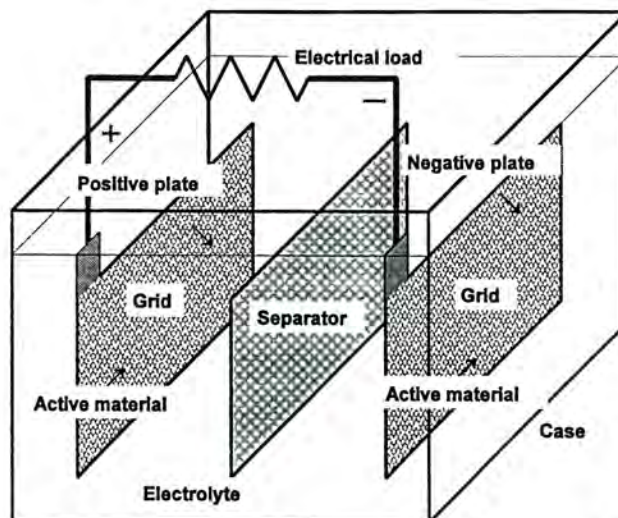
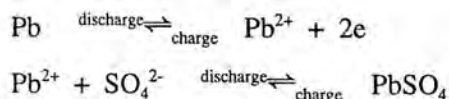


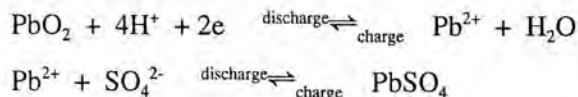
Figure 5.7

Active Material - The raw composition materials forming the positive and negative plates, and the reactants in the electrochemical cell. The amount of active material in a battery is proportional to the capacity a battery can deliver. In lead-acid batteries, the active materials are lead dioxide (PbO_2) in the positive plates and metallic sponge lead (Pb) in the negative plates, which react with a sulfuric acid (H_2SO_4) solution during battery discharging. During charging, the directions of the reactions are reversed. The electrochemical reactions for the lead-acid cell are:

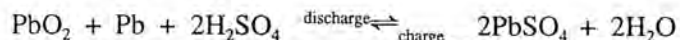
At the negative plate or electrode:



At the positive plate or electrode:



Overall cell reaction:



Grid - A lead alloy framework supporting the active material on a battery plate, and also conducting current (see Figure 5.7). Alloying elements such as antimony and calcium are often used to strengthen the lead grids, and have characteristic effects on battery performance such as cycle performance and gassing.

Plate - A basic battery component, consisting of a grid and active material, sometimes called an electrode (see Figure 5.7). There are generally a number of positive and negative plates in each battery cell, typically connected in parallel at a bus bar or intercell connector at the top of the plates. A pasted plate is manufactured by applying a mixture of lead oxide, sulfuric acid, fibers and water on to the grid.

Separator - A porous, insulating divider between the positive and negative plates in a battery, used to keep the plates from coming into electrical contact and short-circuiting, and that allows the flow of electrolyte and ions between the positive and negative plates (see Figure 5.7). Separators are made from microporous rubber, plastic or glass-wool mats.

Electrolyte - A conducting medium that allows the flow of current through ionic transfer, or the transfer of electrons between the plates in a battery. In a lead-acid battery, the electrolyte is a diluted sulfuric acid solution, either in liquid (flooded) form, gelled or absorbed in glass mats.

Case - Commonly made from a hard rubber or plastic, the case is the container that encloses the *plates*, *separators* and *electrolyte* in a battery. The case is typically enclosed, with the exception of inter-cell connectors that attach the plate assembly from one cell to the next, and *vents* or caps that allow *gassing* products to escape and, if required, permit water additions.

Formation - The process of initial battery *charging* during manufacturing. Formation of a lead-acid battery changes the lead oxide (PbO) on the positive plate grids to lead dioxide (PbO₂), and to metallic sponge lead (Pb) on the negative plates. The extent that a battery is formed during manufacturing, dictates the need for additional cycles (by the user) to achieve rated capacity.

5.3.2 Battery Performance Characteristics

Ampere-Hour (Ah) - The common unit of measure for a battery's electrical storage capacity, obtained by integrating the discharge current in amperes over a specific time period. An ampere-hour is equal to the transfer of one ampere over one hour, equal to 3600 coulombs of charge. (i.e., a battery that delivers 5-amps for 20 hours is said to have delivered 100 ampere-hours.)

Capacity - A measure of a battery's ability to store or deliver electrical energy, commonly expressed in units of ampere-hours. Capacity is generally specified at a specific discharge rate, or over a certain time period. The capacity of a battery depends on several design factors including the quantity of active material, the number, design and physical dimensions of the plates, and the electrolyte specific gravity. Operational factors affecting capacity

include discharge rate, depth of discharge, cut off voltage, temperature, age and cycle history of the battery. A battery's energy storage capacity is sometimes expressed in kilowatt-hours (kWh), which can be approximated by multiplying the rated capacity in ampere-hours by the nominal battery voltage and dividing the product by 1000. (i.e., a nominal 12-volt, 100 ampere-hour battery has an energy storage capacity of $(12 \times 100)/1000 = 1.2$ kilowatt-hours.)

Cut Off Voltage - The lowest voltage that a battery system is allowed to reach in operation, defining the battery capacity at a specific discharge rate. Manufacturers often rate capacity to a specific cut off, or end of discharge voltage at a defined discharge rate. If the same cut off voltage is specified for different rates, the capacity will generally be higher at the lower discharge rate.

Cycle - In battery terminology, a cycle refers to a discharge to a given depth of discharge followed by a complete recharge. A 100 percent depth of discharge cycle provides a measure of the total battery capacity.

Discharge - The process when a battery delivers current, quantified by the discharge current or rate. Discharge of a lead acid battery involves the conversion of lead, lead dioxide and sulfuric acid to lead sulfate and water.

Charge - The process when a battery receives or accepts current, quantified by the charge current or rate. Charging of a lead acid battery involves the conversion of lead sulfate and water to lead, lead dioxide and sulfuric acid.

Rate of Charge/Discharge - The rate of charge or discharge of a battery is expressed as a ratio of the nominal battery capacity to the charge or discharge time period in hours. For example, a 4-amp discharge for a nominal 100 ampere-hour battery would be considered a C/20 discharge rate.

Negative (-) - The lower potential point in a dc electrical circuit. The negative battery terminal is the point that electrons or the current flows from during discharge.

Positive (+) - The higher potential point in a dc electrical circuit. The positive battery terminal is the point that electrons or the current flows from during charging.

Open Circuit Voltage - The voltage when a battery is at rest or steady-state, not during charge or discharge. Depending on the battery design, specific gravity concentration and temperature, the open circuit voltage of a fully charged lead-acid battery is typically 2.1-volts.

Battery Charging - Manufacturers often refer to three recommended modes of battery charging; normal (bulk charge), finishing (float charge) and equalizing charge.

Bulk or Normal Charge - An unregulated charge, usually at higher charge rates, occurring between zero and 80% state of charge.

Float or Finishing Charge - Above 80% SOC most of the active material in the battery has been replenished, and voltage and current regulation are generally employed to limit the amount of overcharge supplied to the battery.

Equalizing Charge - An equalizing or refreshing charge is required periodically for many lead-acid battery types, to attain full-rated battery capacity. An equalizing charge generally consists of a current-limited charge to higher voltage limits than set for the finishing or float charge. The equalizing charge provides overcharge to the battery, and in lead-acid designs is used to reverse the effects of sulfation due to prolonged operation at partial states of charge. Equalization is also used to reestablish consistency among cells in a series string that have become unequal in terms of capacity.

Short-Circuit - An extreme low resistance current path allowing high current flows. Common lead-acid batteries can deliver over 1000 amps short-circuit, and require special precaution when handling. A short-circuit between cell plates within a battery, may discharge the cell.

Specific Gravity (sg) - The ratio of the density of a solution to the density of water, typically measured with a hydrometer. By definition, water has a specific gravity of one. Specific gravity is related to the state of charge in a battery, depending on the electrolyte concentration and temperature. Typical ranges of specific gravity for flooded lead-acid batteries are from 1.28 for a fully charged battery, to 1.00 for a fully discharged battery. In very cold climates, the concentration of the sulfuric acid solutions in lead-acid batteries is often increased above a specific gravity of 1.28 to increase the reaction rate. Similarly, in tropical or very warm climates, the electrolyte is often diluted below 1.28 sg to extend battery life. Although it is not an accurate measure of battery capacity, low specific gravity readings may indicate sulfation, stratification, or lack of equalization between cells. Table 5.1 shows the typical relationship between specific gravity and the freezing point in a lead-acid battery.

Table 5.1 Properties of Sulfuric Acid Solutions

Specific Gravity	H ₂ SO ₄ (Wt%)	H ₂ SO ₄ (Vol%)	Freezing Point (°C)
1.000	0.0	0.0	0
1.050	7.3	4.2	-3.3
1.100	14.3	8.5	-7.8
1.150	20.9	13.0	-15
1.200	27.2	17.1	-27
1.250	33.4	22.6	-52
1.300	39.1	27.6	-71

Sulfation - A process occurring in a lead-acid battery resulting from prolonged operation at partial states of charge and involving the growth of lead sulphate crystal on the positive plate, thus decreasing the active area of the cell. Sulfation leads to higher internal resistance within the battery and makes it more difficult to recharge, limiting capacity. Proper battery and array sizing, and periodic equalization charges can reduce or prevent sulfation.

Stratification - A condition occurring in a flooded battery when the concentration or specific gravity of the electrolyte increases from the bottom to the top of a cell. Stratification results from undercharging, or insufficient gassing to agitate the electrolyte during the finishing charge. Prolonged stratification can shorten battery life because the upper portion of the plates remain in relatively good shape, while the bottom portion may be consumed. Periodic equalization charges, or in extreme cases mechanical agitation can be used, to destratify the electrolyte.

Internal Resistance - A characteristic of batteries that dictates the voltage change in a battery from its open-circuit voltage under a specific charge or discharge current. Many factors affect a battery's internal resistance including the battery design, state of charge, temperature, and operational history. In general, the internal resistance of a battery increases as it ages and becomes fully charged.

Depth of Discharge (DOD) - Battery depth of discharge is defined as the percentage of capacity withdrawn from a battery, compared to the total fully-charged capacity. By definition, the battery depth of discharge and state of charge total 100 percent. The two common qualifiers for depth of discharge are the allowable (maximum DOD) and the average daily DOD described as follows:

Allowable DOD - The maximum percentage of full-rated capacity withdrawn from a battery is its allowable depth of discharge. The allowable DOD is the battery's

maximum discharge limit, generally dictated by the cut off voltage and discharge rate. The low voltage load disconnect (LVD) set point of the battery charge controller in stand-alone PV system, dictates the allowable DOD limit at a given discharge rate. Furthermore, the allowable DOD is generally a seasonal deficit, resulting from low insolation, low temperatures and/or excessive load usage. Depending on the type of battery used in a PV system, the design allowable depth of discharge may be as high as 80% (deep cycle, motive power batteries), to as low as 15-25% (SLI batteries). The allowable DOD is related to the autonomy, in terms of the capacity required to operate the system loads for a given number of days without energy from the PV array. A system design with a lower allowable DOD will result in a shorter autonomy period.

Average Daily DOD - The average daily depth of discharge is the percentage of the full-rated capacity withdrawn from a battery as determined by the average daily load profile. When the load varies seasonally in a PV system, the average daily DOD will be greater in the winter months due to a longer nightly load operation period. For PV systems with a constant daily load, the average daily DOD is generally greater in the winter due to lower battery temperature and lower rated capacity. Depending on the rated capacity and the average daily load energy, the average daily DOD may vary between only a few percent in systems designed with maximum autonomy, or as high as 50 percent for marginally sized battery systems. The average daily DOD is inversely related to autonomy, meaning systems designed for longer autonomy periods have a lower average daily DOD.

State of Charge (SOC) - The amount of energy in a battery, expressed as a percentage of the energy stored in a fully charged battery. Discharging a battery results in a *decrease* in state of charge, while charging results in an *increase* in state of charge. A battery that has had three quarters of its capacity removed, or been discharged 75 percent, is said to be at 25 percent state of charge. Figure 5.8 illustrates the seasonal variation in battery state of charge and depth of discharge for a typical PV system.

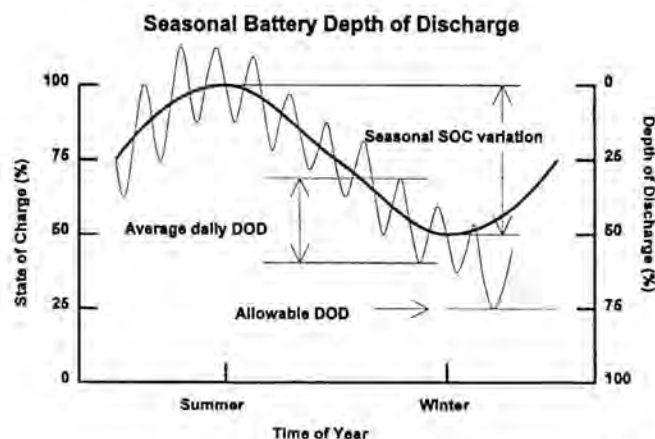


Figure 5.8

Autonomy - Autonomy refers to the time (days of storage) a fully charged battery can supply energy to a stand-alone PV system's loads when there is no energy supplied by the PV array. For common, less critical PV applications, autonomy periods typically range between two and six days. For critical applications involving essential loads or public safety, or where weather patterns dictate, autonomy periods may be greater than ten days.

Longer autonomy periods generally result in a lower average daily DOD, and decrease the probability that either the allowable DOD or the minimum load voltage will be reached.

Minimum Load Voltage - The minimum voltage which electrical loads in the PV system are designed or permitted to operate, determined by the allowable depth of discharge and low voltage load disconnect set point on the battery charge controller.

Self Discharge Rate - In open-circuit mode without any load or charging, a battery undergoes a reduction in state of charge, due to internal mechanisms and losses within the battery. Different battery types have different self discharge rates, with the most significant factor being the active materials and grid alloying elements used in the design. Higher temperatures result in higher discharge rates, particularly for lead-antimony designs. Figure 5.9 shows the effects of battery cell temperature on the self discharge rate for lead-acid batteries with lead-calcium and lead-antimony grids.

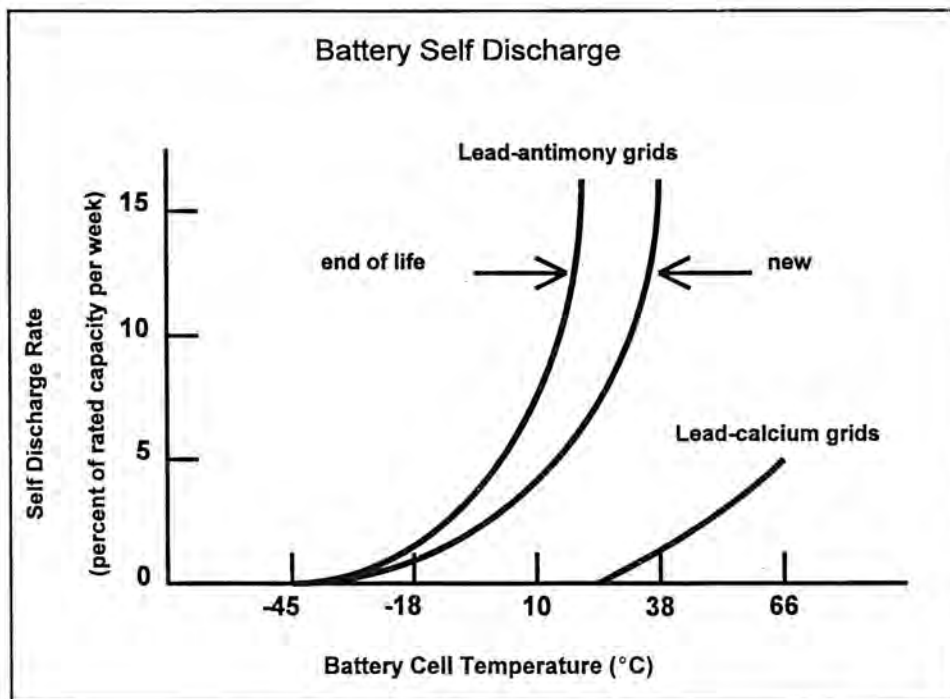


Figure 5.9

Effects of Depth of Discharge on Lead-Acid Battery Cycle Life

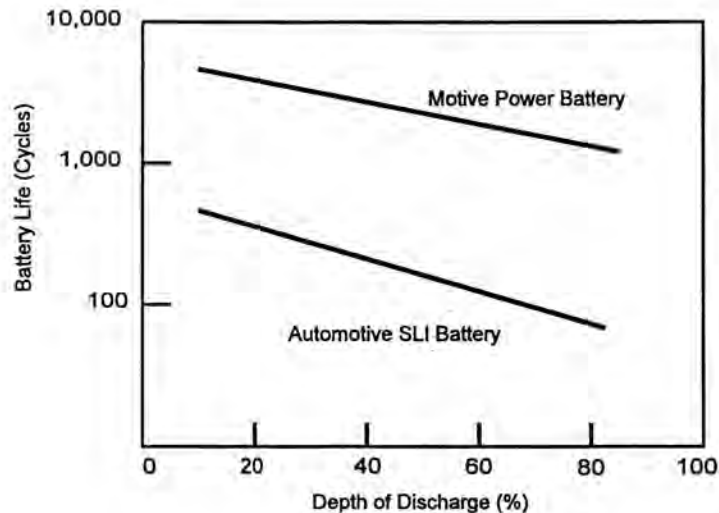


Figure 5.10

Battery Lifetime - Battery lifetime depends on a number of design and operational factors, including the components and materials of battery construction, temperature, frequency and depth of discharge, average state of charge and charging methods. If a battery is not overcharged, overdischarged, or operated at excessive temperatures, its lifetime will be proportional to its average state of charge. A typical flooded lead-acid battery maintained above 90 percent state of charge will provide two to three times more full charge/discharge cycles than a battery allowed to reach 50 percent state of charge before recharging. This suggests limiting the allowable and average daily DOD to prolong battery life.

Lifetime can be expressed in terms of cycles or years, depending on the particular type of battery and its intended application. Due to the number of variables involved, exact battery life quantification is difficult and generally requires battery test results under similar operating conditions. Battery manufacturers often do not rate battery performance under the conditions of charge and discharge experienced in PV systems. However, a reasonable estimate of battery life can be determined with knowledge of PV system operational characteristics and battery performance data.

Temperature Effects - Temperature has important effects on performance in an electrochemical cell such as a battery. As the temperature increases by 10°C , the rate of an electrochemical reaction doubles, resulting in recommendations from battery manufacturers that battery life decreases by a factor of two for every 10°C increase in average operating temperature. Higher operating temperatures accelerate corrosion of the positive plate grids and result in greater gassing and electrolyte loss. Lower operating temperatures generally

increase battery life. However, the capacity is significantly reduced, particularly for lead-acid batteries. When severe temperature variations from room temperatures exist, batteries should be located in an insulated or other temperature regulating enclosure to minimize battery temperature swings. Figure 5.11 shows the effects of temperature on lead-acid battery life.

Effects of Temperature on Lead-Acid Battery Life

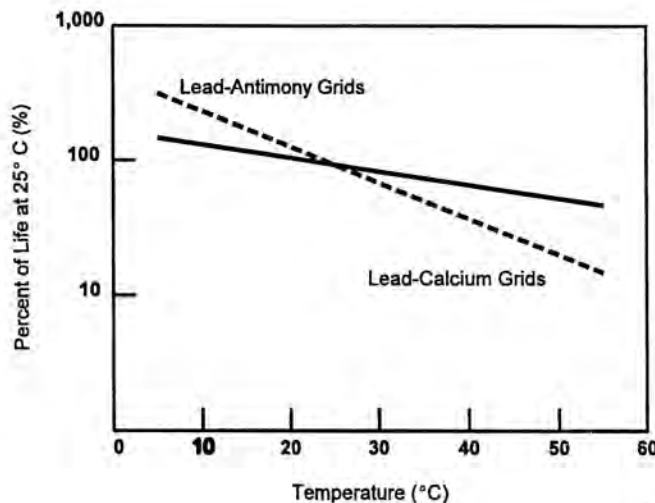


Figure 5.11

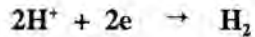
Effects of Discharge Rates - The higher the discharge rate or current, the lower the capacity that can be withdrawn from a battery to a specific allowable DOD or cut off voltage. Higher discharge rates can also result in the voltage under load to be lower than with lower discharge rates, sometimes affecting the selection of the low voltage load disconnect set point. At the same battery voltage, the lower the discharge rates, the lower the battery state of charge compared to higher discharge rates.

Corrosion - The electrochemical activity resulting from the immersion of two dissimilar metals in an electrolyte, or the direct contact of two dissimilar metals causing one material to oxidize (lose electrons) and the other material to undergo reduction (gain electrons). Corrosion of the grids supporting the active material in a battery is an ongoing process and may ultimately dictate the battery's useful lifetime. Battery terminals may also experience corrosion due to electrolyte gassing from the battery, and flooded lead-acid types will require periodic cleaning and tightening. Higher temperature and the flow of electrical current between two dissimilar metals accelerates the corrosion process.

Gassing - A common occurrence in batteries, generally an overcharge or end of charge process resulting in the evolution of gas products. The gas products are either recombined within the cell, or released through cell vents. In a flooded lead-acid battery, gassing results in the formation of hydrogen at the negative plate and oxygen at the positive plate, requiring

periodic water addition to replenish the electrolyte. The gassing, or overcharge reaction in a lead-acid cell is illustrated as follows:

At the negative plate or electrode:



At the positive plate or electrode:



Overall cell overcharge reaction:



Overcharge - A process that occurs when all of the active material in a battery has been converted to its fully charged composition, resulting in gassing and loss of electrolyte. A certain amount of overcharge is needed to fully charge batteries, but excessive overcharge results in considerable water loss and corrosion of the positive plate grids.

Electron - An elementary particle that is a fundamental constituent of matter, with a charge of 1.602×10^{-19} coulombs. Since an ampere is the flow of one coulomb of charge per second, it follows that an ampere equals the flow of 6.24×10^{18} electrons per second.

Voltage Drop - The net potential or voltage difference when measured across a resistance to current flow. Voltage drop limitations are often used to size battery cables to components such as inverters and to the PV array through a charge controller.

5.3.3 Battery Types and Classifications

Many types and classifications of batteries are manufactured today, with specific designs and performance characteristics suited for particular applications. Lead-acid batteries are most common in PV systems, due to their wide availability, low cost and known performance characteristics. A few critical low-temperature applications require nickel-cadmium cells but their high initial cost limits their use in most PV systems. There is no *perfect battery* and it is the task of the PV system designer to decide which battery type is most appropriate for each application. Electric storage batteries can be divided into two major categories, primary and secondary batteries.

Primary Battery - A battery that can store and deliver electrical energy, but can not be recharged. Carbon-zinc and lithium batteries commonly used in consumer electronic devices are primary batteries. Primary batteries *are not used* in PV systems.

Secondary Battery - A battery that can store and deliver electrical energy, and *can also be recharged* by passing a current through it in an opposite direction to the discharge current. The two types of secondary batteries used in PV systems are lead-acid (common automobile

battery) and nickel-cadmium. Table 5.2 lists common secondary battery types and their characteristics, followed by a detailed discussion of each.

Table 5.2 Secondary Battery Types and Characteristics

Battery Type	Cost	Deep Cycle Performance	Maintenance
Flooded Lead-Acid			
Lead-Antimony	low	good	high
Lead-Calcium Open Vent	low	poor	medium
Lead-Calcium Sealed Vent	low	poor	low
Lead-Antimony/Calcium Hybrid	medium	good	medium
Captive Electrolyte Lead-Acid			
Gelled	medium	fair	low
Absorbed Glass Mat	medium	fair	low
Nickel-Cadmium			
Sintered Plate	high	good	none
Pocket-Plate	high	good	medium

5.3.3.1 Lead-Acid Battery Classifications

Many types of lead-acid batteries are used in PV systems, but traction or motive power types are preferred because of their deep cycle capability and long life.

SLI Batteries - Starting, lighting and ignition (SLI) batteries are a type of lead-acid battery (commonly used to power automobile starters) designed primarily for shallow cycle service. SLI batteries have a number of thin positive and negative plates per cell and are designed to increase the total plate active area. The large number of plates per cell allows the battery to deliver high discharge currents for short periods. They are not designed for long life under deep cycle service, but SLI batteries are sometimes used in PV systems in developing countries where they are the only type of battery available locally. SLI batteries may provide up to two years of useful service in small stand-alone PV systems where the average daily depth of discharge is limited to 10-20 percent, and the maximum allowable depth of discharge is limited to 40-60 percent, although they are not recommended for most PV applications.

Motive Power or Traction Batteries - Motive power or traction batteries are a type of lead-acid battery designed for deep discharge cycle service. They are typically used in electrically operated vehicles and equipment such as golf carts, fork lifts and floor sweepers. These

batteries have a fewer number of plates per cell than SLI batteries. However, the plates are much thicker with a more robust construction. High content lead-antimony grids are primarily used in motive power batteries for good deep cycle performance.

Stationary Batteries - Stationary batteries are commonly used in uninterruptible power supplies (UPS) to provide backup power to computers, telephone equipment and other critical loads or sensitive equipment. Stationary batteries may share characteristics of both SLI and motive power batteries, but are generally designed for occasional deep discharge and limited cycle service. Most stationary battery applications use lead-calcium battery designs.

5.3.3.1.1 Types of Lead-Acid Batteries

Manufacturers produce several types of lead-acid batteries. The following sections describe those commonly used in PV systems.

Lead-Antimony Batteries - Lead-antimony batteries are a type of lead-acid battery that uses antimony (Sb) as the primary alloying element with lead in the plate grids. The use of lead-antimony alloys in the grids has both advantages and disadvantages. Advantages include providing greater mechanical strength than pure lead grids and excellent deep discharge and high discharge rate performance. Lead-antimony grids also limit the shedding of active material and when operated at higher temperatures they have better lifetime than lead-calcium batteries. Disadvantages of lead-antimony batteries are a high self-discharge rate and as a result of necessary overcharge (depending on the temperature and amount of overcharge), frequent water additions are required.

Most lead-antimony batteries are flooded, open vent types with removable caps for water additions. They are well suited for use in PV systems because of their deep cycle capability and ability to take abuse. However, they do require periodic water additions. Water additions can be minimized by the use of catalytic recombination caps or battery designs with excess electrolyte reservoirs. The health of flooded, open vent lead-antimony batteries can be easily checked by measuring the specific gravity of the electrolyte with a hydrometer.

Lead-antimony batteries with thick plates and robust design are generally classified as motive power or traction type batteries. They are widely available, and typically used in electrically operated vehicles where deep cycle long-life performance is required.

Lead-Calcium Batteries - A type of lead-acid battery that uses calcium (Ca) as the primary alloying element with lead in the plate grids. Like lead-antimony, the use of lead-calcium alloys in the grids has both advantages and disadvantages. Advantages include providing greater mechanical strength than pure lead grids, a low self-discharge rate, and reduced gassing resulting in lower water loss and lower maintenance requirements than for lead-antimony batteries. Disadvantages include poor charge acceptance after deep discharges, and shortened battery life at higher operating temperatures and if repeatedly discharged to greater than 25 percent depth of discharge.

Flooded Lead-Calcium, Open Vent - Often classified as stationary batteries and typically supplied as individual 2-volt cells with capacity ranges up to and over 1000 ampere-hours. Flooded lead-calcium batteries have the advantages of low self discharge and low water loss, and may last as long as 20 years in stand-by service. Unless these batteries are charged properly, they usually experience short lifetimes in PV applications due to sulfation and stratification of the electrolyte .

Flooded Lead-Calcium, Sealed Vent - Primarily developed as "maintenance free" automotive starting batteries, with a capacity in the range of 50 to 120 ampere-hours, in a nominal 12-volt unit. Like all lead-calcium designs, they are intolerant of overcharging, high operating temperatures and deep discharge cycles. These batteries are employed in small stand-alone PV systems, but must be carefully charged to achieve maximum performance.

Lead-Antimony/Lead-Calcium Hybrid - These are flooded batteries with capacity ratings of over 200 ampere-hours. A common design for this battery type uses lead-calcium tubular positive electrodes and pasted lead-antimony negative plates. This design combines the advantages of both lead-calcium and lead-antimony design, including good deep cycle performance, low water loss and long life. Stratification and sulfation can also be a problem and must be treated accordingly. These batteries are sometimes used in PV systems with larger capacity requirements.

5.3.3.1.2 Captive Electrolyte Batteries

Captive electrolyte batteries are another type of lead-acid battery and as the name implies, the electrolyte is immobilized in some manner. The battery is sealed under normal operating conditions, but the normally sealed vents open under gas pressure and excessive overcharge. Captive electrolyte batteries are often referred to as valve regulated lead-acid (VRLA) batteries, noting the pressure regulating mechanisms on the cell vents. Electrolyte can not be replenished in these battery designs, therefore they do not tolerate overcharge.

Captive electrolyte batteries are popular for PV applications because they are spill proof, easily transported, and require no water additions, making them ideal for remote applications where maintenance is unavailable. However, a common failure mode for these batteries in PV systems is excessive overcharge and loss of electrolyte, which is accelerated in warm climates. For this reason, it is essential that the battery charge controller regulation set points are adjusted properly to prevent overcharging. A benefit of captive or immobilized electrolyte designs is they are less susceptible to freezing compared to flooded batteries. Lead-calcium grids are typically used in captive electrolyte batteries, to minimize gassing. However, some designs use lead-antimony/calcium hybrid grids to gain some of the favorable advantages of lead-antimony batteries. Approximately one-half of the PV systems being installed in the U.S., use captive electrolyte or sealed batteries [4]. The two most common captive electrolyte batteries are the gelled electrolyte and absorbed glass mat designs (AGM).

Gelled Batteries - Initially designed for electronic instruments and consumer electronics, gelled lead-acid batteries generally use lead-calcium grids. The electrolyte is "gelled" by the

addition of silicon dioxide, which is then added to the battery in a warm liquid form that gels as it cools. This battery technology is very sensitive to charging methods, regulation voltage and temperature extremes. Optimal charge regulation voltages for this type of battery vary between designs, so it is necessary to follow manufacturer recommendations. The recommended charging algorithm for gelled batteries is constant-voltage, with temperature compensation of the regulation voltage required to prevent overcharge. Some gelled batteries have a small amount of phosphoric acid added to the electrolyte to improve the deep cycle discharge performance of the battery. The phosphoric acid minimizes grid oxidation at low states of charge and is similar to the common commercial corrosion inhibitors and metal preservers. Gelled batteries represent over 90 percent of the captive electrolyte batteries used in small PV systems in the U.S. [4].

Absorbed Glass Mat (AGM) Batteries - A sealed or valve regulated lead-acid battery that is similar in other respects to gelled batteries. The electrolyte is absorbed in glass mats that are sandwiched between the plates. AGM batteries are also intolerant to overcharge and high operating temperatures. (Recommended charge regulation methods stated for gelled batteries apply to AGM batteries.) The unfavorable performance of AGM batteries in early PV applications has limited their use to less than 10 percent of the captive electrolyte batteries currently used in small PV systems.

5.3.3.2 Nickel-Cadmium Batteries

Nickel-cadmium (Ni-Cad) batteries are secondary or rechargeable batteries. They have several advantages over lead-acid batteries that make them attractive for use in stand-alone PV systems. These advantages include long life, low maintenance, survivability from excessive discharges, excellent low temperature capacity retention, and non-critical voltage regulation requirements. The main disadvantages of nickel-cadmium batteries are their high cost and limited availability, compared to lead-acid designs.

A nickel-cadmium cell consists of electrodes made from nickel-hydroxide and cadmium, immersed in a potassium hydroxide electrolyte solution. The nominal voltage for a nickel-cadmium cell is 1.2-volts compared to 2.1-volts for a lead-acid cell, requiring more cells configured in series to achieve the nominal system voltage. The voltage of a nickel-cadmium cell remains relatively stable until the cell is almost completely discharged and the voltage drops off dramatically. Nickel-cadmium batteries can accept charge rates as high as C/1, and are tolerant of continuous overcharge up to a C/15 rate. Nickel-cadmium batteries are commonly subdivided into two primary types: sintered plate and pocket plate.

Sintered Plate Ni-Cads - Sintered plate nickel cadmium batteries are commonly used in electrical test equipment and consumer electronic devices. They are designed by heat processing the active materials and rolling them into a metallic case. The electrolyte in sintered plate nickel-cadmium batteries is immobilized which prevents leakage and allows any orientation for installation. The main disadvantage of sintered plate designs is the "memory effect", (a battery that is repeatedly discharged to only a percentage of its rated capacity and eventually "memorizes" this cycle pattern). This limits further discharge and

results in a loss of capacity. In some cases, the "memory effect" can be erased by conducting special charge and discharge cycles, restoring some initial rated capacity to the battery.

Pocket Plate Ni-Cads - These large nickel-cadmium batteries are used in remote telecommunication systems and other commercial applications. They are usually a flooded design called flooded pocket plate. Similar to flooded lead-acid design, these batteries require periodic water additions. They can withstand extreme discharges, temperature extremes (better than lead-acid batteries), and they do not experience the "memory effect" associated with sintered plate designs. The main disadvantage of pocket plate nickel cadmium batteries is their high initial cost. However, for some PV applications their long lifetime can result in the lowest life cycle battery cost.

5.3.4 Battery System Design and Selection Criteria

Battery system design and selection criteria involves many decisions and trade-offs. Choosing the right battery for a PV application depends on many factors and since one type of battery is not appropriate for all applications, common sense and a careful review of the battery literature and the particular application will help the designer narrow the choice. Some decisions on battery selection (i.e., physical properties) may be easy to make, while other decisions may be more difficult and might involve trade-offs between desirable and undesirable battery features. Designers should be able to differentiate among battery types and gain some application experience with batteries they are familiar with. Table 5.3 summarizes battery selection and design consideration criteria..

Table 5.3 Battery Design and Selection Criteria

• Type of system and mode of operation • Charging characteristics; internal resistance • Required days of storage (autonomy) • Amount and variability of discharge current • Maximum allowable depth of discharge • Daily depth of discharge requirements • Accessibility of location • Temperature and environmental conditions • Cyclic life and/or calendar life in years • Maintenance requirements • Sealed or unsealed • Self-discharge rate	• Gassing characteristics • Cost and warranty • Susceptibility to freezing • Maximum cell capacity • Energy storage density • Size and weight • Susceptibility to sulfation • Electrolyte concentration • Availability of auxiliary hardware • Terminal configuration • Reputation of manufacturer
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5.3.4.1 Battery Selection

Proper battery selection and design is just as important as proper sizing and treatment, in order to improve battery longevity in PV Systems. Some important battery design characteristics necessary for deep-cycle, long-life performance are:

- ▶ Low-antimony, thick plates for reducing water loss and providing adequate mechanical strength for long cycle life
- ▶ separator envelopes around positive plates, and appropriate plate edge protection to minimize the potential for internal short-circuits
- ▶ large electrolyte volume below the plates to allow for shed materials to accumulate without causing short circuits
- ▶ sufficient electrolyte volume above the plates to minimize frequency of water additions
- ▶ transparent battery containers to allow for visual inspections.

Size and Weight - Physical characteristics of batteries (large size and weight) often place restrictions on battery selection. A typical 12-volt, 100 ampere-hour flooded lead-acid battery weighs between 50 and 75 pounds and special lifting devices may be required for the larger capacity batteries.

The transportation of heavy equipment is difficult in remote PV applications and designers may use several smaller batteries or cells, rather than a few larger batteries. Consideration of the strength and dimensions of the battery enclosure or installation area must also be considered when evaluating the physical properties of batteries.

Costs - First costs often determine the battery selected by a designer. However, recurring costs (including battery maintenance and replacement), are the responsibility of the system owner/operator. The sum of the initial cost and amortized recurring costs determine a battery's life cycle cost. In many cases, a battery with a high initial cost may indeed have the lowest life cycle costs, after all factors are considered. Sometimes this is the case with higher cost nickel-cadmium cells used in critical applications. The best way to compare the cost of competing battery options is by developing a battery cost parameter that incorporates the desired performance characteristics. For any battery cost parameter, the cost of the battery is divided by the parameters to be compared (i.e., the warranty period, depth of discharge limits, cycle or year life, etc.). Based on the designer's parameters of interest, the lower the battery cost parameter, the more cost effective the battery.

Availability - Battery weight and composition (hazardous materials) result in high shipping costs, so regional battery manufacturers supply the majority of their products to local markets. This is also the case in developing countries, where the optimal battery for an application may not be locally available. So, availability is often limited when selecting the proper battery, and special attention to proper sizing and treatment is required in order to maximize battery life.

Maintenance Requirements - Battery maintenance requirements vary significantly depending on the battery design and application. Maintenance considerations may include

tightening terminals, water additions, performance checks, and cleaning cases, cables and terminals. Performance checks may include specific gravity recordings, conductance readings, temperature measurements, cell voltage readings, or even a capacity test. If applicable, auxiliary systems such as ventilation, fire extinguishers and safety equipment may need to be periodically inspected.

Flooded lead-antimony batteries require the most maintenance (water additions and cleaning). Sealed lead-acid batteries (including gelled and AGM types) remain relatively clean and do not require water additions. Battery manufacturers often provide their own maintenance recommendations. In addition, the designer may reference the IEEE publications "Recommended Practice for Installation and Maintenance of Lead-Acid Batteries for Photovoltaic Systems" and "Recommended Practice for Installation and Maintenance of Nickel-Cadmium Batteries for Photovoltaic Systems" [2,3].

5.3.4.2 Battery System Design

Once a particular battery has been selected for a PV system, the battery subsystem must be electrically integrated and connected in the system. Considerations in battery system design include the number of batteries in series and parallel, overcurrent and disconnect requirements, and selection of the proper wire sizes and types. Some of the more important aspects of battery system design follow.

Series Circuit - Batteries connected in a series circuit have only one path for the current to flow. Batteries are arranged in series by connecting the negative terminal of the first battery to the positive terminal of the second battery, the negative of the second battery to the positive of the third battery, and so on, for as many batteries in the series string. For identical batteries connected in series, the total voltage is the sum of the individual battery voltages, and the total capacity is the same as for one battery. If batteries or cells with different capacities are connected in series, the capacity of the string is limited to the lower battery capacity. Figure 5.12 illustrates the series connection of two identical batteries.

Series Connected Batteries

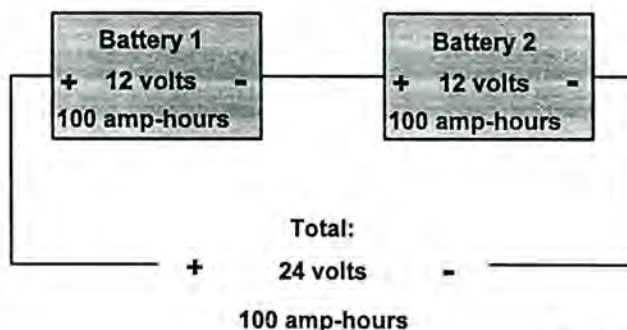


Figure 5.12

Parallel Circuits - Batteries connected in parallel have more than one current path, depending on the number of parallel branches. Batteries (or series strings of batteries) are arranged in parallel by connecting all of the positive terminals to one conductor and all of the negative terminals to another conductor. For similar batteries connected in parallel, the voltage across the entire circuit is the same as the voltage across the individual parallel branches, and the overall capacity is the sum of the parallel branch capacities. Figure 5.13 illustrates the parallel connection of two similar batteries.

Parallel Connected Batteries

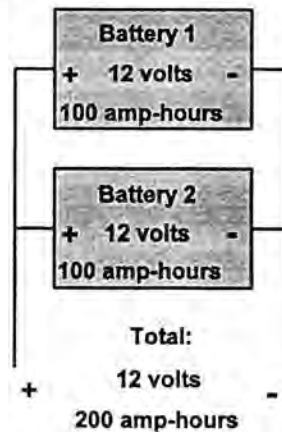


Figure 5.13

Series vs. Parallel Connection - Battery manufacturers generally recommend that their batteries be operated in as few parallel strings as possible. If too many parallel connections are made in a battery bank, slight voltage differences between the parallel strings occur due to the length, resistance and integrity of the connections. The result of these voltage differences can lead to inconsistencies in the treatment received by each battery (cell) in the bank, potentially causing unequal capacities within the bank. The parallel strings with the lowest circuit resistance to the charging source will generally be exercised to a greater extent than the parallel groups of batteries with greater circuit resistance to the charging source. The batteries in parallel strings receiving less charge may begin to prematurely sulfate.

The capacity requirements, size and voltage for the selected battery dictates the series and parallel connections in a given PV application. PV systems with large capacity requirements, (larger, nominal 2-volt cells for lead-acid), may allow for batteries to be configured in one series string, rather than several parallel strings. When batteries must be configured in parallel, the external connection between the battery bank and the PV power system should be made from the positive and negative terminals on opposite sides of the battery bank. This configuration will improve the equalization of charge and discharge from the bank.

Voltage Selection - Battery bank voltage selection is often dictated by load voltage requirements, usually 12-volts or 24-volts for small stand-alone PV systems. For larger loads

requiring a larger PV array, it is sometimes prudent to use higher voltages, to lower the system currents. For example, a 120-watt dc load operating from a 12-volt battery draws 10-amps. However, a 120-watt load operating from a 24-volt battery only draws 5-amps. Lower system currents minimize the size and cost of conductors, fuses, disconnects and other current handling components in the PV system.

Conductor Selection- Conductors, or the wires connecting the battery to other circuits and components in a PV system, must be selected based on the current or ampacity requirements, voltage drop limitations and environmental conditions. Conductors should be adequately sized to handle the current, and limit the voltage drop to acceptable levels (generally less than 5 percent) between the battery and other components at the peak rated currents. Conductor insulating materials should be selected based on temperature, moisture resistance or other application needs. Particular attention should be paid to selecting adequate size conductors for the high currents expected between the battery and inverter.

If the conductors between the PV array, charge controller and battery are too small, the series resistance and resulting voltage drops may force the PV array to operate at a fraction of the array peak rated current. As a result, the charging effectiveness of the PV array is reduced, requiring more modules to do the job. In many cases, the batteries in systems with excessive voltage drops will not be fully recharged. Note: voltage drop limitations generally dictate larger conductor sizes than the sizes required to handle the current alone, particularly in low voltage systems (12-24 volts dc). A further discussion on conductor sizing and selection is given in section 7 of this manual.

Overcurrent and Disconnect Requirements - Batteries can deliver thousands of amperes under short circuit conditions, potentially causing explosions, fires, burns, shock and equipment damage. For these reasons, properly dc-rated overcurrent and disconnect protection devices are required on all PV battery systems. Fuses or circuit breakers used for overcurrent protection must not only be able to operate properly under "normal" high currents resulting from load problems, but must also operate under battery short-circuit conditions. The ampere interrupt rating (AIR) for overcurrent devices must be considered with regard to the potential for battery system short circuit currents, or the device could fail with disastrous results. For ungrounded systems, disconnects are required on both the positive and negative conductors leading to and from the battery. For grounded systems, disconnect and overcurrent protection are only required on the ungrounded conductor. Figure 5.14 illustrates the overcurrent and disconnect requirements for batteries in PV systems.

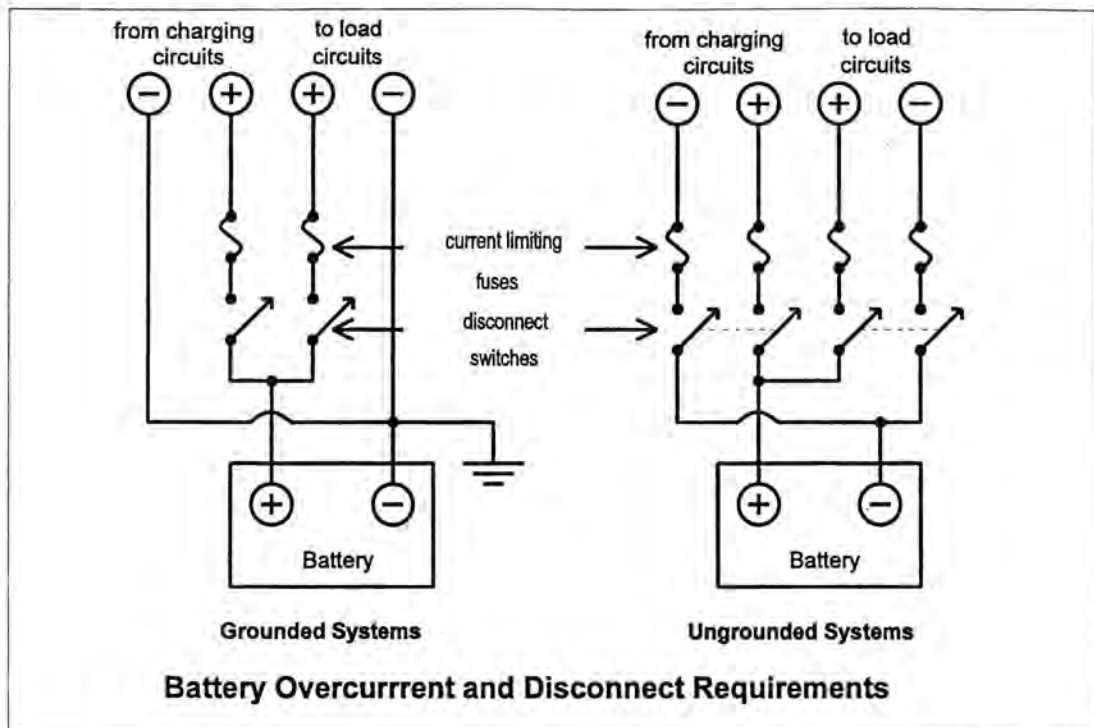


Figure 5.14

5.3.4.3 Battery Test Equipment

Hydrometer - An instrument used to measure the specific gravity of a solution, or the ratio of the solution density to the density of water. In lead-acid batteries, the specific gravity of the electrolyte is related to the battery state of charge. Hydrometers may be constructed with a float ball using *Archimedes' Principle*, or with a prism measuring the refractive index of the solution to determine specific gravity. Temperature corrections are generally required for hydrometer readings taken on solutions that are not at room temperature.

Load Tester - An instrument that draws current from a battery with an electrical load, while recording the voltage, usually done at high discharge rates for short periods. A load test may be used to determine the general health or consistency among batteries in a system, although it is not designed to measure capacity. Load test data are generally expressed as a discharge current over a specific time period.

5.3.4.4 Auxiliary Equipment and Systems

Battery auxiliary equipment includes any system (or other) hardware necessary to safely and effectively operate a battery system. Descriptions of some of the more important equipment follow.

Enclosures - Local electrical codes and safety standards require that batteries be installed in an enclosure separated from controls or other PV system components. This enclosure can be insulated or have other regulation mechanisms to protect the batteries from excessive temperature swings, and must be of sufficient size and strength to hold the batteries. It may also be located below ground, if necessary. If the enclosure is located above ground, direct exposure to sunlight should be limited and some type of shading or reflective coating should be utilized.

Ventilation - Batteries often release toxic and explosive mixtures of gasses (principally hydrogen), which requires adequate ventilation in the battery enclosure. In most cases passive techniques (i.e., vents or ducts) may provide sufficient ventilation. Other cases may require fans to provide mechanical ventilation. The required air change rates are based on maintaining minimum levels of hazardous gasses in the enclosure, and under no circumstances should batteries be kept in an unventilated area or located in an area frequented by personnel.

Fire Protection - A fire extinguisher should be located in close proximity to the battery area. In some critical applications, automated fire sprinkler systems may be required for protection of facilities and expensive load equipment.

Monitoring Systems - Monitoring and instrumentation for battery systems can range from simple analog meters to more sophisticated data acquisition systems. Lower level monitoring of battery systems might include voltage and current meters or battery state of charge indicators, while higher level monitoring might include automated recording of voltage, current, temperature, specific gravity and water levels. For small stand-alone PV systems, monitoring of the battery condition is only needed during occasional maintenance checks.

Safety Systems and Considerations - Batteries must be handled and used with extreme caution. The hazardous materials and chemicals used in their manufacturing and the amount of stored electrical energy in batteries make them potentially dangerous. Depending on the size and location of a battery installation, easy access to safety showers and eye washes may be required. Battery maintenance personnel should wear protective clothing such as aprons, ventilation masks, goggles or face shields, and gloves to protect from acid splashes, spills and fumes. Jewelry on the hands and wrists should be removed, and properly insulated tools should be used to protect against inadvertent battery short-circuits. Note: the physical characteristics of some batteries may require special methods (mechanical lifting devices) to move them.

Catalytic Recombination Caps (CRC) - As a substitute for standard vented caps on lead-antimony batteries, the primary function of catalytic recombination caps, or CRCs, is to reduce the electrolyte loss from the battery. CRCs contain particles of an element such as platinum or palladium, that adsorbs the hydrogen generated from the battery during finishing and overcharge. The hydrogen is then recombined with oxygen in the CRC to form water, which drains back into the battery. During this recombination process, heat is released from the CRC. Since the combination of hydrogen and oxygen to form water is an exothermic

process, temperature increases in CRCs can be used to detect the onset of gassing in the battery. If CRCs are found to be at significantly different temperatures during recharge (some cells are gassing and others are not), an equalization charge may be required. The use of CRCs on open-vent flooded lead-antimony batteries has proven to reduce electrolyte loss by as much as 50 percent.

Flame Arrestor Caps - To lower the possibility of a catastrophic explosion, flame arrestor caps are commonly supplied on larger industrial battery systems. Flame arrestor caps vent through a charcoal filter designed to contain a cell explosion and any ignition sources to that cell, thereby minimizing the potential explosion of the entire battery bank.

Battery Disposal and Recycling - Batteries contain toxic materials (lead, acids and plastics) that can be harmful to humans and the environment, and local laws provide guidelines for battery disposal and recycling. In most areas, batteries can be taken to the local landfill which will then forward them to approved recycling centers. In some cases, battery manufacturers provide guidelines for battery disposal through local distributors, and may even recycle batteries themselves. Batteries should *never* be permanently deposited in landfills or burned, and battery electrolyte should not be allowed to seep into the ground.

5.4 Battery Charge Controllers

A stand-alone photovoltaic system is designed to meet the load requirements under reasonably determined worst-case conditions. When the array is operating under good-to-excellent weather conditions, electricity generated by the array often exceeds demand. To prevent battery damage resulting from overcharging a voltage regulator or charge controller is used to protect the battery. A charge controller should prevent overcharge or overdischarge of a battery regardless of the system sizing/design, seasonal changes in the load profile, operating temperatures and insolation. The algorithm (control strategy) of a battery charge controller determines the effectiveness of battery charging and PV array utilization, and ultimately the system's ability to meet the load demands. Additional features such as temperature compensation, alarms, meters, remote voltage sense leads and special algorithms can enhance the ability of a charge controller to maintain the health and extend the lifetime of a battery, as well as indicate the operational status to the system caretaker.

5.4.1 Purpose of Charge Controllers in PV Systems

The primary function of a charge regulator in a stand-alone PV system is to maintain the battery at the highest possible state of charge, while protecting it from overcharge by the array and overdischarge by the loads. Although some PV systems can be designed effectively without the use of charge control, systems with unpredictable loads, user intervention, and optimized or undersized battery storage (to minimize initial cost), typically require a battery charge regulator. Considerations for designs that operate effectively without the use of charge regulation are discussed later in this section.

Seven of the most important functions of battery charge regulators and controls in PV systems are:

1. ***Prevents Battery Overcharge*** — Limits the energy supplied to the battery by the PV array when the battery becomes fully charged.
2. ***Prevents Battery Overdischarge*** — Disconnects the battery from electrical loads when the battery reaches low state of charge.
3. ***Provides Load Control Functions*** — Automatically connects and disconnects an electrical load at a specified time (i.e., operating a lighting load from sunset to sunrise).
4. ***Provides Status Information to System Users/Operators*** — Displays or indicates system operational information (battery voltage and current, charging status, load operation), and other data.
5. ***Interfaces and Controls Backup Energy Sources*** — Integrates alternative sources (wind turbine, backup generator) with the PV electrical system.
6. ***Diverts PV Energy to an Auxiliary Load*** — Supplies energy to non-critical (secondary loads) when the main battery bank reaches full state of charge and the array energy would be otherwise wasted.
7. ***Serves as a Wiring Center*** — Provides a termination or connection point for other components in the system, including the PV array, battery and electrical load.

5.4.1.1 Prevents Battery Overcharge

The primary function of a battery charge controller, and perhaps the single most important issue related to battery performance and life, is charge regulation. The purpose of a charge controller is to supply power to the battery in a manner that fully recharges the battery without overcharging. If the battery is fully charged, unregulated charging will cause the battery voltage to reach exceedingly high levels, causing severe gassing, electrolyte loss, internal heating and accelerated grid corrosion. In most cases if a battery in a PV system is not protected from overcharge, premature battery failure and loss of load are likely occurrences.

5.4.1.2 Prevents Battery Overdischarge

During periods of below average insolation and/or during periods of excessive electrical load usage, the energy produced by the PV array may not be sufficient enough to keep the battery fully recharged. When a battery is deeply discharged, the reaction in the battery occurs close to the grids, and weakens the bond between the active materials and the grids. When a battery is excessively discharged repeatedly, loss of capacity and life will occur. To protect

batteries from overdischarge, most charge regulators include an optional feature to disconnect the system loads once the battery reaches a low voltage or low state of charge condition.

Overdischarge protection in charge regulators is usually accomplished by open-circuiting the connection between the battery and electrical load when the battery reaches a pre-set or adjustable low voltage load disconnect (LVD) set point. Most charge regulators also have an indicator light or audible alarm to alert the system user/operator to the load disconnect condition. Once the battery is recharged to a certain level, the loads are again reconnected to a battery.

5.4.1.3 Provides Load Control Functions

In some cases, regulators may have optional features that regulate or control the system electrical load. Load control in PV lighting system regulators is a popular feature and can be timed for sunrise or sunset, as sensed by a photosensor, array current, or voltage output. In other cases the controller may have a timing function to cycle load operation for a specified period or at a certain time of day. Load control functions may require adjustment and proper specification according to array type and site conditions (i.e., temperature and background lighting). These features add to the cost and complexity of the controller, but can also greatly simplify PV system use and operation.

5.4.1.4 Provides Status Information To Users

Many PV system charge regulators provide status information on system operations and battery condition. These optional regulator features help users manage their energy use, better understand system operations and fully utilize the system's potential.

Charge regulators can relate essential information on battery voltage and/or state of charge. This information may be conveyed by a "gas gauge" with a simple dial voltmeter showing green, yellow or red regions corresponding to different battery voltage ranges. (A digital readout of exact battery voltage can be provided for more sophisticated users.) Random battery voltage readings are interesting, but the user must know how to interpret the information and when (voltage level) to curtail their energy usage.

Many regulators also indicate with a lamp or ammeter whether the array is charging the battery, or if the array or load is disconnected. Some regulator/controller designs also display load currents or the net battery amp-hours. Knowledge of the array and load currents gives users a sense of how much energy is being produced with the array and consumed by electrical loads, and allows planning load usage with energy availability during low insolation periods.

5.4.1.5 Interfaces and Controls Backup Energy Sources

A hybrid PV power system uses one or more alternative backup energy sources, in addition to the array. Advanced system control centers may be designed to interface these alternate

sources with the PV electrical system. One example is a controller that activates a backup generator at low battery state of charge. The control center starts the generator at a pre-set low battery voltage, and turns it off when the battery is recharged or reaches a higher voltage limit.

The control of backup energy sources can also be performed by other components in the PV system. For example, some stand-alone inverters used in PV systems will start a backup generator or divert the loads to utility power when the battery reaches low state of charge. Once the battery has been recharged to a pre-set level, the loads are reconnected to and powered by the battery bank.

5.4.1.6 Diverts PV Energy To Auxiliary Load

The batteries in photovoltaic systems are often fully recharged by the middle of the day during summer months. At this point, the charge regulator usually disconnects the array to prevent battery overcharge and the waste of valuable array energy. To utilize this excess energy, some controllers allow the diversion of array energy to power an auxiliary load once the primary battery bank is fully charged. In most cases, the regulator will be bypassed, directly-coupling the PV array to the auxiliary load. The auxiliary load is typically a backup battery, DC water pump, resistive element in a water heater, fan, or some other simple motor load that can be operated from the array without voltage regulation. (All the energy produced by the array is utilized for some purpose.) When the battery voltage falls and array power is needed again to run the regular loads, the auxiliary loads are disconnected. The auxiliary load must be an optional, non-critical load that can be operated whenever excess array energy is available.

5.4.1.7 Serves As Wiring Center

In most cases, the charge regulator or system controller serves as the termination and connection point between the conductors leading to the various PV system components. For example, the charge regulator in a small residential lighting system commonly has the PV array, battery and load connected to the regulator terminals. A fuse or circuit breaker for array and battery protection can be also be included in the regulator design.

Larger PV systems generally have overcurrent protection and disconnect devices included as part of the system control center, and with these devices included in the system controller, the conductors leading to the PV array, battery and loads are connected at a centralized point in the system. The control center may also be the principle grounding point in the system and include surge suppression devices. The installation, operation and maintenance of the system is greatly simplified with this centralized configuration for system connection and controls.

5.4.2 Fundamentals of Charge Controllers

The specific regulation method or algorithm may vary among different charge regulators, but all have basic functions and characteristics. Charge regulator manufacturers' data generally

provides information about these functions and their specifications. Typical manufacturers' specifications include the ratings for PV array and load currents, operating voltages and temperatures, parasitic losses, regulation and load disconnect set points, and other information. The system designer must understand these specifications in order to properly select a charge regulator for a given PV application.

5.4.2.1 Nominal System Voltage

The voltage that a battery and charge regulator operate at, is the nominal system voltage. Most charge regulators are designed to operate at a specific nominal system voltage, while some may operate at multiple voltages (i.e., 12-volt or 24-volt systems).

The selection of the nominal system voltage has important ramifications for many aspects of design and equipment selection. For systems with high power-demand loads, a higher nominal system voltage is used to lower the peak operating currents and reduce the size and ratings of conductors, overcurrent and disconnect devices, and the charge regulator. However, most equipment for small stand-alone PV systems is widely available in 12-volt or 24-volt dc models and this may dictate the designer's selection of the nominal system voltage.

5.4.2.2 Nominal Load and PV Array Current

Charge regulators are rated for their ability to handle certain maximum and nominal currents for the PV array and load. The regulator must be able to control any power surges that may come from the array or loads.

5.4.2.3 Charge Controller Set Points

Regulator set points are the battery voltage levels that a charge regulator performs control or switching functions. Four basic control set points are defined for most charge regulators that have battery overcharge and overdischarge protection features. The voltage regulation (VR) and the array reconnect voltage (ARV) refer to the voltage set points when the array is connected and disconnected from the battery. The low voltage load disconnect (LVD) and load reconnect voltage (LRV) refer to the voltage set points when the load is disconnected from the battery to prevent overdischarge.

The simplified diagram in Figure 5.15 illustrates the basic regulator set points, by plotting battery voltage versus time elapsed, during a charge and discharge cycle. A detailed discussion of each charge controller set point follows.

Charge Controller Set Points

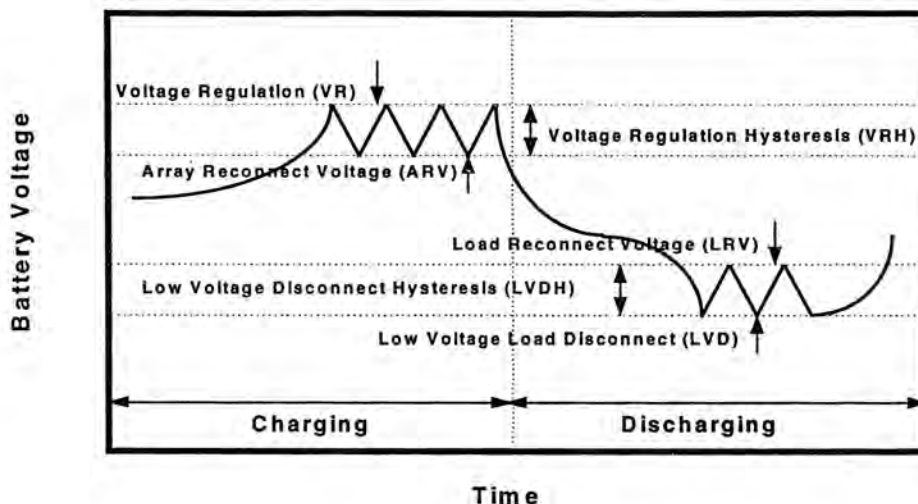


Figure 5.15

5.4.2.3.1 Voltage Regulation (VR) Set Point

Voltage regulation (VR) set point (one of the key specifications for charge regulators), is defined as the maximum voltage the charge regulator allows the battery to reach while limiting overcharge. When the controller senses that the battery has reached the voltage regulation set point, it will either discontinue battery charging or begin to regulate (limit) the amount of current delivered to the battery. In some regulator designs, dual regulation set points may be used. For example, a higher regulation voltage may be used for the first charge cycle of the day to provide a little battery overcharge, gassing and equalization, while a lower regulation voltage may be used on subsequent cycles through the remainder of the day to effectively "float charge" the battery.

Proper selection of the voltage regulation set point may depend on many factors, including the specific battery chemistry and design, size of the load and array with respect to the battery, operating temperatures, and electrolyte loss considerations. Select the voltage regulation point in flooded batteries at a point that allows a minimal level of gassing. Gassing should be avoided for sealed, valve-regulated lead-acid (VRLA) batteries. Temperature compensation of the voltage regulation set point is often incorporated in charge controller design, and is highly recommended for VRLA batteries and if battery temperatures exceed $\pm 5^{\circ}\text{C}$ from normal ambient temperatures (25°C). A discussion on voltage regulation set point selection and temperature compensation appear later in this section.

An important note regarding the voltage regulation set point is, the values required for

optimal battery performance in stand-alone PV systems are generally much higher than the regulation or "float voltages" recommended by battery manufacturers. The battery in a PV system must be recharged within a limited time period (during sunlight hours), while battery manufacturers generally allow for much longer recharge times when determining their optimal regulation voltage limits. By using a higher regulation voltage in PV systems, the battery can be recharged in a shorter time period. However, some degree of overcharge and gassing will occur and the designer should select the optimal voltage regulation set point to maintain the highest possible battery state of charge without causing significant overcharge.

5.4.2.3.2 Array Reconnect Voltage (ARV) Set Point

Once the array current is disconnected at the voltage regulation set point in interrupting (on-off) type regulators, the battery voltage will begin to decrease. The rate of the battery voltage decrease depends on many factors, including the charge rate prior to disconnect and the discharge rate dictated by the electrical load. If the charge and discharge rates are high, the battery voltage will decrease at a greater rate than if these rates are low. When the battery voltage decreases to a predefined voltage, the array is reconnected to the battery to resume charging. The voltage at which the array is reconnected is referred to as the array reconnect voltage (ARV) set point.

If the array remained disconnected for the rest of the day, after the regulation voltage was initially reached, the battery would not be fully recharged. By allowing the array to reconnect after the battery voltage reduces to a set value, the array current will "cycle" into the battery in an on-off manner, disconnecting at the regulation voltage set point and reconnecting at the array reconnect voltage set point. In this way, the battery will be brought up to a higher state of charge by "pulsing" the array current into the battery.

It is important to note that for some regulator designs, namely constant-voltage and pulse-width-modulated (PWM) types, there is no clearly distinguishable difference between the VR and ARV set points. In these designs, the array current is not regulated in a simple or interrupting (on-off) fashion, but is only limited, as the battery voltage is held at a relatively constant value through the remainder of the day. A discussion on these types of regulators is included later in this section.

5.4.2.3.3 Voltage Regulation Hysteresis (VRH)

The voltage span or difference between the voltage regulation set point and the array reconnect voltage is often called the voltage regulation hysteresis (VRH). The VRH is a major factor determining the effectiveness of battery recharging for interrupting (on-off) type regulators. If the hysteresis is too great, the array current remains disconnected for long periods, effectively lowering array energy utilization and making it very difficult to fully recharge the battery. If the regulation hysteresis is too small, the array will cycle on and off rapidly, perhaps damaging regulators that use electro-mechanical switching elements. The designer must carefully determine the hysteresis values based on the system charge and discharge rates and the charging requirements of the particular battery.

Most interrupting (on-off) type regulators have hysteresis values between 0.4 volts and 1.4 volts for nominal 12-volt systems. For example, a regulator with a voltage regulation set point of 14.5 volts and a regulation hysteresis of 1.0 volts has an array reconnect voltage of 13.5 volts. In general, a smaller regulation hysteresis is required for PV systems that do not have a daytime load.

5.4.2.3.4 Low Voltage Load Disconnect (LVD) Set Point

Overdischarging a battery can make it susceptible to freezing and shorten its operating life. If battery voltage drops too low (i.e., due to prolonged bad weather), certain non-essential loads can be disconnected from the battery to prevent further discharge. This can be done using a low voltage load disconnect (LVD) device connected between the battery and non-essential loads. The LVD is either a relay or a solid-state switch that interrupts the current from the battery to the load, and is included as part of most regulator designs. In some cases, the low voltage load disconnect unit may be separate from the main charge regulator.

In regulators or controls incorporating a load disconnect feature, the low voltage load disconnect (LVD) set point is the voltage at which the load is disconnected from the battery to prevent overdischarge. *The LVD set point defines the actual allowable maximum depth-of-discharge and available capacity of the battery operating in a PV system.* The available capacity must be carefully estimated using the actual depth of discharge dictated by the LVD set point in the PV system design and sizing process.

A hierarchy of load importance can be established in more sophisticated designs, so the more critical loads can be shed at progressively lower battery voltages. Very critical loads can remain connected directly to the battery for uninterrupted operation.

The proper LVD set point will maintain a healthy battery while providing the maximum battery capacity and load availability. To determine the proper load disconnect voltage, the designer must consider the rate at which the battery is discharged. Since the battery voltage is affected by the rate of discharge, a lower load disconnect voltage set point is needed for high discharge rates to achieve the same depth of discharge limit. In general, the low discharge rates in most small stand-alone PV systems do not have a significant effect on the battery voltage. Typical LVD values used are between 11.0 volts and 11.5 volts, which corresponds to about 75-90% depth of discharge for most nominal 12-volt lead-acid batteries at discharge rates lower than C/30.

Note: when selecting the low voltage load disconnect set point, battery manufacturers rate discharge capacity to a specified cut-off voltage that corresponds to 100% depth of discharge for the battery. This cut-off voltage is typically 10.5 volts for a nominal 12-volt (1.75 volts per cell) lead-acid battery. A battery in a PV systems should never be allowed to completely discharge, as this will shorten its service life. The low voltage load disconnect set point in PV systems is selected to discharge the battery to no greater than 75-80% depth of discharge.

In cases where starting (SLI) batteries are used, or it is necessary to limit the battery depth of

discharge to prevent freezing or prolong cycle life, a higher LVD set point may be desired. To protect the battery from freezing, the LVD set point may be temperature compensated to automatically increase the load disconnect voltage with decreasing battery temperature.

The designer must know how the battery voltage is affected at different states of charge and discharge rates in order to properly specify the LVD set point in PV systems. In a few designs, current compensation may be included in the LVD circuitry to lower the LVD set point with increasing discharge rates, and effectively keep a consistent depth of discharge limit at which the LVD occurs.

5.4.2.3.5 Load Reconnect Voltage (LRV) Set Point

The load reconnect voltage (LRV) is the battery voltage point that a regulator allows the load to be reconnected to the battery. After the regulator disconnects the load from the battery at the LVD set point, the battery voltage rises to its open-circuit voltage. When additional charge is provided by the array or a backup source, the battery voltage rises even more. The point that the controller senses the battery voltage and state of charge are high enough to reconnect the load, is called the load reconnect voltage set point.

The selection of the load reconnect set point should be high enough to ensure the battery is somewhat recharged, while not high enough to sacrifice load availability (allowing the load to be disconnected too long). Many controller designs effectively "lock out" loads until the next day or when the controller senses that the array is recharging the battery again. Typically, the LVD set points used in small PV systems are between 12.5 volts and 13.0 volts for most nominal 12-volt lead-acid batteries. If the LRV set point is selected too low, the load may be reconnected before the battery has been charged, possibly cycling the load on and off and keeping the battery at low state of charge, thus shortening its lifetime.

The designer must consider the charge rates for the loads and array and how these rates affect battery voltage at different states of charge.

5.4.2.3.6 Low Voltage Load Disconnect Hysteresis (LVDH)

The low voltage disconnect hysteresis (LVDH) is the voltage span or difference between the LVD set point and the load reconnect voltage. If the LVDH is too small, the load may cycle on and off rapidly at low battery state-of-charge (SOC), possibly damaging the load or controller and extending the time it takes to fully charge the battery. If the LVDH is too large, the load may remain off for extended periods until the array fully recharges the battery. Battery health may be improved with a large LVDH, due to reduced battery cycling. However, this may also result in a reduction of load availability. The proper LVDH selection for a given system will depend on load availability requirements, battery chemistry and size, and the PV and load currents.

5.4.2.4 Adjustability of Controller Set Points

While some charge controllers use fixed resistors to pre-set the controller set points, many have the ability to adjust or change the regulation and load disconnect set points. Some also have provisions to adjust the hysteresis values. Adjustments are typically made with potentiometers (single or multi-turn), DIP (dual in-line package) switches, or circuit board jumpers. Although the system designer or installer may need access to properly set the controller for the type of battery and system configuration, user/operator access to regulator adjustments should be discouraged.

5.4.2.5 Regulation/Control Element Design

The regulation or switching control element in charge regulators can be either a solid-state device or an electro-mechanical relay. Simple interrupting (on-off) regulators may use relay. However, in most cases, MOSFETs or power transistors are used rather than relays because they have lower power requirements, are smaller, and can operate for many more cycles. The regulator switching elements must be properly rated for the application. The steady-state dc current ratings for the regulator element should be at least 125% of the maximum PV array short-circuit current. The peak (surge) dc current ratings for the element should be at least 150% of maximum expected PV array short-circuit current.

The switching element that controls the low voltage load disconnect circuit is generally an electro-mechanical relay, because the number of cycles this switching element experiences is very limited, compared to the regulation element. Generally, relay contacts should be plated, or hermetically sealed, and rated to handle at least 125% of the rated dc load current. Peak (surge) dc current ratings for the load switching element should also be able to handle expected high current surges from the system loads.

5.4.2.6 Environmental and Mechanical Specifications

The environmental and mechanical specifications of charge regulators are an important consideration for most PV applications. PV systems and components are usually installed in remote areas, in unconditioned spaces, and are subject to weather extremes. For these reasons, most regulators have minimum and maximum ratings for ambient temperature, battery temperature and relative humidity. The designer should consider these specifications when selecting charge regulators for extreme environmental conditions.

Packaging and physical characteristics are other important characteristics of charge regulators. The regulator circuitry should be sealed from the environment, either by conformably coating the circuitry, or by "potting" it. The regulator should be protected by a rigid case, or it can be installed in a weather-proof enclosure. Terminations that connect wiring to the charge regulator should be large, corrosion resistant, and sturdy enough to accept all possible conductor sizes in the system.

5.4.2.7 Surge Protection and Grounding

Most regulators include some type of surge suppression devices on the array and load circuits. Commonly, these devices are metal-oxide varistors (MOVs) that are connected between the positive and negative terminals, and from these terminals to ground. Under normal operating conditions, MOVs are high impedance devices. However, under surge conditions, MOVs shunt energy to ground, bypassing sensitive electrical circuits of the controller. While these devices do not always protect the controller circuitry from harmful surges, they are strongly recommended for regulators used in lightning prone areas and in dc/ac systems using inverters.

5.4.3 Charge Controller Designs

The discussion in the preceding section shows the different ways battery charge regulation can be configured in photovoltaic systems. There are also a number of variations in the function and electronic design of charge regulators.

Two basic methods exist for controlling (regulating) the battery charging from a PV module or array, 1) shunt regulation, and 2) series regulation. Both of these methods are effective, and each may incorporate a number of variations that alter their basic performance and applicability. Simple designs interrupt or disconnect the array from the battery during regulation, while more sophisticated designs limit the current to the battery in a linear manner that maintains a high battery voltage.

The algorithm (control strategy) of a battery charge regulator determines the effectiveness of battery charging and PV array utilization, and ultimately the ability of the system to meet the electrical load demands. More importantly, the controller algorithm defines the way the PV array power is applied to the battery in the system. In general, interrupting (on-off) type controllers require a higher regulation set point to bring batteries up to full state of charge, than controllers that gradually limit the array current.

Some of the more common design approaches for charge regulators are described in this section. The next section presents typical daily charging profiles for a few of the common types of regulators used in small PV lighting systems.

5.4.3.1 Shunt Regulator Designs

Since photovoltaic cells are current-limited by design (unlike batteries), PV modules and arrays can be short-circuited without any harm. The ability to short-circuit modules or an array is the primary function of shunt regulators.

Figure 5.16 shows an electrical design of a typical shunt type regulator. The shunt controller regulates the charging of a battery from the PV array by short-circuiting the array within the regulator. All shunt regulators *must have* a blocking diode in series between the battery and the shunt element to prevent the battery from short-circuiting when the array is regulating.

Because there is some voltage drop between the array and regulator and because of wiring and resistance of the shunt element, the array is never entirely short-circuited, resulting in some power dissipation within the controller. For this reason, most shunt controllers require a heat sink to dissipate power and are generally limited to use in PV systems with array currents less than 20 amps.

The regulation element in shunt regulators is typically a power transistor or MOSFET, depending on the specific design. There are a couple of variations in the shunt regulator design. The first is a simple interrupting (on-off) type regulator design. The second type limits the array current in a gradual manner by increasing the resistance of the shunt element as the battery reaches full state of charge. These two variations of the shunt regulator are discussed below.

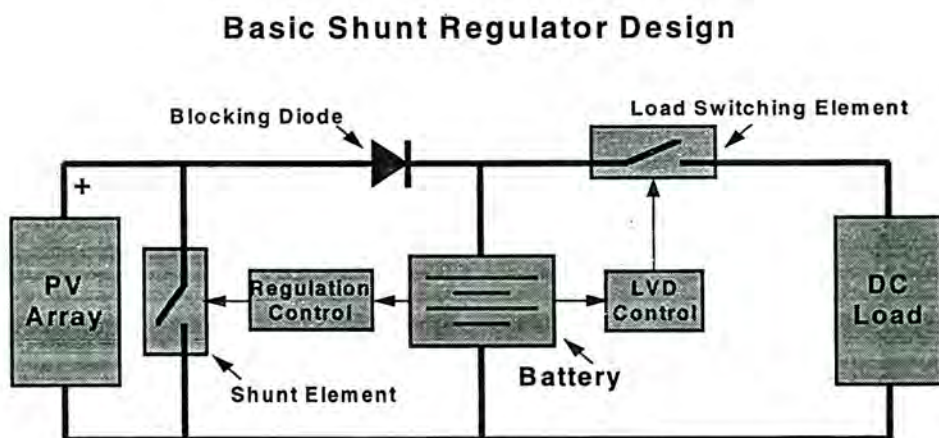


Figure 5.16

5.4.3.1.1 Shunt-Interrupting Design

The shunt-interrupting regulator completely disconnects the array current in an interrupting (on-off) fashion when the battery reaches the voltage regulation set point. When the battery decreases to the array reconnect voltage, the regulator connects the array to resume charging the battery. This cycling between the regulation voltage and array reconnect voltage is why these regulators are often called "on-off" or "pulsing" controllers. Shunt-interrupting

regulators are widely available and low cost. However, they are generally limited to use in systems with array currents less than 20 amps, due to heat dissipation requirements. On-off shunt regulators consume less power than series type regulators that use relays (discussed later), so they are best suited for small systems where even minor parasitic losses become a significant part of the system load.

Shunt-interrupting charge regulators can be used on all battery types, but the way they apply power to the battery may not be optimal for all battery designs. Constant-voltage, PWM or linear regulator designs are recommended by manufacturers of gelled and AGM lead-acid batteries. However, shunt-interrupting regulators are simple, low cost and perform well in most small stand-alone PV systems.

5.4.3.1.2 Shunt-Linear Design

Once a battery becomes almost fully charged, a shunt-linear regulator maintains the battery near a fixed voltage by gradually shunting the array through a semiconductor regulation element. In some designs, a comparator circuit in the regulator senses the battery voltage, and makes corresponding adjustments to the impedance of the shunt element, thus regulating the array current. Other designs use simple Zener power diodes that are the limiting factor in the cost and power ratings for these regulators. There is generally more heat dissipation in shunt-linear regulators than in shunt-interrupting types.

Shunt-linear regulators are popular for use with sealed VRLA batteries. This algorithm applies power to the battery in a preferential method for these types of batteries by limiting the current, while holding the battery at the regulation voltage.

5.4.3.2 Series Regulator Designs

This type of regulator works in series between the array and battery, rather than in parallel as for the shunt regulator. There are several variations to the series type regulator, and all use some type of control or regulation element in series between the array and the battery. This type of controller is commonly used in small PV systems, but it is also the practical choice for larger systems, due to the current limitations of shunt controllers.

Figure 5.17 illustrates an electrical design of a typical series type regulator. In a series regulator design, a relay or solid-state switch either opens the circuit between the array and the battery to discontinue charging, or limits the current in a series-linear manner to hold the battery voltage at a high value. In the simpler series-interrupting design, the regulator reconnects the array to the battery once the battery falls to the array reconnect voltage set point. As these on-off charge cycles continue, the *on* time becomes shorter and shorter as the battery becomes fully charged.

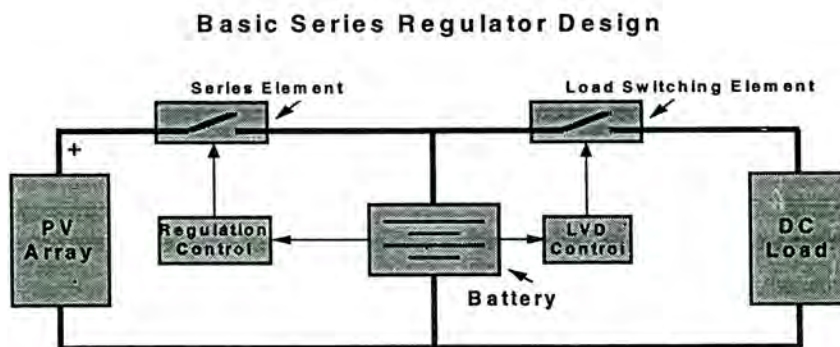


Figure 5.17

Because the series regulator open-circuits rather than short-circuits the array (as in shunt-controllers), no blocking diode is needed to prevent the battery from short-circuiting when the controller regulates.

5.4.3.2.1 Series-Interrupting Design

The most simple series regulator is the series-interrupting type. This design features a one-step control that turns the array charging current either on or off. The charge regulator constantly monitors battery voltage and disconnects (open-circuits) the array in series once the battery reaches the regulation voltage set point. After a pre-set period of time, or when battery voltage drops to the array reconnect voltage set point, the array and battery are reconnected and the cycle repeats. As the battery becomes more fully charged, the time for the battery voltage to reach the regulation voltage becomes shorter each cycle, lessening the amount of array current passed through to the battery each time. In this way, full charge is approached gradually in small steps or pulses, similar in operation to the shunt-interrupting type controller.

Similar to the shunt-interrupting type regulator, the series-interrupting designs are best suited for use with flooded batteries rather than the sealed VRLA types, due to the way power is applied to the battery.

5.4.3.2.2 Series-Interrupting, 2-step, Constant-Current Design

This type of controller is similar to the series-interrupting type. However, when the voltage regulation set point is reached, instead of totally interrupting the array current, a limited constant current remains applied to the battery. This "trickle charging" continues either for a pre-set period of time, or until the voltage drops to the array reconnect voltage (due to load

demand), then full array current is allowed to flow again and the cycle repeats. Full charge is approached in a continuous fashion instead of smaller steps, as described above for the on-off type regulators. Some two-stage controls increase array current as soon as battery voltage is pulled down by a load. Other two-state controls keep the current at the small trickle charge level until the battery voltage has been pulled down below some intermediate value (usually 12.5 volts to 12.8 volts), before they allow full array current to resume.

5.4.3.2.3 Series-Interrupting, 2-Step, Dual Set Point Design

This type of regulator operates similarly to the series-interrupting type. However, there are *two* distinct voltage regulation set points. During the first charge cycle of the day, the controller uses a higher regulation voltage to provide some equalization charge to the battery. Once the array is disconnected from the battery at the higher regulation set point, the voltage level drops to the array reconnect voltage and the array is reconnected to the battery. However, on the second and subsequent cycles of the day, a lower regulation voltage set point is used to limit battery overcharge and gassing.

This type of regulation strategy can effectively maintain high battery state of charge, while minimizing battery gassing and water loss for flooded lead-acid types. The designer must ensure that the dual regulation set points are properly adjusted for the battery type used. For example, typical set point values (at 25 °C) for this type of controller (used with a flooded lead-antimony battery) might be 15.0 volts to 15.3 volts for the higher regulation voltage, and between 14.2 volts and 14.4 volts for the lower regulation voltage.

5.4.3.2.4 Series-Linear, Constant-Voltage Design

In a series-linear, constant-voltage regulator design, the regulator maintains the battery voltage at the voltage regulation set point. The series regulation element functions like a variable resistor and is controlled by the battery voltage sensing circuit of the regulator. The series element dissipates the balance of the power that is not used to charge the battery and generally requires heat sinking. The current is inherently controlled by the series element and the voltage drop across it.

Series-linear, constant-voltage regulators can be used on all types of batteries. They are generally more effective at fully charging batteries than on-off type regulators, because they apply power to the battery in a controlled manner. These designs, along with PWM types are recommended over on-off type regulators for sealed VRLA type batteries.

5.4.3.2.5 Series-Interrupting, Pulse Width Modulated (PWM) Design

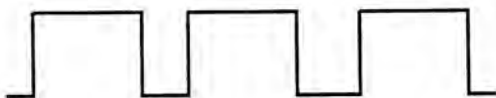
This algorithm uses a semiconductor switching element between the array and battery. The element switches on/off at a variable frequency with a variable duty cycle, in order to maintain the battery at, or very close to the voltage regulation set point. Although a series

type PWM design is discussed here, shunt-type PWM designs are also popular and perform battery charging in similar ways. Similar to the series-linear constant-voltage algorithm in performance, power dissipation within the regulator is considerably lower in the series-interrupting PWM design.

By electronically controlling the high speed switching element, the PWM regulator breaks the array current into pulses at some constant frequency, and varies the width and time of the pulses to regulate the amount of charge flowing into the battery (see Figure 5.18). When the battery is discharged, the current pulse width is almost completely *on* all the time. As the battery voltage rises, the pulse width is decreased, effectively reducing the magnitude of the charge current.

Pulse-Width-Modulated (PWM) Regulator Design

Battery at Low State of Charge



Until the battery is fully charged, the current pulses to the battery are wide.

Battery at High State of Charge



Once the battery becomes fully charged, the current pulses to the battery become narrower.

Figure 5.18

The PWM design allows greater control over exactly how a battery approaches full charge and it generates less heat. PWM type regulators can be used with all battery types, but their use with sealed VRLA type batteries over on-off type controls is preferred, because of the controlled manner that power is applied to the batteries. The voltage regulation set points for PWM and constant-voltage controllers are generally specified lower than those for on-off

type regulators, in order to limit overcharge and gassing. For example, a PWM regulator operating with a nominal 12-volt flooded lead-antimony battery might use a VR set point of 14.4 volts to 14.6 volts (at 25 °C), while an on-off regulator used with the same battery might require a VR set point of between 14.7 volts and 15.0 volts to fully recharge the battery on a typical day.

5.4.4 Daily Operational Profiles for Charge Controllers

The following sections present typical daily operational profiles for a few of the different types of battery charge regulators commonly used in small stand-alone PV systems. These daily profiles show how the different charge controller algorithms regulate the current and voltage from the PV array to protect the battery from overcharge.

5.4.4.1 About the Charge Controller Daily Profiles

The data presented in the graphs for this section were measured during tests in February 1993, on operational PV lighting systems at the Florida Solar Energy Center (FSEC). Several identical systems were monitored, with the exception that each system used a different battery charge controller. The data presented here are for a selected "clear day" (no cloud cover), and show the charge controller regulation effects.

To properly understand the data presented in the graphs, it is helpful to know how they were measured. The measured parameters included: solar irradiance (Sun), battery voltage (Vbat) and current (Ibat), and PV array voltage (Vpv) and current (Ipv). The designations (in parenthesis) are used in the legend key for the daily profiles. Each parameter was sampled every 10 seconds, averaged over a six-minute period, and recorded for a total of 240 data points daily. In addition, the minimum and maximum of the battery voltage samples were recorded every six minutes. These minimum and maximum voltages (based on 10-second samples) are key to understanding how a battery charge controller operates.

There are two graphs showing charge controller daily performance in each of the following figures. The top graph shows the battery and PV array voltage versus time for the clear day. Note: for clarity, the battery voltage is plotted on the left y-axis, while the PV array voltage is plotted on the right y-axis (on a different scale). The bottom graph shows the solar irradiance and the battery and PV array currents over the day. Note: the currents are plotted on the left y-axis, and the irradiance is plotted on the right y-axis.

The sizing of the battery, PV array and load in the test systems was configured to typify commercially available PV lighting systems. The different charge controllers were selected from those commonly used in these types and sizes of systems. The following table lists the nominal specifications for the FSEC test systems.

Table 5.4

Nominal Specifications for FSEC Test Systems	
Design Insolation:	5 kWh/m ² -day
PV Array:	Nominal 100 watt Pmp, 6 amps Imp
Battery:	Flooded Lead Antimony, 12 volt, 100 Ah @ 20 hr rate
Load:	Nominal 3 amps, 8 hours nightly, 24 amp-hours per day
Controller:	Variable

Since these test systems were designed to investigate both the behavior of the different controllers and the effects the regulation set points had on maintaining battery state of charge, the set points were not always optimized for the specific system design. In some cases this was intentional, while in others it was the result of the controller operating characteristics. The main point to emphasize is, the daily profiles presented here show how the charge controllers typically operate in PV systems.

5.4.4.2 Daily Profile for Shunt-Interrupting Charge Regulator

A 24-hour daily profile for a small stand-alone PV lighting system operating with a shunt-interrupting (on-off) type battery charge regulator is shown in Figure 5.19. Beginning at the left of the two graphs (midnight), the load is operating and battery voltage decreasing steadily from 12.1 volts to 11.9 volts while being discharged at 3 amps. At 0400 hours, the load current is disconnected by the charge controller load regulation/timing circuit. At this point the battery current goes to zero, and there is a sharp rise in the battery voltage as it approaches an open-circuit (no load) voltage of 12.35 volts. At sunrise (0700 hours), the battery voltage begins to increase as the PV array current is fed into the battery. Until noon time (1200 hours), the PV array current and the battery voltage increase steadily with increasing insolation as the battery is recharged. Note: during this period, the battery charge controller is not regulating and nearly all the PV array current is fed into the battery.

At approximately noon time (1200 hours), the battery voltage reaches the regulation voltage set point for the battery charge controller, and the controller begins to regulate the PV array current. When this occurs, the battery current decreases in a jagged manner characteristic of the interrupting (on-off) algorithm. The shunt characteristic is demonstrated because once regulation begins, the PV array current continues to follow the same profile as the solar irradiance, while the six-minute average PV array voltage decreases to an average of 5 volts. In effect, this controller shunts or "short-circuits" the PV array at regulation, causing the PV voltage to reduce and forcing the current to the array short-circuit current point.

Up until regulation, the minimum and maximum battery voltages closely match the six-minute average battery voltage throughout the morning and during load operation. With the onset of regulation, the minimum and maximum battery voltages are different from the six-minute averaged voltages, and indicate the approximate controller set points. During regulation, the maximum battery voltage is between 14.3 volts and 14.5 volts. This maximum battery voltage corresponds to the voltage regulation set point for the battery charge controller.

The minimum battery voltage is consistently 13.7 volts, corresponding to the voltage that the charge controller reconnects the array to the battery and resumes charging. The fact that the minimum voltage is consistent over the regulation period indicates that the controller is regulating or "cycling" the battery voltage between the voltage regulation and array reconnect set points at least once every six minutes. The differences in the minimum and maximum battery voltages during regulation demonstrate the operation of an interrupting (on-off) type controller algorithm. This voltage difference is often referred to as the controller's hysteresis or array regulation voltage span. The hysteresis is an important specification for on-off controllers, and must be selected properly to achieve good array energy utilization and proper battery recharging. Towards the end of the sunlight hours (1600-1700 hours), the PV array current output reduces to a sufficiently low value, in this case about 2.5 amps, so regulation is not required to limit the battery voltage below the regulation set point of the controller. Once the sun sets (1800 hours), the battery voltage begins a gradual decrease to its open-circuit voltage.

Note: the open-circuit voltage at this time is higher than in the morning

(before the battery was recharged), indicating a higher state of charge. At 2030 hours, the 3-amp load is reconnected and the battery voltage begins to steadily decrease in transition to the next day.

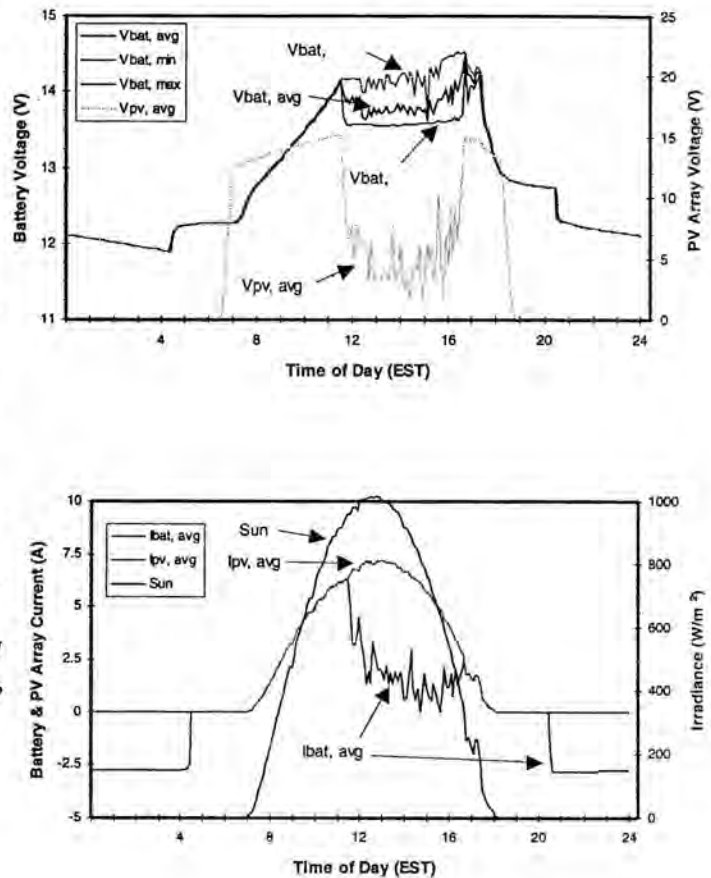


Figure 5

5.4.4.3 Daily Profile for Series-Interrupting Charge Regulator

Figure 5.20 illustrates a 24-hour daily profile for a small stand-alone PV lighting system operating with a series-interrupting (on-off) type battery charge regulator. Beginning at the left on the two graphs (midnight), the load is operating and battery voltage decreasing steadily from 11.9 volts to 11.7 volts while being discharged at 3 amps. At 0400 hours, the load current is disconnected by the charge controller load regulation/timing circuit. At this point the battery current goes to zero and there is a sharp rise in battery voltage as it approaches an open-circuit (no load) voltage of 12.1 volts. At sunrise (0700 hours) battery voltage begins to increase as the PV array current begins to recharge the battery. Until noon time (1200 hours) the PV array current and the battery voltage increase steadily with increasing insolation as the battery is being recharged. Note: during this period, the battery charge controller is not regulating and the PV array current is approximately the same as the battery current. However, the minimum battery voltage shows values slightly lower than the average and maximum battery voltages during the morning charging period. This is a particular characteristic of the charge controller in the test system (the array is periodically disconnected from the battery to sense nighttime conditions).

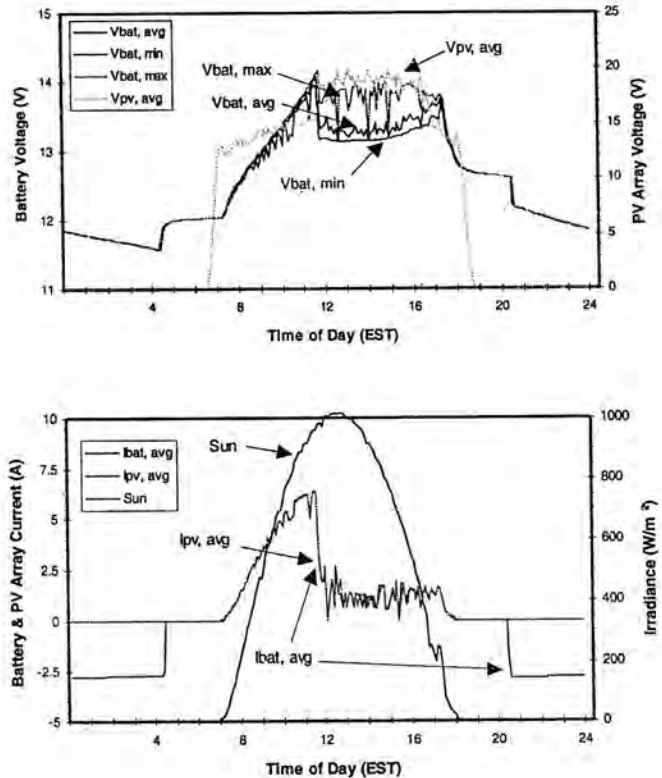


Figure 5.20

At noon time (1200 hours), the battery voltage reaches the regulation voltage of the battery charge controller (14.1 volts) and the controller begins to regulate the PV array current. When this occurs, the battery current decreases to the jagged characteristic of the interrupting (on-off) algorithm. The series characteristic shows that once regulation begins, the average PV array current also decreases, while the average PV array voltage approaches the array open-circuit voltage. In effect, this controller open-circuits the array in a series manner during regulation, resulting in zero PV current and operating the array at the open-circuit voltage point.

With the onset of regulation, the minimum and maximum battery voltages are distinguished

from the six-minute average voltage and show the approximate controller set points. After regulation, the maximum battery voltage is approximately 4.1 volts. This maximum battery voltage corresponds to the voltage regulation set point for the battery charge controller. The minimum battery voltage is between 13.2 volts and 13.4 volts, corresponding to the voltage point the charge controller reconnects the array to the battery to resume charging.

Once the sun sets (1800 hours) the battery voltage begins a gradual decrease to its open-circuit voltage. Note: the open-circuit voltage at this time is higher than in the morning before the battery was recharged. At 2030 hours the 3-amp load is reconnected and the battery voltage begins to steadily decrease in transition to the next day.

In comparison with the shunt-interrupting controller previously discussed, the regulation set point for this series-interrupting controller is considerably lower, resulting in a lower battery state of charge. This is indicated by the lower battery voltage just prior to the load being disconnected in the early morning.

5.4.4.4 Daily Profile for Modified Series Charge Regulator

Figure 5.21 shows a 24-hour daily profile for a small stand-alone PV lighting system operating with a modified series type battery charge regulator. Beginning at the left of the two graphs (midnight), the load is operating and battery voltage decreases steadily from 12.25 volts to 12 volts while being discharged at 3 amps. At 0430 hours the load current is disconnected by the charge controller load regulation/timing circuit. At this point the battery current goes to zero, and there is a sharp rise in the battery voltage as it approaches an open-circuit (no load) voltage of 12.4 volts. At sunrise (0700 hours) the battery voltage begins to increase as the PV array current recharges the battery. Until noon time (1200 hours) the PV array current and the battery voltage increase steadily with increasing insolation as the battery is being recharged.

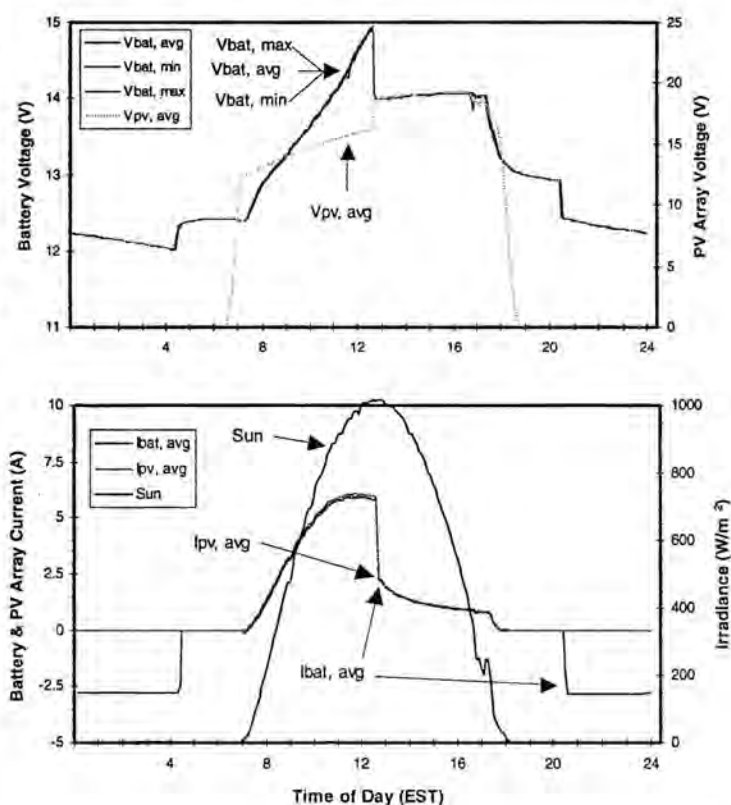


Figure 5

Note: during this period, the battery charge controller is not regulating and the PV array current is approximately the same as the battery current.

At noon time (1200 hours) the battery voltage reaches the regulation voltage set point for the battery charge controller (14.9 volts) and the controller begins to regulate the PV array current. In contrast to the series-interrupting and shunt-interrupting controllers previously discussed, the battery current is not entirely disconnected from the battery, it is only limited to a lower value. When this occurs, the battery current decreases to below 2 amps, and remains in a current-limited mode through the remainder of the day. The series characteristic is shown by the fact that once regulation begins, the average PV array current also decreases, while the average PV array voltage approaches the open-circuit array voltage. In principle, this controller regulates the array in a series-linear manner by increasing the resistance between the PV array and battery. The resistance is held at such a value that a limited amount of current is allowed to flow from the PV array to the battery after initial regulation.

With the onset of regulation, the minimum and maximum battery voltages are indistinguishable from the six-minute average voltage, indicating that the controller is not an interrupting (on-off) type design. After the initial battery regulation at 14.9 volts, the voltage after subsequent regulation remains at about 14.1 volts through the remainder of the day.

Once the sun sets (1800 hours) the battery voltage begins a gradual decreasing to its open-circuit voltage. At 2030 hours the 3-amp load is reconnected and the battery voltage begins to steadily decrease as the battery is discharged.

5.4.4.5 Daily Profile for Constant-Voltage Series Charge Regulator

Figure 5.22 shows a 24-hour daily profile for a small stand-alone PV lighting system operating with a constant-voltage series type battery charge controller. Beginning at the left on the two graphs (midnight), the load is operating and battery voltage decreases steadily from 12.1 volts to 11.9 volts while being discharged at 3 amps. At 0430 hours the load current is disconnected by the charge controller load regulation/timing circuit. At this point the battery current goes to zero and there is a sharp rise in battery voltage as it approaches an open-circuit (no load) voltage of 12.3 volts. At sunrise (0700 hours) the battery voltage begins to increase as the PV array current charges the battery. Until noon time (1200 hours) the PV array current and the battery voltage increase steadily with greater insolation as the battery is recharged. Note: during this period the battery charge controller is not regulating and the PV array current is approximately the same as the battery current.

At noon time (1200 hours) battery voltage reaches the regulation voltage set point for the battery charge controller (14.5 volts), and the controller begins to regulate the PV array current. When this occurs, the battery current gradually decreases to 1 amp by the end of the day. The series characteristic of this controller is shown because once regulation begins, the average PV array current also decreases, while the average PV array voltage approaches the open-circuit array voltage.

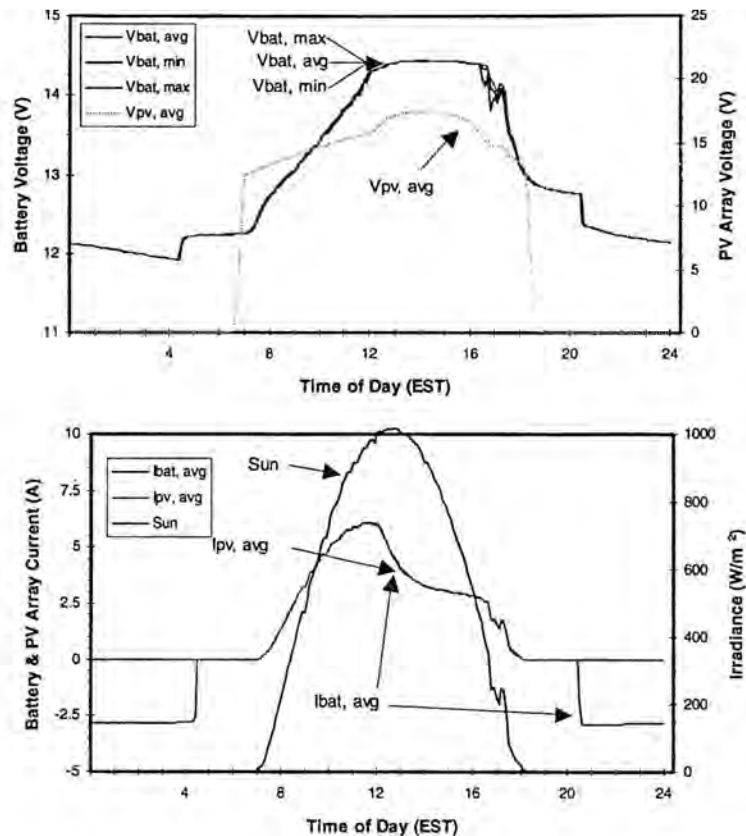


Figure 5.22

In principle, this controller regulates the array in a series-linear manner, by increasing the resistance between the PV array and battery through semiconductor devices, such as MOSFETs. The resistance is held at a value that limits the amount of current allowed to flow from the PV array to the battery after initial regulation, while holding the array voltage at a constant value corresponding to the controller's regulation voltage.

With the onset of regulation, the minimum and maximum battery voltages are indistinguishable from the six-minute average voltage, indicating that the controller is not an interrupting (on-off) type design. Regulation begins at 14.5 volts and remains at this level through the remainder of the day. Moving toward sunset (1800 hours), the array current is no longer high enough to maintain the battery at the regulation voltage, and the battery voltage begins a gradual decrease to its open-circuit voltage. At 2030 hours the 3-amp load is again reconnected and the battery voltage begins to steadily decrease until the next day when charging resumes.

5.4.4.6 Daily Profile for Pulse-Width-Modulated Series Charge Regulator

Figure 5.23 shows a 24-hour daily profile for a small stand-alone PV lighting system operating with a pulse-width-modulated (PWM) series type battery charge regulator. Beginning at the left of the two graphs (midnight) the load is operating and battery voltage decreasing steadily from 12.2 volts to 11.9 volts while being discharged at about 3 amps. At 0430 hours the load current is disconnected by the charge controller load regulation/timing circuit. At this point the battery current goes to zero and there is a sharp rise in the battery voltage as it approaches an open-circuit (no load) voltage of 12.3 volts. At sunrise (0700 hours) the battery voltage begins to increase as the PV array current charges the battery.

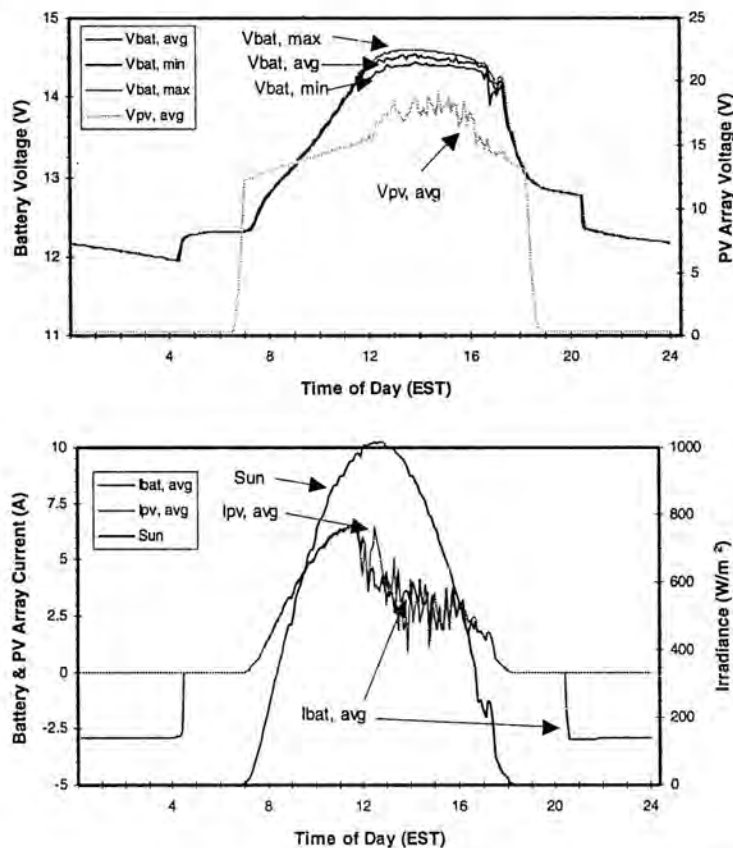


Figure 5.23

Until noontime (1200 hours) the PV array current and the battery voltage increase steadily with increasing insolation as the battery is recharged. Note: during this period, the battery charge controller is not regulating and the PV array current is approximately the same as the battery current.

At noon time (1200 hours) the battery voltage reaches the regulation voltage set point for the battery charge controller (14.5 volts) and the controller begins to regulate the PV array current. When this occurs the battery current decreases in a jagged manner and remains in a current-limited mode through the remainder of the day. The series characteristic can be seen because once regulation begins, the average PV array current also decreases, while the average PV array voltage approaches the open-circuit array voltage. In principle, this controller regulates the array in a series manner by decreasing the width or time of the current pulses supplied to the battery. In the PWM design, an oscillating signal operating at a frequency of several hundred Hertz is used to regulate the array current. When the controller is not regulating, the full array current is applied to the battery. When the regulation voltage is reached, the current pulses are gradually reduced to hold the battery voltage at the regulation set point. In effect, the PWM design operates similarly to the constant-voltage controller, with the exception of a small hysteresis between the minimum and maximum battery voltage after regulation. The PWM is essentially a high switching speed interrupting (on-off) type controller that does not allow the battery voltage to drop significantly during regulation.

Once the sun sets (1800 hours) the battery voltage begins a gradual decrease to its open-circuit voltage. At 2030 hours the 3-amp load is reconnected and the battery voltage begins to steadily decrease in transition to the next day.

5.4.5 Voltage Regulation Set Point Selection

As previously discussed, to achieve optimal battery performance and lifetime in PV systems it is critical that the voltage regulation set point of a charge regulator be properly selected. The set points are probably more important than the particular type of regulator design. If a very sophisticated charge regulator design is used, but it is adjusted to an improper charge regulation voltage, no benefit will result, and battery performance is likely to suffer. A relatively simple design with the set points adjusted properly will work better than a sophisticated controller which is not set properly for the application.

The optimal selection of the voltage regulation set point will ensure that the battery is maintained at the highest possible state of charge without overcharging. The specific set point values to use for a particular battery type, regulator design, and application depend on a number of factors. While there are no simple methods to arrive at the optimal set points, some general guidelines for voltage regulation set point selection follow.

A battery in a stand-alone PV system is charged much differently than battery manufacturers recommend, because it must be fully recharged during the few daylight hours which is a much shorter time period than manufacturers use. For this reason, the voltage regulation set point must be high enough to permit high utilization of the array current, but not so high that the battery will excessively overcharge. Therefore, determining when a battery is being overcharged is the key issue limiting the voltage regulation set point used in PV system charge regulators.

5.4.5.1 Battery Gassing is Key To Voltage Regulation Set Point Selection

The gassing characteristics of a battery provide key information regarding voltage regulation set point selection. As discussed earlier, gassing occurs during battery charging when a certain voltage is reached. The specific gassing voltage is dependent on temperature and type of battery.

Some degree of gassing and overcharge is required for flooded lead-acid batteries, but can be harmful to sealed VRLA captive electrolyte type batteries (lost electrolyte cannot be replaced). For these battery types, the charging process should be carefully controlled, to avoid gassing. In general, sealed "maintenance free" valve-regulated batteries (using lead-calcium grids) require lower charge regulation voltage set points than flooded deep cycling batteries (using lead-antimony grids).

The onset of gassing in a lead-acid cell is not only determined by the cell voltage but by the temperature. As temperature increases, the corresponding gassing voltage decreases for a particular battery. This is the primary reason why temperature compensation is used for the voltage regulation set point.

Regardless of the charge rate, gassing voltage remains constant. However, gassing begins at a lower battery state of charge at higher charge rates, due to the higher battery voltage under charge. The grid design, whether lead-antimony or lead-calcium, also affects gassing. Battery manufacturers should be consulted to determine the gassing voltages for specific designs. Figure 5.24 shows the relationships between cell voltage, state of charge, charge rate and temperature for a typical lead-acid cell with lead-antimony grids.

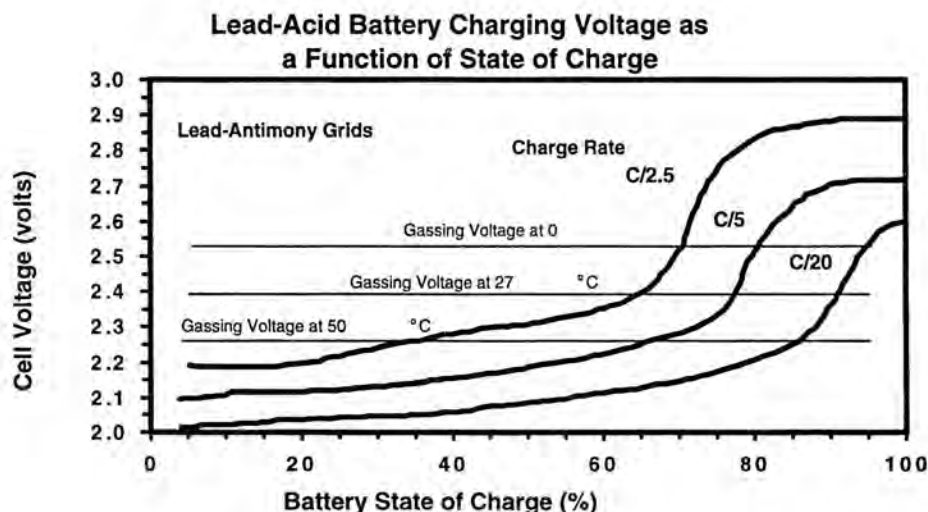


Figure 5.24

Figure 5.24 shows, at 27 °C and a charge rate of C/20 the gassing voltage of 2.35 volts per cell is reached at 90% state of charge. At a charge rate of C/5, at 27 °C, the gassing voltage is reached at 75% state of charge. At a battery temperature of 0 °C, the gassing voltage increases to about 2.5 volts per cell, or 15 volts for a nominal 12-volt battery. The effects of temperature on the gassing voltage is the reason the charge regulation voltage is sometimes temperature compensated, to fully charge batteries in cold weather and to limit overcharge during warm weather. This type of information is needed to properly select battery charge controller voltage regulation set points in order to limit the amount of gassing for a specific battery design and operating conditions.

5.4.5.2 Suggestions for Voltage Regulation Set Point Selection

The recommended ranges for charge regulation voltages at 25 °C for different battery types used in PV systems are presented in Table 5.5. These values are typical of voltage regulation set points for battery charge controllers used in small PV systems. These are only general recommendations and specific battery manufacturers should be consulted for their suggested values.

Table 5.5 Voltage Regulation Set Point Suggestions

Regulator Design Type	Charge Regulation Voltage at 25°C	Battery Type			
		Flooded Lead-Antimony	Flooded Lead-Calcium	Sealed, Valve Regulated Lead-Acid	Flooded Pocket Plate Nickel-Cadmium
On-Off, Interrupting	Per nominal 12-volt battery	14.6 - 14.8	14.2 - 14.4	14.2 - 14.4	14.5 - 15.0
	Per Cell	2.44 - 2.47	2.37 - 2.40	2.37 - 2.40	1.45 - 1.50
Constant-Voltage, PWM, Linear	Per nominal 12-volt battery	14.4 - 14.6	14.0 - 14.2	14.0 - 14.2	14.5 - 15.0
	Per Cell	2.40 - 2.44	2.33 - 2.37	2.33 - 2.37	1.45 - 1.50

The charge regulation voltage ranges presented in Table 5.5 are much higher than the typical charge regulation values presented in manufacturer's literature, because battery manufacturers often refer to regulation voltage in terms of the float voltage, or the voltage limit suggested when batteries are float charged for extended periods (i.e., in uninterruptible power supply (UPS) system). In these and many other commercial battery applications, batteries can be "trickle" or float charged for an extended period, requiring a voltage low enough to limit gassing. Typical float voltages are between 13.5 volts and 13.8 volts for a

nominal 12-volt battery, or between 2.25 volts and 2.30 volts for a single cell. However, to ensure that the battery is fully recharged in a PV system, recharging must occur within a limited time (usually during sunlight hours), and requires that the regulation voltage be much higher than the manufacturer's float voltage. If charge regulation voltages in a typical PV system were set at the manufacturer's recommended float voltage, the batteries would never be fully charged.

5.4.5.3 Temperature Compensation

As discussed previously, the electrochemical reaction and gassing in a battery is highly temperature dependent. Lower battery temperatures slow down the reaction, reduce their capacity and increase the voltage required for gassing. Conversely, higher temperatures accelerate the reaction, increase grid corrosion, and lower the gassing voltage. For these reasons, temperature compensation (TC) of the VR set point is often used in PV systems.

When environmental conditions cause battery temperatures to vary more than $\pm 5^{\circ}\text{C}$ from the rated conditions, compensation of the charge regulation set point is highly recommended. TC is also strongly recommended for all types of sealed VRLA captive electrolyte batteries, that are sensitive to overcharge. By using TC a battery can be fully charged during cold weather and protected from overcharge during hot weather.

Charge regulators measure or estimate the battery temperature to perform TC. Battery temperatures may be sensed with an external probe connected to the regulator or approximated with an on-board sensor in regulator circuitry. If battery temperatures are lower than the design condition, the regulation voltage is increased to allow the battery to reach a moderate gassing level and fully recharge. Conversely, the regulation set point is reduced if battery temperatures are greater than design conditions. A widely accepted value of TC for lead-acid batteries is $-5\text{ mV}/^{\circ}\text{C}/\text{cell}$. For a nominal 12-volt battery this amounts to 30 mV per $^{\circ}\text{C}$. If battery temperatures vary by as much as 30°C , TC may result in the regulation set point varying by as much as 1.0-volts in a 12-volt system. It is important to notice that the TC coefficient is negative, meaning increases in temperature require a reduction in the charge regulation voltage.

If the electrolyte concentration has been adjusted for local ambient temperature (increase in specific gravity for cold environments, decrease in specific gravity for warm environments) and temperature variation of the batteries is minimal, compensation may not be as critical. Typically, the LVD set point is not temperature compensated unless the batteries operate below 0°C on a frequent basis.

5.4.6 Operating Without a Charge Regulator

In most cases a charge regulator is required for the successful operation of a stand-alone PV system. However, there are special circumstances where a charge regulator may not be needed in small systems with well-defined loads. Beacons and aids to navigation are popular PV applications that operate without charge regulation. Eliminating the need for the sensitive

electronic charge regulator simplifies the design, lowers the cost, and improves reliability.

The system design requirements and conditions for operating without a charge regulator must be well understood, because the system is operating without any overcharge and overdischarge protection for the batteries. There are two cases when a battery charge regulation may not be required: 1) a low voltage "self-regulating module" is used in the proper climate and, 2) the battery is very large compared to the array.

5.4.6.1 Using Low-Voltage "Self-Regulating" Modules

"Low-voltage" or "self-regulating" PV modules can allow the system to operate without battery charge regulation. This does not mean that the modules have an electronic charge regulator built-in, rather it refers to the low voltage design of the PV modules. When a low voltage module, battery, and load are properly configured, the design is called a "self-regulating system".

Silicon power modules used for charging nominal 12-volt batteries usually have 36 solar cells connected in series, to produce an open-circuit voltage of greater than 21 volts and a maximum power voltage of about 17 volts. Why do we generally use modules with a maximum power voltage of 17 volts when we are only charging a 12-volt battery to maybe 14.5 volts? In most systems, the voltage drop in the wiring, disconnects, overcurrent devices/controls, and higher array operating temperatures, tends to reduce the array voltage measured at the battery terminals. By using a standard 36-cell PV module, we are assured of operating to the left of the "knee" on the array I-V curve, allowing the array to deliver its rated maximum power current. Even when the array is operating at a high temperature, the maximum power voltage is still sufficient to charge the battery. If the array is operated to the right of the I-V curve "knee", the peak array current would be reduced, possibly prohibiting the system from meeting the load demands.

In the case of "self-regulating" modules without battery charge regulation, the advantage is that the array current falls off sharply as the voltage increases above the maximum power point. In a "self-regulating" low voltage PV module, there are generally only 28-30 silicon cells connected in series, resulting in an open-circuit voltage of about 18 volts and a maximum power voltage of about 15 volts at 25 °C. Under typical operating temperatures, the "knee" of the IV curve falls within the range of typical battery voltages. As a battery charges during a typical day, its voltage rises and the array operating voltage increases towards the maximum power point or "knee" of the IV curve. In addition, the module temperature increases, resulting in a reduction of the maximum power voltage. At some point, the battery voltage is high enough that the operating point on the IV curve is to the right of the "knee". In this region of the IV curve, the current reduces sharply with any further increases in voltage, effectively reducing the charge current and overcharge to the battery.

In summary, a "self-regulating system" design can greatly simplify the system by eliminating the need for a charge regulator. However, these types of designs are only appropriate for

certain applications and conditions. In most common stand-alone PV system designs, a charge regulator is required.

5.4.6.2 Using a Large Battery or Small Array

A charge regulator may not be needed if the charge rates delivered by the array to the battery are small enough to prevent the battery voltage from exceeding the gassing voltage limit, when the battery is fully charged and the full array current is applied. In certain applications a long autonomy period may be used, resulting in a large amount of battery storage capacity. In these cases, the charge rates from the array may be very low and can be accepted by the battery at any time without overcharging. These situations are common in critical applications requiring large battery storage, such as remote navigational aides or telecommunication repeaters in alpine conditions. It might also be the case when a very small load and array are combined with a large battery, as in remote telemetry systems.

In general, a charging rate of $C/100$ or less is considered low enough to be tolerated for long periods, even when the battery is fully charged. Even during the peak of the day, the array is charging the battery bank at the 100-hour rate or slower, equivalent to the typical trickle charge rate that a regulator would produce.

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Exercises

1. What are the two general types of photovoltaic systems? List the distinguishing features of each type.
2. Sketch block diagrams for each of the following stand-alone photovoltaic systems:
 - a) direct-coupled
 - b) battery storage without charge control
 - c) battery storage with charge control
 - d) battery storage with ac and dc loads
3. List at least one advantage and one disadvantage of using dc loads versus ac loads.
4. Explain why energy efficiency is more important in selecting electrical loads (i.e., end-use appliances or equipment) for photovoltaic systems than for conventionally powered applications.
5. An inverter is used to operate a 100-watt incandescent light bulb. What is the inverter efficiency if the 12-volt battery is providing 14 amperes to the inverter?
6. Sketch the waveforms for the sine, quasi-sine, and square wave inverters.
7. An inverter has a minimum load capability of 15 watts. What happens if an electrical appliance with a significantly lower power requirement is switched on with no other electrical load operating?
8. Explain why the heating time of a microwave oven may be increased when operating from a typical stand-alone inverter.
9. Why are induction motors with low power factors more difficult to start than induction motors with high power factors?
10. List three safety checks that should be performed before using an inverter.
11. What is the difference between a primary and a secondary battery?
12.
 - a) What are the most common units of battery capacity?
 - b) List three design features that affect battery capacity.
 - c) List five operational factors that affect battery capacity.

Exercises (cont.)

13. How do changes in temperature affect:
 - a) battery life?
 - b) battery capacity?

14. A 12-volt battery costs \$64, operates at an average daily depth-of-discharge (DOD) of 12%, has a cycle life of 400 at that DOD, and has an energy storage capacity of 0.9 kWh. Compute the battery cost parameter.

15. Define battery autonomy.

16. List seven battery system design considerations.

17. For battery charge controllers:
 - a) List the two primary functions.
 - b) List six secondary functions.

18. Discuss the problem that would result if a charge controller used with flooded electrolyte batteries was inserted into a system using absorbed glass mat (AGM) batteries, assuming no adjustments were made to the set points. Explain why compatibility between the charge controller and batteries is so important in photovoltaic system design.



Stand-Alone System Sizing Procedures

6

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Stand-alone System Sizing Procedures

6

Objectives

- 1) *Size a stand-alone PV system.*
- 2) *Size a stand-alone engine generator system.*
- 3) *Size a hybrid PV and engine generator system.*
- 4) *Size a PV water pumping system.*

Key Words

Battery bus voltage

Rated wattage

Design temperature

Days of storage desired or required

Allowable depth of discharge

Required battery capacity

Design tilt

Battery round-trip efficiency

Generator

Battery charger

Direct-coupled

Peak flow rate

Peak velocity

Suction lift or head

Discharge head

Pressure head

Static head

Dynamic head

Velocity head

Friction head

Total system head

Hydraulic energy

Hydraulic power

6.1 The Sizing Procedure

The design of a stand-alone system is readily accomplished by systematically considering the load to be powered, the type and size of batteries required, the photovoltaic array size, additional electrical and structural components, and costs. The block diagram in figure 6.1 illustrates the sizing procedure.

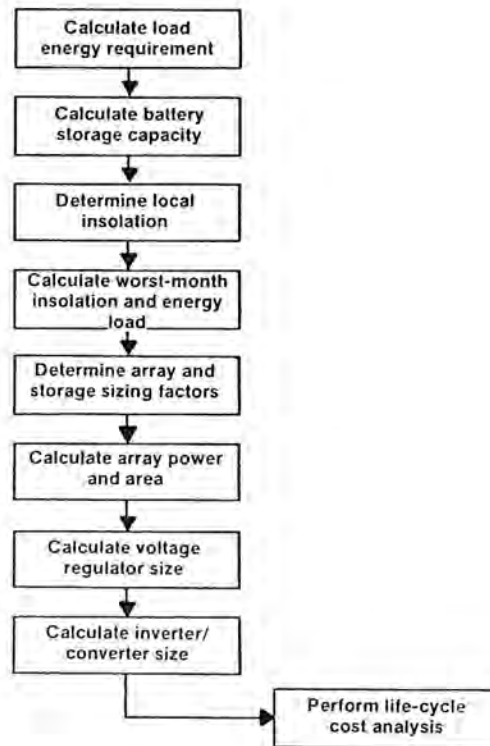


Figure 6.1 The sizing process

The type of photovoltaic system determines both the system components and the sizing procedure. This section presents sizing procedures for four types of stand-alone systems: stand-alone photovoltaic with battery storage, stand-alone generator with battery storage, stand-alone photovoltaic/generator hybrid with battery storage and stand-alone direct-coupled pumping systems with no battery storage. Each procedure is explained with a completed example. Please refer to the Appendix for a more detailed explanation of the steps involved for each sizing process.

6.2 Example 1: Sizing a Stand-Alone Photovoltaic System

The application for this introductory sizing example is a residence in the rural area outside of Tallahassee, Florida (30.38° North latitude). The site is five miles from the nearest utility line. Because of the high cost to extend a line to the site, a stand-alone photovoltaic system with battery storage is being investigated as an alternative means of supplying electricity to the residence.

The appliances that require electricity include five lights, a refrigerator, three ceiling fans, a clothes washer, a television and a toaster. All of this equipment operates on 110 volts ac, and thus requires an inverter between the battery storage system and the appliances.

For this application, the average operating efficiency of the inverter is assumed to be 0.85, which is a reasonable value for properly sized stand-alone inverters.

The required nominal input voltage for the selected inverter is 24 volts dc, thus establishing the battery bus voltage at this level.

The approach presented here gives a good approximation of the size components required to design an effective and reliable stand-alone photovoltaic system with constant loads. Note that this method is a “point-sizing approach,” designed to meet the load under the worst case insolation conditions, usually in the winter months for the northern hemisphere. Seasonal variation of the load, for example, in lighting systems that operate more hours in the winter than in the summer, may require looking at the worst month insolation to load ratio to insure availability of the loads at all times.

The following is the completed sizing worksheet used for this example. Detailed explanations on the completion of each step follow the worksheet.

Sizing of Stand-Alone Photovoltaic Systems WORKSHEET

Application Stand - Alone Home 5 miles from Utility Line
 Location Tallahassee, FL Latitude 30.38

A. Loads

A1 Inverter efficiency (decimal) .85
 A2 Battery bus voltage 24 volts
 A3 Inverter ac voltage 110 volts

Appliance	A4 Rated Wattage	A5 Adjustment Factor 1.0 for dc (A1) for ac	A6 Adjusted Wattage (A4 / A5)	A7 Hours Per Day Used	A8 Energy Per Day (A6 x A7)
5 lights 30W ea.	150	.85	176	2	352
Refrigerator	500	.85	588	5	2940
3 ceiling fans 45W ea.	135	.85	159	8	1272
Washer	1500	.85	1765	6 hrs/week = .86 day	1518
Television	200	.85	235	4	940
Toaster	1500	.85	1765	.25	441

A9 Total energy demand per day (summation of A8) 7463 watt-hours
 A10 Total amp-hour demand per day (A9 / A2) 311 amp-hours
 A11 Maximum ac power requirement (summation of A4) 3985 watts
 A12 Maximum dc power requirement (summation of A6) 4688 watts

B. Battery Sizing

Design Temperature 25°C

B1 Days of storage desired/required 7 days
 B2 Allowable depth-of-discharge limit (decimal) .8
 B3 Required battery capacity (A10 x B1 / B2) 2721 amp-hours
 B4 Amp-hour capacity of selected battery * 478 amp-hours
 B5 Number of batteries in parallel (B3 / B4) 6
 B6 Number of batteries in series (A2 / battery voltage) 2
 B7 Total number of batteries (B5 x B6) 12
 B8 Total battery amp-hour capacity (B5 x B4) 2868 amp-hours
 B9 Total battery kilowatt-hour capacity (B8 x A2 / 1000) 68.8 kilowatt-hours
 B10 Average daily depth of discharge (.75 x A10 / B8) .08

* Use amp-hour capacity at a rate of discharge corresponding to the total storage period, B1.

C. Photovoltaic Array Sizing Design Tilt 40° Design Month December

C1	Total energy demand per day (A9)	<u>7463</u>	watt-hours
C2	Battery round-trip efficiency (0.70 - 0.85)	<u>0.85</u>	
C3	Required array output per day (C1 / C2)	<u>8780</u>	watt-hours
C4	Selected PV module max power voltage at STC x 0.85	<u>14.8</u>	volts
C5	Selected PV module guaranteed power output at STC	<u>47.7</u>	watts
C6	Peak sun hours at design tilt for design month	<u>3.77</u>	hours
C7	Energy output per module per day (C5 x C6)	<u>180</u>	watt-hours
C8	Module energy output at operating temperature. Use derating factor, DF = 0.80 for hot climates and critical applications; DF = 0.90 for moderate climates and non-critical applications (DF x C7)	<u>162</u>	watt-hours
C9	Number of modules required to meet energy requirements (C3 / C8)	<u>55</u>	modules
C10	Number of modules required per string (A2 / C4) rounded to next higher integer	<u>2</u>	modules
C11	Number of strings in parallel (C9 / C10) rounded to next higher integer	<u>28</u>	strings
C12	Number of modules to be purchased (C10 x C11)	<u>56</u>	modules
C13	Nominal rated PV module output	<u>53</u>	watts
C14	Nominal rated array output (C13 x C12)	<u>2968</u>	watts

D. Balance-of-System (BOS) Requirements

1. A voltage regulator is recommended unless array output current (at 1000 W/m² condition), less any continuous load current, is less than 5% of the selected battery bank capacity (at the 8-hour discharge rate).
2. Wiring should be adequate to ensure that losses are less than 1% of the energy produced.
3. In low voltage (i.e., less than 50 volts) systems, germanium or Schottky blocking diodes are preferred over silicon diodes.
4. Fuses, fuse holders, switches, and other components should be selected to satisfy both voltage and current requirements.
5. All battery series branches should contain fuses.
6. Fused disconnects are strongly recommended to isolate the battery bank from the rest of the system.
7. Refer to electrical and mechanical design sections for other considerations.

APPLICATION: Stand-alone home 5 miles from utility line

LOCATION: Tallahassee, FL

LATITUDE: 30.38° North

A. LOADS

- (A1): Inverter efficiency (decimal). This quantity is used as a power adjustment factor when current is changed from dc to ac. The efficiency of the inverter selected for this application is assumed to be **0.85**.
- (A2): Battery bus voltage. This is the nominal dc operating voltage of the system. The battery bus voltage for this application is **24 volts**, which corresponds to the required dc input voltage for the inverter.
- (A3): Inverter ac voltage. The output voltage of the inverter selected for this application is **110 volts**.

The components (appliances) that the system will power are:

5 lights (30W ea.), combined rated wattage 150, used 2 hrs/day.
 Refrigerator, rated wattage 500, used 5 hrs/day.
 3 ceiling fans (45W ea.), combined rated wattage 135, used 8 hrs/ day.
 Washer, rated wattage 1500, used 6 hrs/wk or 0.86 hrs/day.
 Television, rated wattage 200, used 4 hrs/day.
 Toaster, rated wattage 1500, used 0.25 hrs/day.

The appliances are listed under the column heading **Appliance**.

- (A4): The rated wattage is listed for each appliance in column (A4). Note that the rated wattage for some appliances may vary from actual power consumed due to load variation or cycling (i.e., refrigeration, motors, etc).

<u>Appliance</u>	(A4) <u>Rated Wattage</u>
5 lights (30W ea.)	150
Refrigerator	500
3 ceiling fans (45W ea.)	135
Washer	1500
Television	200
Toaster	1500

- (A5): Adjustment factor. The adjustment factor is related to the efficiency of the inverter and reflects the actual power consumed from the battery bank to operate ac loads from the inverter. For ac loads, the value (A1) is inserted in column (A5). For this application the adjustment factor is **0.85**. For dc loads operating from the battery bank an adjustment factor of **1.0** is used.
- (A6): Adjusted wattage. Dividing the rated wattage (A4) by the adjustment factor (A5) adjusts the wattage to compensate for the inverter inefficiency and gives the actual wattage consumed from the battery bank. $(A4) / (A5)$.

<u>Appliance</u>	<u>(A4) / (A5)</u>	=	<u>Adjusted Wattage (A6)</u>
5 lights (30W ea.)	150 / 0.85	=	176
Refrigerator	500 / 0.85	=	588
3 ceiling fans (45W ea.)	135 / 0.85	=	159
Washer	1500 / 0.85	=	1765
Television	200 / 0.85	=	235
Toaster	1500 / 0.85	=	1765

- (A7): Hours per day used. The number of hours each appliance is used per day is listed in column (A7). The duty cycle, or actual time of load operation, must be considered here. For example, a refrigerator may be functional 24 hours a day, but the compressor may only operate 5 hours per day.
- (A8): Energy per day. The amount of energy each appliance requires per day is determined by multiplying each appliance's adjusted wattage (A6) by the number of hours used per day (A7). $(A6) \times (A7)$

<u>Appliance</u>	<u>(A6) x (A7)</u>	=	<u>Energy Per Day (A8)</u>
5 lights (30W ea.)	176 x 2	=	352
Refrigerator	588 x 5	=	2940
3 ceiling fans (45W ea.)	159 x 8	=	1272
Washer	1765 x 0.86	=	1518
Television	235 x 4	=	940
Toaster	1765 x 0.25	=	441
	Total	=	7463

- (A9): Total energy demand per day. The sum of the quantities in column (A8) determines the total energy demand required by the appliances per day. For this application the total energy demand per day for the load is **7463 watt-hours**.
- (A10): Total amp-hour demand per day. The battery storage subsystem is sized independently of the photovoltaic array. In order to size the battery bank the total electrical load is converted from watt-hours to amp-hours. Amp-hours are determined by dividing the total energy demand per day (A9) by the battery bus voltage (A2). $(A9) / (A2)$.

$$7463 \text{ watt-hours} / 24 \text{ volts} = \mathbf{311 \text{ amp-hours.}}$$

- (A11): Maximum ac power requirement. The sum of the rated wattages (A4) for all appliances is equal to **3985 watts**. Note that this is the maximum continuous power required and does not include surge requirements. This value (A11) is the maximum continuous ac power output required of the inverter if all loads were to operate simultaneously. The peak, or surge, requirement (due to motor starting, etc.) must also be considered when selecting an inverter.
- (A12): Maximum dc power requirement. The sum of the adjusted wattages (A6), or dc power, for all appliances is equal to **4688 watts**. This value (A12) is the maximum dc input power required by the inverter and is necessary to determine wire sizes, fusing and disconnect requirements. If load management techniques are employed to eliminate the possibility of loads operating simultaneously, the inverter maximum output requirements may be reduced accordingly.

B. BATTERY SIZING

DESIGN TEMPERATURE: The location where batteries are stored should be designed to minimize fluctuations in battery temperature. For this application the design temperature is assumed to be **25°C**.

- (B1): Days of storage desired/required (autonomy). The loss of electricity for the residence in this application, although undesirable, would not be catastrophic. Consequently, the battery storage system is designed to provide the necessary electrical energy for a period equivalent to **7 days** without any sunshine. This time period is considered a moderate level of storage for the southeastern U.S. for non-critical applications. Less critical applications may use 3 to 4 days of storage, although this would increase the depth of battery cycling and reduce battery life. For critical applications such as those that would impact public safety, more days of storage may be desirable.

- (B2): Allowable depth-of-discharge limit (decimal). The maximum fraction of capacity that can be withdrawn from the battery as specified by the designer. Note that the battery selected must be capable of this limit or greater depth of discharge. For this application the allowable depth-of-discharge is **0.8**.
- (B3): Required battery capacity. The required battery capacity is determined by first multiplying the total amp-hours per day (A10) by the days of storage required (B1), $311 \times 7 = 2177$, and then dividing this number by the allowable depth of discharge limit (B2). $[(A10) \times (B1) / (B2)]$.

$$311 \times 7 / .8 = 2721 \text{ amp-hours.}$$

- (B4): Amp-hour capacity of selected battery. Once the required number of amp-hours has been determined (B3), batteries or battery cells can be selected using manufacturers' information. Exide 6E95-11 industrial grade batteries were selected for this application because of their long cycle life and rugged construction. Figure 6.2 shows that Exide 6E95-11's capacity for a 5 day rate is **478 amp-hours**. Since battery capacity may vary with the rate of discharge, the amp-hour capacity that corresponds to the required days of storage should be used.

To 1.90 Volts Per Cell

TYPE	VOLTS PER UNIT	NOMINAL A.H. CAP.	20 DAY (480 HR)		10 DAY (240 HR)		5 DAY (120 HR)		3 DAY (72 HR)		32°F (0°C) 500 HR A.H.
			A.H.	AMPS	A.H.	AMPS	A.H.	AMPS	A.H.	AMPS	
6E95-5	12	180	192	0.40	192	0.80	192	1.60	192	2.67	184
6E95-7	12	270	288	0.60	288	1.20	288	2.40	288	4.00	276
6E95-9	12	360	383	0.80	383	1.60	383	3.19	383	5.32	368
6E95-11	12	450	478	1.00	478	1.99	478	3.98	478	6.64	459
6E120-9	12	500	538	1.12	538	2.24	538	4.48	538	7.47	516
6E120-11	12	625	673	1.40	673	2.80	673	5.61	673	9.35	646
6E120-13	12	750	808	1.68	808	3.37	808	6.73	808	11.22	776
6E120-15	12	875	942	1.96	942	3.93	942	7.85	942	13.08	904
3E120-17	6	1000	1077	2.24	1077	4.49	1077	8.98	1077	14.96	1034
3E120-19	6	1125	1212	2.53	1212	5.05	1212	10.10	1212	16.83	1163
3E120-21	6	1250	1346	2.80	1346	5.61	1346	11.22	1346	18.69	1292
3E120-23	6	1375	1481	3.09	1481	6.17	1481	12.34	1481	20.57	1422
3E120-25	6	1500	1616	3.37	1616	6.73	1616	13.47	1616	22.44	1551
3E120-27	6	1625	1750	3.65	1750	7.29	1750	14.58	1750	24.31	1680
3E120-29	6	1750	1885	3.93	1885	7.85	1885	15.71	1885	26.18	1809

Figure 6.2 Exide battery specifications at 25°C

- (B5): Number of batteries in parallel. The number of batteries or battery cells needed to provide the required battery subsystem capacity is determined by dividing the required battery capacity (B3) by the amp-hour capacity of the selected battery (B4). $(B3) / (B4)$.

$$2721 \text{ amp-hours} / 478 \text{ amp-hours} = 6 \text{ (round up from 5.6).}$$

- (B6): Number of batteries in series. The number of batteries needed to provide the necessary dc system voltage is determined by dividing the battery bus voltage (A2) by the selected battery or battery cell voltage (taken from manufacturer's information). $(A2) / \text{battery voltage}$.

$$24 \text{ volts} / 12 \text{ volts} = 2.$$

- (B7): Total number of batteries. Multiplying the number of batteries in parallel (B5) by the number of batteries or battery cells in series (B6) determines the total number of batteries needed. $(B5) \times (B6)$.

$$6 \times 2 = 12.$$

- (B8): Total battery amp-hour capacity. The total rated capacity of selected batteries is determined by multiplying the number of batteries in parallel (B5) by the amp-hour capacity of the selected battery (B4). $(B5) \times (B4)$.

$$6 \times 478 \text{ amp-hours} = 2868 \text{ amp-hours.}$$

- (B9): Total battery kilowatt-hour capacity. Based on the selected batteries, the kWh or energy capacity is determined by first multiplying the total amp-hour capacity (B8) times the battery bus voltage (A2), and then dividing this number by 1000. $[(B8) \times (A2)] / 1000$

$$[2868 \text{ amp-hours} \times 24 \text{ volts}] / 1000 = 68.8 \text{ kilowatt-hours.}$$

- (B10): Average daily depth of discharge. The actual daily depth of discharge to be expected on the average for the selected battery subsystem is determined by first multiplying 0.75 by the total amp-hour demand per day (A10), and then dividing this number by the total battery amp-hour capacity (B8). The 0.75 factor is used by assuming that the PV array meets the load during peak sun hours or 0.25 of the day and the batteries supply the load for the other 0.75 of the day. For a lighting load profile that operates only at night this factor would be 1-0, due to the load being entirely supplied by the batteries. $[0.75 \times (A10)] / (B8)$.

$$[0.75 \times 311] / 2868 = 0.08.$$

C. PHOTOVOLTAIC ARRAY SIZING

The size of the photovoltaic array is determined by considering the available solar insolation, the tilt and orientation of the array and the characteristics of the photovoltaic modules being considered. The array is sized to meet the average daily load requirements for the month or season of the year with the lowest ratio of daily insolation to the daily load.

The available insolation striking a photovoltaic array varies throughout the year and is a function of the tilt angle and azimuth orientation of the array. If the load is constant, the designer must consider the time of the year with the minimum amount of sunlight (in the Northern hemisphere, typically December or January). Knowing the insolation available (at tilt) and the power output required, the array can be sized using module specifications supplied by manufacturers.

Using module power output and daily insolation (in peak sun hours), the energy (watt-hours or amp-hours) delivered by a photovoltaic module for an average day can be determined. Then, knowing the requirements of the load and the output of a single module, the array can be sized.

The array is sized to meet the average daily demand for electricity during the worst insolation month of the year, which is December in Tallahassee. The array will face south and because the sun is low in the sky during December will be tilted at an angle of 40° from horizontal in order to maximize the amount of insolation received during December.

DESIGN MONTH: December

DESIGN TILT: 40° for maximum insolation during the design month.

- (C1): Total energy demand per day (A9). **7463 watt-hours.**
- (C2): Battery round-trip efficiency. A factor between 0.70 and 0.85 is used to estimate battery round-trip efficiency. For this application **0.85** is used because the battery selected is relatively efficient and because a significant percentage of the energy is used during daylight hours.
- (C3): Required array output per day. The watt-hours required by the load are adjusted (upwards) because batteries are less than 100% efficient. Dividing the total energy demand per day (C1) by the battery round-trip efficiency (C2) determines the required array output per day. $(C1) / (C2)$.

$$7463 \text{ watt-hours} / 0.85 = 8780 \text{ watt-hours.}$$

- (C4): Selected PV module max power voltage at STC $\times 0.85$. Maximum power voltage is obtained from the manufacturer's specifications for the selected photovoltaic module, and this quantity is multiplied by 0.85 to establish a design operating voltage for each module (not the array) to the left of the maximum power voltage and to ensure acceptable module output current.

Siemens Solar M55 modules are used in this application. According to figure 6.3 the maximum power voltage at STC for the Siemens Solar M55 is 17.4 volts.

$$17.4 \text{ volts} \times 0.85 = \mathbf{14.8 \text{ volts.}}$$

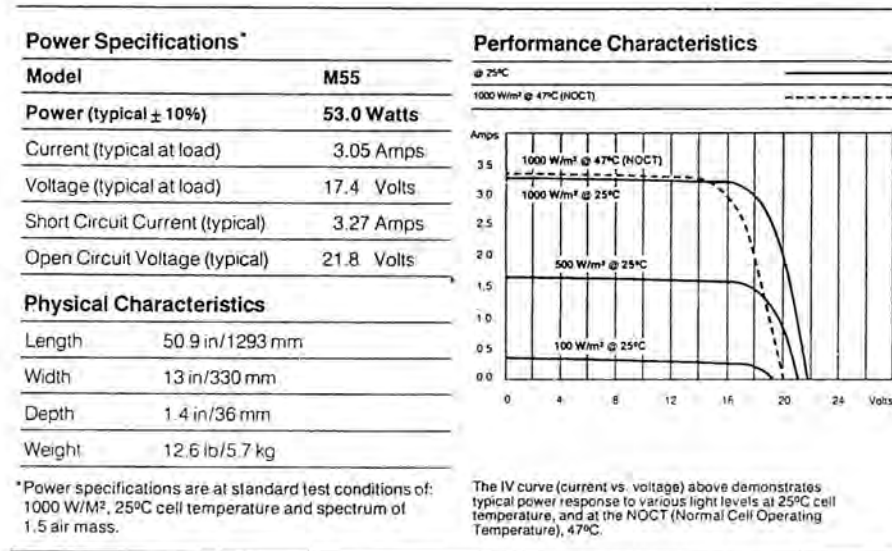


Figure 6.3 Siemens Solar M55 module specifications

- (C5): Selected PV module guaranteed power output at STC. This number is also obtained from the manufacturer's specifications for the selected module. Figure 6.3 shows that the nominal power output at 1000 watts/m² and 25°C is 53 watts. The guaranteed power output is 90% of this value, or **47.7 watts**.
- (C6): Peak sun hours at optimum tilt. This figure is obtained from solar radiation data (shown in figure 6.4) for the design location and array tilt for an average day during the worst month of the year. Peak sun hours at 40° tilt for Tallahassee in December equals 3.77 hours.

City	Tilt	Insolation (kWh/m ² /day)												Annual
		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	
Tallahassee, FL Latitude 30.38	Horizontal	2.77	3.59	4.67	5.75	6.11	5.94	5.52	5.29	4.71	4.16	3.18	2.56	4.52
	15	3.32	4.07	4.98	5.83	5.97	5.72	5.36	5.27	4.90	4.62	3.77	3.15	4.75
	20	3.47	4.20	5.04	5.81	5.87	5.60	5.25	5.22	4.93	4.74	3.93	3.31	4.78
	25	3.61	4.30	5.08	5.76	5.74	5.88	5.12	5.14	4.93	4.83	4.07	3.46	4.79
	30	3.72	4.38	5.09	5.67	5.58	5.26	4.97	5.04	4.90	4.89	4.19	3.59	4.77
	35	3.82	4.44	5.07	5.56	5.39	5.05	4.79	4.91	4.85	4.92	4.28	3.69	4.73
	40	3.89	4.47	5.02	5.41	5.17	4.82	4.59	4.76	4.77	4.93	4.35	3.77	4.66

Figure 6.4 Insolation data for Tallahassee, Florida.

- (C7): Energy output per module per day. The amount of energy produced by the array per day during the worst month is determined by multiplying the selected photovoltaic power output at STC (C5) by the peak sun hours at design tilt (C6).
 $(C5) \times (C6)$.

$$47.7 \times 3.77 = 180 \text{ watt-hours.}$$

- (C8): Module energy output at operating temperature. A derating factor of 0.90 (for moderate climates and non-critical applications) is used in this application to determine the module energy output at operating temperature. Multiplying the derating factor (DF) by the energy output per module (C7) establishes an average energy output from one module. $DF \times (C7)$.

$$0.90 \times 180 \text{ watt-hours} = 162 \text{ watt-hours.}$$

- (C9): Number of modules required to meet energy requirements. Dividing the required output per day (C3) by the module energy output at operating temperature (C8) determines the number of modules required to meet energy requirements.
 $(C3) / (C8)$.

$$8780 \text{ watt-hours} / 162 \text{ watt-hours} = 55 \text{ modules.}$$

- (C10): Number of modules required per string. Dividing the battery bus voltage (A2) by the module design operating voltage (C4), and then rounding this figure to the next higher integer determines the number of modules required per string.
 $(A2) / (C4)$.

$$24 \text{ volts} / 14.8 \text{ volts} = 1.62 \text{ (rounded to 2 modules).}$$

- (C11): Number of strings in parallel. Dividing the number of modules required to meet energy requirements (C9) by the number of modules required per string (C10) and then rounding this figure to the next higher integer determines the number of strings in parallel. $(C9) / (C10)$.

$$55 \text{ modules} / 2 \text{ modules} = 27.5 \text{ (rounded to } \mathbf{28 \text{ strings})}.$$

- (C12): Number of modules to be purchased. Multiplying the number of modules required per string (C10) by the number of strings in parallel (C11) determines the number of modules to be purchased. $(C10) \times (C11)$.

$$2 \times 28 = \mathbf{56 \text{ modules}}.$$

- (C13): Nominal rated PV module output. The rated module output in watts as stated by the manufacturer. Photovoltaic modules are usually priced in terms of the rated module output (\$/watt). The Siemens Solar M55's rated module power is **53 watts**.

- (C14): Nominal rated array output. Multiplying the number of modules to be purchased (C12) by the nominal rated module output (C13) determines the nominal rated array output. This number will be used to determine the cost of the photovoltaic array. $(C12) \times (C13)$.

$$56 \text{ modules} \times 53 \text{ watts} = \mathbf{2968 \text{ watts}}.$$

6.3 Example 2: Sizing a Stand-Alone Engine Generator System

The application for this example is the same as for example 1 – a residence in rural Tallahassee, Florida, with the same electrical appliances. Rather than using a photovoltaic system, however, this example considers a gasoline-powered engine generator. To minimize the run-time of the engine and to utilize it efficiently, battery storage is provided. Because the electrical output of the generator is alternating current, a battery charger is needed to convert the ac signal to dc to charge the batteries.

Because the appliances use ac power, an inverter is required between them and the battery subsystem. A smaller battery subsystem than that required in the stand-alone photovoltaic system can be used because available sunshine is not a factor for this system. Exide industrial grade batteries are used with different capacities than those used in example 1.

For this application the average operating efficiency of the inverter is assumed to be 0.85. The required nominal input voltage for the selected inverter is 24 volts dc, thus establishing the battery bus voltage at this level.

The following is a copy of the completed sizing worksheet for stand-alone generator systems. Detailed explanations on the completion of each step follow the worksheet.

Sizing of Stand-Alone Generator Systems WORKSHEET

Application Stand-Alone Home 5 miles from Utility Line
 Location Tallahassee, FL Latitude 30.38

A. Loads

A1 Inverter efficiency (decimal) .85
 A2 Battery bus voltage 24 volts
 A3 Inverter ac voltage 110 volts

Appliance	A4 Rated Wattage	A5 Adjustment Factor 1.0 for dc (A1) for ac	A6 Adjusted Wattage (A4 / A5)	A7 Hours Per Day Used	A8 Energy Per Day (A6 x A7)
<u>5 lights 30W ea.</u>	<u>150</u>	<u>.85</u>	<u>176</u>	<u>2</u>	<u>352</u>
<u>Refrigerator</u>	<u>500</u>	<u>.85</u>	<u>588</u>	<u>5</u>	<u>2940</u>
<u>3 ceiling fans 45W ea.</u>	<u>135</u>	<u>.85</u>	<u>159</u>	<u>8</u>	<u>1272</u>
<u>Washer</u>	<u>1500</u>	<u>.85</u>	<u>1765</u>	<u>6 hrs/wk = .86 day</u>	<u>1518</u>
<u>Television</u>	<u>200</u>	<u>.85</u>	<u>235</u>	<u>4</u>	<u>940</u>
<u>Toaster</u>	<u>1500</u>	<u>.85</u>	<u>1765</u>	<u>.25</u>	<u>441</u>

A9 Total energy demand per day (summation of A8) 7463 watt-hours
 A10 Total amp-hour demand per day (A9 / A2) 311 amp-hours
 A11 Maximum ac power requirement (summation of A4) 3985 watts
 A12 Maximum dc power requirement (summation of A6) 4688 watts

B. Battery Sizing

Design Temperature 25°C

B1 Daily depth of discharge desired (decimal) .50
 B2 Allowable depth-of-discharge limit (decimal) .80
 B3 Required battery capacity (A10 / B1) 622 amp-hours
 B4 Amp-hour capacity of selected battery * 625 amp-hours
 B5 Number of batteries in parallel (B3 / B4) 1
 B6 Number of batteries in series (A2 / battery voltage) 2
 B7 Total number of batteries (B5 x B6) 2
 B8 Total battery amp-hour capacity (B5 x B4) 625 amp-hours
 B9 Total battery kilowatt-hour capacity (B8 x A2 / 1000) 15 kilowatt-hours
 B10 Average daily depth of discharge (A10 / B8) 0.50
 B11 Maximum allowable battery charge rate (B8 / 3 hours) 208 amps
 B12 Days of storage (B2 x B8 / A10) 1.6 days

* Use amp-hour capacity at 24-hour rate of discharge.

C. Generator/Battery Charger Sizing

C1	Choose battery charger to meet the maximum allowable battery charge rate, B11, at the nominal battery bus voltage, A2	<u>Photron</u> <u>P-24200</u> model #
C2	Battery charger maximum dc output power	<u>4800</u> watts
C3	Battery charger maximum ac input power	<u>6192</u> watts
C4	Battery charger average ac input power	<u>4644</u> watts
C5	Battery charger average dc output power	<u>3575</u> watts
C6	Battery charger average efficiency (C5 / C4)	<u>1.77</u>
C7	Choose generator which will meet the peak battery charger ac input power, C3, and the peak load, A11. Choose the larger of the two.	<u>0.25</u> <u>75TB-3CR</u> model #
C8	Peak generator output	<u>7500</u> watts
C9	Generator/battery charger turn-on point [BSOC] (1 - B10)	<u>0.50</u>
C10	Generator/battery charger turn-off point [BSOC]	<u>1.0</u>
C11	Required generator/battery charger amp-hour production during daily charging cycle (A10 / 0.85)	<u>366</u> amp-hours
C12	Battery charger average charge rate (estimate from battery charger literature between turn-on and turn-off [BSOC], C9 and C10) **	<u>70</u> amps
C13	Average daily generator/battery charger on-time (C11 / C12)	<u>5.2</u> hours
C14	Average yearly generator/battery charger on-time (C13 x 365)	<u>1898</u> hours
C15	Average generator ac output power (C12 x A2 / C6)	<u>2182</u> watts
C16	Average yearly generator energy production (C15 x C14) / 1000)	<u>4141</u> kilowatt-hour
C17	Average generator load (fraction of generator peak ac output), (C15 / C8)	<u>0.29</u>

** If unavailable, use B11 / 3.

APPLICATION: Stand-alone home 5 miles from utility line

LOCATION: Tallahassee, FL

LATITUDE: 30.38° North

A. LOADS

- (A1): Inverter efficiency (decimal). This quantity is used as a power adjustment factor when current is changed from dc to ac. The efficiency of the inverter selected for this application is assumed to be **0.85**.
- (A2): Battery bus voltage. This is the nominal dc operating voltage of the system. The battery bus voltage for this application is **24 volts**, which corresponds to the required dc input voltage for the inverter.
- (A3): Inverter ac voltage. The output voltage of the inverter selected for this application is **110 volts**.

The components (appliances) that the system will power are:

5 lights (30W ea.), combined rated wattage 150, used 2 hrs/day.

Refrigerator, rated wattage 500, used 5 hrs/day.

3 ceiling fans (45W ea.), combined rated wattage 135, used 8 hrs/day.

Washer, rated wattage 1500, used 6 hrs/wk or 0.86 hrs/day.

Television, rated wattage 200, used 4 hrs/day.

Toaster, rated wattage 1500, used 0.25 hrs/day.

The appliances are listed under the column heading **Appliance**.

- (A4): The rated wattage is listed for each appliance in column (A4). Note that the rated wattage for some appliances may vary from actual power consumed due to variation or cycling (i.e., refrigeration, motors, etc.).

<u>Appliance</u>	(A4) <u>Rated Wattage</u>
5 lights (30W ea.)	150
Refrigerator	500
3 ceiling fans (45W ea.)	135
Washer	1500
Television	200
Toaster	1500

(A5): Adjustment factor. The adjustment factor is related to the efficiency of the inverter and reflects the actual power consumed from the battery bank to operate ac loads from the inverter. For ac loads the value (A1) is inserted in column (A5). For this application the adjustment factor is **0.85**. (For dc loads operating from the battery bank an adjustment factor of **1.0** is used.)

(A6): Adjusted wattage. Dividing the rated wattage (A4) by the adjustment factor (A5) adjusts the wattage to compensate for the inverter inefficiency and gives the actual wattage consumed from the battery bank. $(A4) / (A5)$.

<u>Appliance</u>	<u>(A4) / (A5)</u>	=	<u>Adjusted Wattage (A6)</u>
5 lights (30W ea.)	150 / 0.85	=	176
Refrigerator	500 / 0.85	=	588
3 ceiling fans (45W ea.)	135 / 0.85	=	159
Washer	1500 / 0.85	=	1765
Television	200 / 0.85	=	235
Toaster	1500 / 0.85	=	1765

(A7): Hours per day used. The number of hours each appliance is used per day is listed in column (A7). The duty cycle, or actual time of load operation, must be considered here. For example, a refrigerator may be functional 24 hours a day, but the compressor may only operate 5 hours per day.

(A8): Energy per day. The amount of energy each appliance requires per day is determined by multiplying each appliance's adjusted wattage (A6) by the number of hours used per day (A7). $(A6) \times (A7)$.

<u>Appliance</u>	<u>(A6) x (A7)</u>	=	<u>Energy Per Day (A8)</u>
5 lights (30W ea.)	176 x 2	=	352
Refrigerator	588 x 5	=	2940
3 ceiling fans (45W ea.)	159 x 8	=	1272
Washer	1765 x 0.86	=	1518
Television	235 x 4	=	940
Toaster	1765 x 0.25	=	441
	Total	=	7463

- (A9): Total energy demand per day. The sum of the quantities in column (A8) determines the total energy demand required by the appliances per day. For this application the total energy demand per day for the load is **7463 watt-hours**.
- (A10): Total amp-hour demand per day. In order to size the battery bank the total electrical load is converted from watt-hours to amp-hours. Amp-hours are determined by dividing the total energy demand per day (A9) by the battery bus voltage (A2). $(A9) / (A2)$.

$$7463 \text{ watt-hours} / 24 \text{ volts} = \mathbf{311 \text{ amp-hours.}}$$

- (A11): Maximum ac power requirement. The sum of the rated wattages (A4) for all appliances is equal to **3985 watts**. Note that this is the maximum continuous power required and does not include surge requirements. This value (A11) is the maximum continuous ac power output required of the inverter if all loads were to operate simultaneously. The peak, or surge, requirement (due to motor starting, etc.) must also be considered when selecting an inverter.
- (A12): Maximum dc power requirement. The sum of the adjusted wattages (A6), or dc power, for all appliances is equal to **4688 watts**. This value (A12) is the maximum dc input power required by the inverter and is necessary to determine wire sizes, fusing and disconnect requirements. If load management techniques are employed to eliminate the possibility of loads operating simultaneously, the inverter maximum output requirements may be reduced accordingly.

B. BATTERY SIZING

DESIGN TEMPERATURE: The location where batteries are stored should be designed to minimize fluctuations in battery temperature. For this application the design temperature is assumed to be **25°C**.

- (B1): Daily depth of discharge desired (decimal). The daily depth of discharge is the planned fraction of battery capacity to be extracted on a daily basis. This figure is chosen by the designer. For a stand-alone generator system a daily depth of discharge of **0.50** is used.
- (B2): Allowable depth-of-discharge limit (decimal). The maximum fraction of capacity that can be withdrawn from the battery as specified by the designer. Note that the battery selected must be capable of this limit or greater depth of discharge. For this application the allowable depth of discharge is **0.80**.

- (B3): Required battery capacity. The required battery capacity (capacity needed) is determined by dividing the total amp-hour demand per day (A10) by the daily depth of discharge desired (B1). (A10) / (B1).

$$311 / 0.50 = 622 \text{ amp-hours.}$$

- (B4): Amp-hour capacity of selected battery. Once the required number of amp-hours has been determined (B3), batteries or battery cells can be selected using manufacturers' information. Amp-hour capacity at 24-hour rate of discharge is used. The battery selected for this application is model Exide 6E120-11. Figure 6.5 shows the amp-hour capacity of this battery is **625 amp-hours**.

To 1.90 Volts Per Cell

TYPE	VOLTS PER UNIT	NOMINAL A.H.CAP.	20 DAY (480 HR)		10 DAY (240 HR)		5 DAY (120 HR)		3 DAY (72 HR)		32°F (0°C) 500 HR A.H.
			A.H.	AMPS	A.H.	AMPS	A.H.	AMPS	A.H.	AMPS	
6E95-5	12	180	192	0.40	192	0.80	192	1.60	192	2.67	184
6E95-7	12	270	288	0.60	288	1.20	288	2.40	288	4.00	276
6E95-9	12	360	383	0.80	383	1.60	383	3.19	383	5.32	368
6E95-11	12	450	478	1.00	478	1.99	478	3.98	478	6.64	459
6E120-9	12	500	538	1.12	538	2.24	538	4.48	538	7.47	516
6E120-11	12	625	673	1.40	673	2.80	673	5.61	673	9.35	646
6E120-13	12	750	808	1.68	808	3.37	808	6.73	808	11.22	776
6E120-15	12	875	942	1.96	942	3.93	942	7.85	942	13.08	904
3E120-17	6	1000	1077	2.24	1077	4.49	1077	8.98	1077	14.96	1034
3E120-19	6	1125	1212	2.53	1212	5.05	1212	10.10	1212	16.83	1163
3E120-21	6	1250	1346	2.80	1346	5.61	1346	11.22	1346	18.69	1292
3E120-23	6	1375	1481	3.09	1481	6.17	1481	12.34	1481	20.57	1422
3E120-25	6	1500	1616	3.37	1616	6.73	1616	13.47	1616	22.44	1551
3E120-27	6	1625	1750	3.65	1750	7.29	1750	14.58	1750	24.31	1680
3E120-29	6	1750	1885	3.93	1885	7.85	1885	15.71	1885	26.18	1809

Figure 6.5 Exide battery specifications at 25°C

- (B5): Number of batteries in parallel. The number of batteries or battery cells needed to provide the required battery subsystem capacity is determined by dividing the required battery capacity (B3) by the amp-hour capacity of the selected battery (B4). (B3) / (B4).

$$662 \text{ amp-hours} / 625 \text{ amp-hours} = 1.$$

- (B6): Number of batteries in series. The number of batteries needed to provide the necessary voltage is determined by dividing the battery bus voltage (A2) by the selected battery or battery cell voltage (taken from manufacturer's information). (A2) / battery voltage.

$$24 \text{ volts} / 12 \text{ volts} = 2.$$

- (B7): Total number of batteries. Multiplying the number of batteries or battery cells in parallel (B5) by the number of batteries or battery cells in series (B6) determines the total number of batteries needed. $(B5) \times (B6)$.

$$1 \times 2 = 2.$$

- (B8): Total battery amp-hour capacity. The total rated capacity of selected batteries is determined by multiplying the number of batteries in parallel (B5) by the amp-hour capacity of selected battery (B4). $(B5) \times (B4)$.

$$1 \times 625 \text{ amp-hours} = 625 \text{ amp-hours.}$$

- (B9): Total battery kilowatt-hour capacity. Based on the selected batteries, the energy capacity is determined by first multiplying the total amp-hour capacity (B8) by the battery bus voltage (A2), and then dividing this number by 1000. $[(B8) \times (A2)] / 1000$.

$$[625 \text{ amp-hours} \times 24 \text{ volts}] / 1000 = 15 \text{ kilowatt-hours.}$$

- (B10): Average daily depth of discharge. The actual depth of discharge to be expected on the average for the selected battery subsystem is determined by dividing the total amp-hour demand per day (A10) by the total battery amp-hour capacity (B8). $(A10) / (B8)$.

$$311 / 625 = 0.50.$$

- (B11): Maximum allowable battery charge rate. The peak design current for the battery charger is determined by dividing the total battery amp-hour capacity by the maximum charge rate in hours for the selected battery. Note that the actual charging current must not exceed limits established by the battery manufacturer. For the example the maximum charge rate is 3 hours. $(B8) / 3$.

$$625 / 3 = 208 \text{ amps.}$$

- (B12): Days of storage. The amount of energy stored in batteries that will supply power to the load for an equivalent number of days without charging is determined by multiplying the allowable depth of discharge limit (B2) by the total battery amp-hour capacity (B8), and then dividing this number by the total amp-hour demand per day (A10). $[(B2) \times (B8)] / (A10)$.

$$[0.80 \times 625] / 311 = 1.6 \text{ days.}$$

C. GENERATOR/BATTERY CHARGER SIZING

- (C1): Battery charger. The output of an engine generator (ac) cannot charge a battery (dc) directly. The battery charger converts ac to dc. The battery charger is selected to meet the maximum allowable battery charge rate (200 amps) (B11) at the nominal bus voltage (A2). The battery charger selected for this application is the **Photron P-24200**.
- (C2): Battery charger maximum dc output power. This figure is obtained from the manufacturer's data for the battery charger selected in (C1). Figure 6.6 indicates that the maximum dc output power for the Photron P-24200 is **4800 watts**.

TABLE I: BATTERY CHARGER SPECIFICATIONS													
MODEL NUMBER	OUTPUT DATA					INPUT DATA						PHYSICAL DATA	
	DC VOLTS		DC AMPS	DC WATTS		AC AMPS (max)			AC WATTS		CABINET STYLE	WT. IN LBS.	
	(nominal)	(max.)	(avg.)	(max.)	(avg.)	120V	240V	480V	(max.)	(avg.)			
P-2460	24	60	39	1,440	1,073	15.4	7.7	---	1,848	1,386	I	78	
P-2470	24	70	46	1,680	1,265	18.0	9.0	---	2,160	1,620	I	86	
P-2490	24	90	59	2,160	1,623	23.3	11.6	5.8	2,784	2,088	I	99	
P-24105	24	105	68	2,520	1,870	27.0	13.5	6.8	3,240	2,430	I	110	
P-24115	24	115	75	2,760	2,063	29.6	14.8	7.4	3,552	2,664	II	127	
P-24125	24	125	81	3,000	2,228	32.2	16.1	8.1	3,864	2,898	II	137	
P-24150	24	150	98	3,600	2,695	---	19.4	9.7	4,656	3,492	II	146	
P-24170	24	170	111	4,080	3,053	----	22.0	11.0	5,280	3,960	II	158	
P-24200	24	200	130	4,800	3,575	---	25.8	12.9	6,192	4,644	II	170	
P-24240	24	240	156	5,760	4,290	----	31.0	15.5	7,440	5,580	II	183	
P-24270	24	270	176	6,480	4,840	----	35.0	17.5	8,400	6,300	II	195	

Figure 6.6 Photron battery charger specifications

- (C3): Battery charger maximum ac input power. This figure is also obtained from manufacturer's data for the selected battery charger as shown in figure 6.6. The maximum ac input for the Photron P-24200 is **6192 watts**.
- (C4): Battery charger average ac input power. This figure is obtained from manufacturer's data for the selected battery charger as shown in figure 6.6. The average ac input power for the Photron P-24200 is **4644 watts**.
- (C5): Battery charger average dc output power. This figure is obtained from manufacturer's data for the selected battery charger as shown in figure 6.6. The average dc output power for the Photron P-24200 is **3575 watts**.

- (C6): Battery charger average efficiency. The battery charger's average efficiency is determined by dividing the battery charger's average dc output power (C5) by its average ac input power (C4). $(C5) / (C4)$.

$$3575 \text{ watts} / 4644 \text{ watts} = 0.77.$$

- (C7): Generator. This device converts mechanical power into electrical power. The generator produces alternating current. The selected generator must meet the peak battery charger ac input power (C3) and the peak load (A11). The generator selected for this application is the **Onan 7.5JB-3CR**. This generator produces 120 or 240 volt single-phase power, depending on the battery charger requirements.
- (C8): Peak generator output power. The level of maximum electrical output power from the generator is obtained from manufacturer's data for the selected generator, as shown in figure 6.7. Peak generator output power for the Onan 7.5JB-3CR is **7500 watts**.

BRUSHLESS, BROAD RANGE ALTERNATORS - RECONNECTIBLE MODELS											
MODEL	ELECTRICAL CHARACTERISTICS						GENERAL UTILITY RATING		ENGINE		
	VOLTAGE	AMP	VOLTAGE	AMP	HERTZ	PHASE	WIRE	kW	kVA and PF	RPM	START
7.5 JB-18R*	120/208	26.0	240/416	13.0	60	3	4	7.5	9.37 AT 0.8-PF	1800	Remote
	127/220	24.5	254/440	12.3							
	139/240	22.5	277/480	11.3							
	120/240	22.5	--	--							
6.0 JB-518R*	110/190	22.7	220/380	11.4	50	3	4	6.0	7.5 at 0.8-PF	1500	Remote
	115/200	21.7	230/400	10.9							
	120/208	20.8	240/416	10.4							
	127/220	19.7	254/440	9.8							
	110/220	19.7	--	--							
	115/230	18.8	--	--							
	120/240	18.1	--	--							
BRUSHLESS ALTERNATORS - RECONNECTIBLE SINGLE-PHASE											
7.5 JB-3CR**	120/240	31.3	--	--	60	1	4	7.5	7.5 at 1.0-PF	1800	Remote
6.0 JB-53CR**	120/240	25.0	--	--	50	1	4	6.0	6.0 at 1.0-PF	1500	

Figure 6.7 Onan generator specifications

- (C9): Generator/battery charger turn-on point [BSOC]. The battery state of charge at which the generator turns on to recharge the battery is equal to full state of charge [1.0] minus the average daily depth of discharge (B10). $1.0 - (B10)$.

$$1.0 - 0.5 = 0.5.$$

- (C10): Generator/battery turn-off point [BSOC]. The battery state of charge at which the generator turns off corresponds to full state of charge or **1.0**.

(C11): Required generator/battery charger amp-hour production during the daily charging cycle. The total amount of charge required by the combination of the generator and battery charger is determined by dividing the total amp-hour demand per day (A10) by the round trip battery efficiency (assume 0.85). $(A10) / 0.85$.

$$311 \text{ amp-hours} / 0.85 = 366 \text{ amp-hours.}$$

(C12): Battery charger average charge rate. Average current output from the battery charger is an estimated number between turn-on (C9) and turn-off (C10) determined from battery charger literature as shown in figure 6.8. This number is multiplied by the battery charger's maximum dc amps (obtained from manufacturer's data). The average battery charger charge rate for the Photron P-24200 is 0.35×200 amps which equals 70 amps.

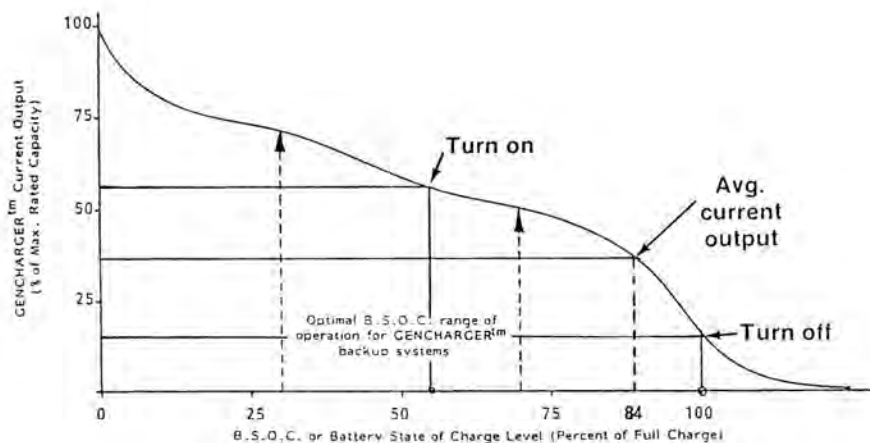


Figure 6.8 Battery charger current output versus state of charge

(C13): Average daily generator/battery charger on-time. To determine the average amount of time that the generator/battery charger is on per day, the required generator/battery charger amp-hour production during the daily charging cycle (C11) is divided by the battery charger average charge rate (C12). $(C11) / (C12)$.

$$366 \text{ amp-hours} / 70 \text{ amps} = 5.2 \text{ hours.}$$

- (C14): Average yearly generator/battery charger on-time. The average amount of time that the generator/battery charger is on per year is determined by multiplying the average daily generator/battery charger on-time (C13) by 365. $(C13) \times 365$.

$$5.2 \text{ hours} \times 365 = \mathbf{1898 \text{ hours.}}$$

- (C15): Average generator ac output power. The generator operates over a range of output power. To determine the average of this operating range, the battery charger average charge rate (C12) is first multiplied by the battery bus voltage (A2) and then divided by the battery charger average efficiency (C6). $[(C12) \times (A2)] / (C6)$.

$$[70 \text{ amps} \times 24 \text{ volts}] / 0.77 = \mathbf{2182 \text{ watts.}}$$

- (C16): Average yearly generator energy production. The number of kilowatt-hours that the generator will produce in one year is determined by first multiplying the average generator ac output power (C15) by the average yearly generator/battery charger on-time (C14). Then this number is divided by 1000. $[(C15) \times (C14)] / 1000$.

$$[2182 \text{ watts} \times 1898 \text{ hours}] / 1000 = \mathbf{4141 \text{ kilowatt-hours.}}$$

- (C17): Average generator load. The generator system does not operate at peak power output. Dividing the average generator ac output power (C15) by the peak generator output (C8) determines the average generator load (fraction of generator ac output). $(C15) / (C8)$.

$$2182 \text{ watts} / 7500 \text{ watts} = \mathbf{0.29.}$$

6.4 Example 3: Sizing of a Hybrid Photovoltaic-Generator System

This example is an extension of examples 1 and 2. The Tallahassee residence and associated appliances are the same. Rather than using a photovoltaic system or an engine-generator system by itself, the hybrid system combines the best features of both.

Because the generator is available, the battery storage requirement is much less than for the photovoltaic system by itself. The array can also be sized somewhat smaller, as can the engine-generator.

Design criteria for hybrid systems are less defined and less universally accepted than those for other systems. The procedure presented may differ significantly from other approaches encountered. The designer is encouraged to try this approach and then vary some of the component sizes (i.e., PV array, generator, batteries, etc.) to assure the most practical and economic system configuration.

It should also be pointed out that the value of hybrid systems is heavily dependent upon the application and the economic assumptions used in assessing net present value. These economic assumptions will be discussed further in section 10.

The following is a copy of the completed worksheet used in this example. Detailed explanations on the completion of each step follow the worksheet.

Sizing of Hybrid Photovoltaic-Generator Systems WORKSHEET

Application Stand-Alone Home 5 miles from Utility Line
 Location Tallahassee, FL Latitude 30.38

A. Loads

A1 Inverter efficiency (decimal) .85
 A2 Battery bus voltage 24 volts
 A3 Inverter ac voltage 110 volts

Appliance	A4 Rated Wattage	A5 Adjustment Factor 1.0 for dc (A1) for ac	A6 Adjusted Wattage (A4 / A5)	A7 Hours Per Day Used	A8 Energy Per Day (A6 x A7)
5 lights 30W ea.	150	.85	178	2	352
Refrigerator	500	.85	588	5	2940
3 ceiling fans 45W ea.	135	.85	159	8	1272
Washer	1500	.85	1765	6 hrs/wk = .86/day	1518
Television	200	.85	235	4	940
Toaster	1500	.85	1765	.25	441

A9 Total energy demand per day (summation of A8) 7463 watt-hours
 A10 Total amp-hour demand per day (A9 / A2) 311 amp-hours
 A11 Maximum ac power requirement (summation of A4) 3985 watts
 A12 Maximum dc power requirement (summation of A6) 4688 watts

B. Battery Sizing

Design Temperature 25°C

B1 Daily depth of discharge desired (decimal) .50
 B2 Allowable depth-of-discharge limit (decimal) .80
 B3 Required battery capacity (A10 x .75 / B1) 467 amp-hours
 B4 Amp-hour capacity of selected battery * 500 amp-hours
 B5 Number of batteries in parallel (B3 / B4) 1
 B6 Number of batteries in series (A2 / battery voltage) 2
 B7 Total number of batteries (B5 x B6) 2
 B8 Total battery amp-hour capacity (B5 x B4) 500 amp-hours
 B9 Total battery kilowatt-hour capacity (B8 x A2 / 1000) 12 kilowatt-hours
 B10 Average daily depth of discharge (.75 x A10 / B8) 0.47
 B11 Maximum allowable battery charge rate (B8 / 3 hours) 167 amps
 B12 Days of storage (B2 x B8 / A10) 1.3 days

* Use amp-hour capacity at 24-hour rate of discharge.

C. Photovoltaic Array Sizing Design Tilt 30° Design Month Annual Avg.

C1	Total energy demand per day (A9)	<u>7463</u>	watt-hours
C2	Battery round-trip efficiency (0.70 - 0.85)	<u>.80</u>	
C3	Required array output per day (C1 / C2)	<u>9329</u>	watt-hours
C4	Selected PV module max power voltage at STC x 0.85	<u>14.8</u>	volts
C5	Selected PV module guaranteed power output at STC	<u>47.7</u>	watts
C6	Peak sun hours at design tilt for design month	<u>4.77</u>	hours
C7	Energy output per module per day (C5 x C6)	<u>228</u>	watt-hours
C8	Module energy output at operating temperature. Use derating factor, DF = 0.80 for hot climates and critical applications; DF = 0.90 for moderate climates and non-critical applications (DF x C7)	<u>205</u>	watt-hours
C9	Number of modules required to meet energy requirements (C3 / C8)	<u>46</u>	modules
C10	Number of modules required per string (A2 / C4) rounded to next higher integer	<u>2</u>	modules
C11	Number of strings in parallel (C9 / C10) rounded to next higher integer	<u>23</u>	strings
C12	Number of modules to be purchased (C10 x C11)	<u>46</u>	modules
C13	Peak watts of array (C12 x C5)	<u>2194</u>	watts
C14	Peak sun hours at design tilt for worst month	<u>3.59</u>	hours
C15	Usable average daily PV energy during worst month (C14 x DF x C13 x C2)	<u>5671</u>	watt-hours
C16	Average daily PV amp-hours production during worst month (C15/A2)	<u>236</u>	amp-hours
C17	Nominal rated PV module output	<u>53</u>	watts
C18	Nominal rated array output (C17 x C12)	<u>2438</u>	watts

D. Generator/Battery Charger Sizing

D1	Choose generator to meet or exceed peak ac power demand, A11	<u>Onan</u> <u>5-0CCX-30R</u>	model #
D2	Peak generator output power	<u>5000</u>	watts
D3	Choose battery charger so that the maximum battery charger input ac watts is nearly equal to but less than D2, and the charger dc voltage is the same as the nominal battery bus voltage, A2	<u>Photron</u> <u>P-24150</u>	model #
D4	Battery charger maximum charge rate *	<u>150</u>	amps
D5	Battery charger maximum ac input power	<u>4656</u>	watts
D6	Battery charger average ac input power	<u>3492</u>	watts
D7	Battery charger average dc output power	<u>2695</u>	watts
D8	Battery charger average efficiency (D7 / D6)	<u>.77</u>	
D9	Generator turn-on point [BSOC], (1 - B10 - .05) **	<u>0.48</u>	
D10	Average daily PV energy deficit during worst month (A9 - C15)	<u>1792</u>	watt-hours

* Make sure this charge rate does not exceed the maximum safe battery charge rate, B11.

** Not less than (1 - B2).

D11	Average daily PV amp-hour deficit during worst month (D10 / A2)	<u>75</u>	amp-hours
D12	Fraction of battery capacity supplied to battery from generator/battery charger during worst month (D11 / B8)	<u>0.15</u>	
D13	Generator/battery charger turn-off point [BSOC] (1 - B10 + D12)	<u>0.68</u>	
D14	Number of months for which peak sun hours per day at design tilt are less than design month peak hours, C6	<u>4</u>	
D15	Required number of months for which generator/battery charger backup is required daily (D14)	<u>4</u>	
D16	Required generator/battery charger amp-hour production during charging cycle (D13 - D9) x B8 / .85)	<u>118</u>	amp-hours
D17	Average yearly generator/battery charger amp-hour production ((D15 / 12) x 365 x D16)	<u>14357</u>	amp-hours
D18	Battery charger average charge rate (estimate from battery charger literature between turn-on and turn-off [BSOC], D9 and D13) ***	<u>95</u>	amps
D19	Average generator/battery charger on-time during charging cycle (D16 / D18) ****	<u>1.24</u>	hours
D20	Average yearly generator/battery charger on-time (D17 / D18)	<u>151</u>	hours
D21	Average generator ac output power (D18 x A2 / D8)	<u>2961</u>	watts
D22	Average yearly generator energy production (D21 x D20 / 1000)	<u>447</u>	kilowatt-hours
D23	Average generator load (fraction of generator peak ac output), (D21 / D2)	<u>.59</u>	

*** If unavailable, use B11 / 2.

**** Do not design generator to run less than 15 minutes (0.25 hours).

APPLICATION: Stand-alone home 5 miles from utility line

LOCATION: Tallahassee, FL

LATITUDE: 30.38° North

A. LOADS

- (A1): Inverter efficiency (decimal). This quantity is used as a power adjustment factor when current is changed from dc to ac. The efficiency of the inverter selected for this application is assumed to be **0.85**.
- (A2): Battery bus voltage. This is the nominal dc operating voltage of the system. The battery bus voltage for this application is **24 volts**, which corresponds to the required dc input voltage for the inverter.
- (A3): Inverter ac voltage. The output voltage of the inverter selected for this application is **110 volts**.

The components (appliances) that the system will power are:

5 lights (30W ea.), combined rated wattage 150, used 2 hrs/day.
 Refrigerator, rated wattage 500, used 5 hrs/day.
 3 ceiling fans (45W ea.), combined rated wattage 135, used 8 hrs/day.
 Washer, rated wattage 1500, used 6 hrs/wk or 0.86 hrs/day.
 Television, rated wattage 200, used 4 hrs/day.
 Toaster, rated wattage 1500, used 0.25 hrs/day.

The appliances are listed under the column heading **Appliance**.

- (A4): The rated wattage is listed for each appliance in column (A4). Note that the rated wattage for some appliances may vary from actual power consumed due to the load variation or cycling (i.e., refrigeration, motors, etc.).

<u>Appliance</u>	(A4) <u>Rated Wattage</u>
5 lights (30W ea.)	150
Refrigerator	500
3 ceiling fans (45W ea.)	135
Washer	1500
Television	200
Toaster	1500

- (A5): Adjustment factor. The adjustment factor is related to the efficiency of the inverter and reflects the actual power consumed from the battery bank to operate ac loads from the inverter. For ac loads, the value (A1) is inserted in column (A5). For this application the adjustment factor is **0.85**. For dc loads operating from the battery bank an adjustment factor of **1.0** is used.
- (A6): Adjusted wattage. Dividing the rated wattage (A4) by the adjustment factor (A5) adjusts the wattage to compensate for the inverter inefficiency and gives the actual wattage consumed from the battery bank. $(A4) / (A5)$.

<u>Appliance</u>	<u>(A4) / (A5)</u>	=	<u>Adjusted Wattage (A6)</u>
5 lights (30W ea.)	150 / 0.85	=	176
Refrigerator	500 / 0.85	=	588
3 ceiling fans (45W ea.)	135 / 0.85	=	159
Washer	1500 / 0.85	=	1765
Television	200 / 0.85	=	235
Toaster	1500 / 0.85	=	1765

- (A7): Hours per day used. The number of hours each appliance is used per day is listed in column (A7). The duty cycle, or actual time of load operation, must be considered here. For example, a refrigerator may be functional 24 hours a day, but the compressor may only operate 5 hours per day.
- (A8): Energy per day. The amount of energy each appliance requires per day is determined by multiplying each appliance's adjusted wattage (A6) by the number of hours used per day (A7). $(A6) \times (A7)$.

<u>Appliance</u>	<u>(A6) x (A7)</u>	=	<u>Energy Per Day (A8)</u>
5 lights (30W ea.)	176 x 2	=	352
Refrigerator	588 x 5	=	2940
3 ceiling fans (45W ea.)	159 x 8	=	1272
Washer	1765 x 0.86	=	1518
Television	235 x 4	=	940
Toaster	1500 x 0.25	=	441
	Total	=	7463

- (A9): Total energy demand per day. The sum of the quantities in column (A8) determines the total energy demand required by the appliances per day. For this application the total energy demand per day for the load is **7463 watt-hours**.
- (A10): Total amp-hour demand per day. The battery storage subsystem is sized independently of the photovoltaic array. In order to size the battery bank the total electrical load is converted from watt-hours to amp-hours. Amp-hours are determined by dividing the total energy demand per day (A9) by the battery bus voltage (A2). $(A9) / (A2)$.

$$7463 \text{ watt-hours} / 24 \text{ volts} = \mathbf{311 \text{ amp-hours.}}$$

- (A11): Maximum ac power requirement. The sum of the rated wattages (A4) for all appliances is equal to **3985 watts**. Note that this is the maximum continuous power required and does not include surge requirements. This value (A11) is the maximum continuous ac power output required of the inverter if all loads were to operate simultaneously. The peak, or surge, requirement (due to motor starting, etc.) must also be considered when selecting an inverter.
- (A12): Maximum dc power requirement. The sum of the adjusted wattages (A6), or dc power, for all appliances is equal to **4688 watts**. This value (A12) is the maximum dc input power required by the inverter and is necessary to determine wire sizes, fusing and disconnect requirements. If load management techniques are employed to eliminate the possibility of loads operating simultaneously, the inverter maximum output requirements may be reduced accordingly.

B. BATTERY SIZING

DESIGN TEMPERATURE: The location where batteries are stored should be designed to minimize fluctuations in battery temperature. For this application the design temperature is assumed to be **25°C**.

- (B1): Daily depth of discharge desired (decimal). The daily depth of discharge is the planned fraction of battery capacity to be extracted on a daily basis. This figure is chosen by the designer. For a stand-alone generator system a daily depth of discharge of **0.50** is used.
- (B2): Allowable depth-of-discharge limit (decimal). The maximum fraction of capacity that can be withdrawn from the battery as specified by the designer. Note that the battery selected must be capable of this limit or greater depth of discharge. For this application the allowable depth of discharge is **0.80**.

- (B3): Required battery capacity. The required battery capacity (capacity needed) is determined by multiplying the total amp-hour demand per day (A10) by 0.75. This number is then divided by the daily depth of discharge desired (B1).
 $[(A10) \times 0.75] / (B1)$.

$$[311 \times 0.75] / 0.50 = 467 \text{ amp-hours.}$$

- (B4): Amp-hour capacity of selected battery. Once the required number of amp-hours has been determined (B3), batteries or cells can be selected using manufacturer's information. The battery selected for this application is the Exide 6E120-9. Figure 6.9 shows the manufacturer's data for the Exide 6E120-9. Amp-hour capacity of the selected battery is 500 amp-hours.

To 1.90 Volts Per Cell

TYPE	VOLTS PER UNIT	NOMINAL A.H.CAP.	20 DAY (480 HR)		10 DAY (240 HR)		5 DAY (120 HR)		3 DAY (72 HR)		32°F (0°C) 500 HR A.H.
			A.H.	AMPS	A.H.	AMPS	A.H.	AMPS	A.H.	AMPS	
6E95-5	12	180	192	0.40	192	0.80	192	1.60	192	2.67	184
6E95-7	12	270	288	0.60	288	1.20	288	2.40	288	4.00	276
6E95-9	12	360	383	0.80	383	1.60	383	3.19	383	5.32	368
6E95-11	12	450	478	1.00	478	1.99	478	3.98	478	6.64	459
6E120-9	12	500	538	1.12	538	2.24	538	4.48	538	7.47	516
6E120-11	12	625	673	1.40	673	2.80	673	5.61	673	9.35	646
6E120-13	12	750	808	1.68	808	3.37	808	6.73	808	11.22	776
6E120-15	12	875	942	1.96	942	3.93	942	7.85	942	13.08	904
3E120-17	6	1000	1077	2.24	1077	4.49	1077	8.98	1077	14.96	1034
3E120-19	6	1125	1212	2.53	1212	5.05	1212	10.10	1212	16.83	1163
3E120-21	6	1250	1346	2.80	1346	5.61	1346	11.22	1346	18.69	1292
3E120-23	6	1375	1481	3.09	1481	6.17	1481	12.34	1481	20.57	1422
3E120-25	6	1500	1616	3.37	1616	6.73	1616	13.47	1616	22.44	1551
3E120-27	6	1625	1750	3.65	1750	7.29	1750	14.58	1750	24.31	1680
3E120-29	6	1750	1885	3.93	1885	7.85	1885	15.71	1885	26.18	1809

Figure 6.9 Exide battery specifications

- (B5): Number of batteries in parallel. The number of batteries or cells needed to provide the required battery subsystem capacity is determined by dividing the required battery capacity (B3) by the amp-hour capacity of the selected battery or battery cell (B4). $(B3) / (B4)$.

$$466 \text{ amp-hours} / 500 \text{ amp-hours} = 1.$$

- (B6): Number of batteries in series. The number of batteries needed to provide the necessary voltage is determined by dividing the battery bus voltage (A2) by the selected battery or battery cell voltage (taken from manufacturer's information on selected battery or cell). $(A2) / \text{battery voltage}$.

$$24 \text{ volts} / 12 \text{ volts} = 2.$$

- (B7): Total number of batteries. Multiplying the number of batteries or cells in parallel (B5) by the number of batteries or cells in series (B6) determines the total number of batteries needed. $(B5) \times (B6)$.

$$1 \times 2 = 2.$$

- (B8): Total battery amp-hour capacity. The total rated capacity of the selected batteries is determined by multiplying the number of batteries in parallel (B5) by the amp-hour capacity of the selected battery (B4). $(B5) \times (B4)$.

$$1 \times 500 \text{ amp-hours} = \mathbf{500 \text{ amp-hours}}.$$

- (B9): Total battery kilowatt-hour capacity. Based on the selected batteries, the energy capacity is determined by first multiplying the total amp-hour capacity (B8) times the battery bus voltage (A2), and then dividing this number by 1000. $[(B8) \times (A2)] / 1000$.

$$[500 \text{ amp-hours} \times 24 \text{ volts}] / 1000 = \mathbf{12 \text{ kilowatt-hours}}.$$

- (B10): Average daily depth of discharge. The depth of discharge to be expected on the average for the selected battery subsystem is determined by first multiplying 0.75 by the total amp-hour demand per day (A10), and then dividing this number by the total battery amp-hour capacity (B8). $[0.75 \times (A10)] / (B8)$.

$$[0.75 \times 311] / 500 = \mathbf{0.47}.$$

- (B11): Maximum allowable battery charge rate. This is the peak design current for the battery charger and is determined by dividing the total amp-hour capacity (B8) by 3 hours. Note that the actual charging current must not exceed limits established by the battery manufacturer. $(B8) / 3$.

$$500 / 3 = \mathbf{167 \text{ amps}}.$$

- (B12): Days of storage. The amount of energy stored in batteries that will supply power to load for equivalent number of days without charging is determined by first multiplying the allowable depth of discharge limit (B2) by the total battery amp-hour capacity (B8), and then dividing this number by the total amp-hour demand per day (A10). $[(B2) \times (B8)] / (A10)$.

$$[0.80 \times 500] / 311 = \mathbf{1.3 \text{ days}}.$$

C. PHOTOVOLTAIC ARRAY SIZING

The size of the photovoltaic array is determined by considering the load, available solar insolation, the tilt of the array and the characteristics of the photovoltaic modules being considered.

Using module power output and daily insolation (in peak sun hours), the energy delivered by a photovoltaic module for an average day can be determined. Then, knowing the requirements of the load and the capability of a single module, the array can be sized.

For photovoltaic/generator hybrid systems, there are several operational strategies that will meet the load. However, it is desirable to size the PV array such that the overall life-cycle costs of the system are minimized and reliability maximized. For this example, a design tilt of 30° (latitude) will be used to maximize the PV array annual energy output. The annual average will be used for the design insolation. The generator will then be required to meet the load when the PV array does not. However, it must be noted that this may not be the optimal combination for all applications due to such factors as load variability, maintenance and overall costs of the system. Alternatively, the PV array may be downsized to meet only a fraction of the load under the design conditions.

DESIGN TILT: 30° (latitude) in order to maximize the array output over the year.

DESIGN MONTH: For this application, because of the availability of the engine-generator, the average daily insolation over the entire year (i.e. annual average) is used.

(C1): Total energy demand per day. (A9). **7463 watt-hours.**

(C2): Battery round-trip efficiency. A factor between 0.70 and 0.85 is used to estimate battery round-trip efficiency. A factor of 0.80 is used for this application because the battery selected is relatively efficient and because a significant percentage of the energy is used during daylight hours.

(C3): Required array output per day. The watt-hours required by the load are adjusted (upwards) because batteries are less than 100% efficient. Dividing the total energy demand per day (C1) by the battery round-trip efficiency (C2) determines the required array output per day. (C1) / (C2).

$$7463\text{-watt hours} / 0.80 = \mathbf{9329\text{ watt-hours.}}$$

- (C4): Selected PV module max power voltage at STC x 0.85. Maximum power voltage is obtained from the manufacturer's specifications for the selected photovoltaic module, and this quantity is multiplied by 0.85 to establish a design operating voltage for each module (not the array). For this application, Siemens Solar M-55 modules are used.

Figure 6.10 shows the maximum power voltage for these modules is 17.4 volts. Maximum power voltage x 0.85.

$$17.4 \text{ volts} \times 0.85 = \mathbf{14.8 \text{ volts.}}$$

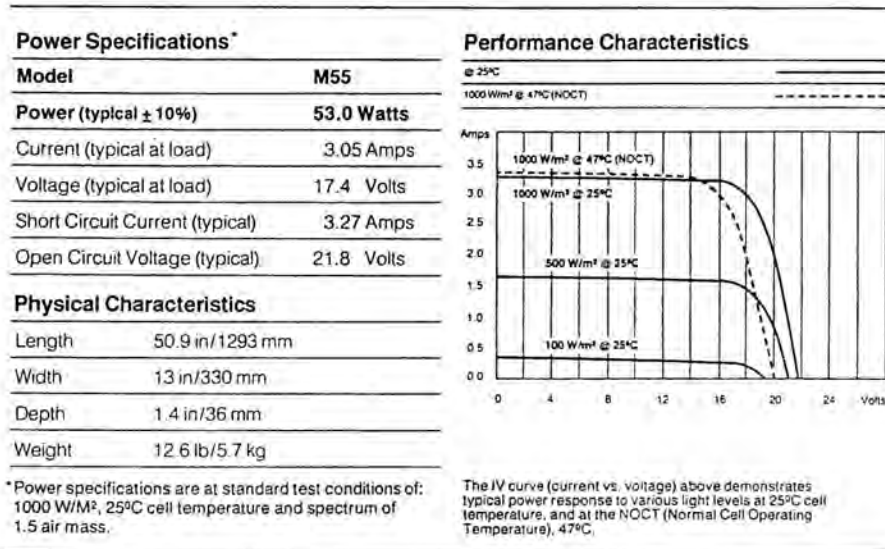


Figure 6.10 Siemens Solar M-55 module specifications

- (C5): Selected PV module guaranteed power output at STC. This number is also obtained from the manufacturer's specifications shown in figure 6.10. For Siemens Solar M-55 the nominal power output at 1000 watts/m² and 25°C is 53 watts. The guaranteed power output is 90% of this or **47.7 watts**.
- (C6): Peak sun hours at design tilt for design month. This figure is obtained from solar insolation data for the design location and array tilt for an average annual day as shown in figure 6.11. The peak sun hours for Tallahassee, Florida at 30° tilt, annual average are **4.77 hours**.

City	Tilt	Insolation (kWh/m ² /day)												Annual
		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	
Tallahassee, FL Latitude 30.38	Horizontal	2.77	3.59	4.67	5.75	6.11	5.94	5.52	5.29	4.71	4.16	3.18	2.56	4.52
	15	3.32	4.07	4.98	5.83	5.97	5.72	5.36	5.27	4.90	4.62	3.77	3.15	4.75
	20	3.47	4.20	5.04	5.81	5.87	5.60	5.25	5.22	4.93	4.74	3.93	3.31	4.78
	25	3.61	4.30	5.08	5.76	5.74	5.88	5.12	5.14	4.93	4.83	4.07	3.46	4.79
	30	3.72	4.38	5.09	5.67	5.58	5.26	4.97	5.04	4.90	4.89	4.19	3.59	4.77
	35	3.82	4.44	5.07	5.56	5.39	5.05	4.79	4.91	4.85	4.92	4.28	3.69	4.73
	40	3.89	4.47	5.02	5.41	5.17	4.82	4.59	4.76	4.77	4.93	4.35	3.77	4.66

Figure 6.11 Insolation data for Tallahassee, Florida

- (C7): Energy output per module per day. To determine the energy output per module per day multiply the photovoltaic module output at STC (C5) by the peak sun hours at design tilt (C6). (C5) x (C6).

$$47.7 \text{ watts} \times 4.77 \text{ hours} = 228 \text{ watt-hours.}$$

- (C8): Module energy output at operating temperature. A derating factor of 0.90 (for moderate climates and non-critical applications) is used in this application to determine module energy output. Multiplying the derating factor (DF) by the energy output per module (C7) determines the average energy output from one module. DF x (C7).

$$0.90 \times 228 \text{ watt-hours} = 205 \text{ watt-hours.}$$

- (C9): Number of modules required to meet energy requirements. Dividing the required array output per day (C3) by the module energy output at operating temperature (C8) determines the number of modules needed to meet the energy requirements. (C3) / (C8).

$$9329 / 205 = 46 \text{ modules.}$$

- (C10): Number of modules required per string. The number of modules required per string is determined by dividing the battery bus voltage (A2) by the module design operating voltage (C4). This number is rounded to the next higher integer. (A2) / (C4).

$$24 \text{ volts} / 14.8 \text{ volts} = 1.6 \text{ (rounded to 2 modules).}$$

- (C11): Number of strings in parallel. The number of strings in parallel is determined by dividing the number of modules required to meet energy requirements (C9) by the number of modules per string (C10). This number is rounded to the next higher integer. $(C9) / (C10)$.

$$46 \text{ modules} / 2 \text{ modules} = \mathbf{23 \text{ strings.}}$$

- (C12): Number of modules to be purchased. Determine the number of modules to be purchased by multiplying the number of modules per string (C10) by the number of strings in parallel (C11). $(C10) \times (C11)$.

$$2 \text{ modules} \times 23 \text{ strings} = \mathbf{46 \text{ modules.}}$$

- (C13): Peak watts of array. Multiplying the number of modules to be purchased (C12) by the selected module guaranteed power output at STC (C5) determines the peak watts of the array. $(C12) \times (C5)$.

$$46 \text{ modules} \times 47.7 \text{ watts} = \mathbf{2194 \text{ watts.}}$$

- (C14): Peak sun hours at design tilt for worst month. Obtain this value from insolation data as shown in figure 6.11. For this application the peak sun hours at design tilt for the worst month (December) are **3.59 hours**.

- (C15): Usable average daily photovoltaic energy during worst month. The usable average daily photovoltaic energy during the worst month is determined by multiplying peak sun hours at design tilt for worst month (C14) by a derating factor of 0.90. This number is then multiplied by peak array watts (C13) and the battery round-trip efficiency (C2). $[(C14) \times 0.90 \times (C13)] \times (C2)$.

$$[3.59 \text{ hrs.} \times 0.90 \times 2194\text{W}] \times 0.80 = \mathbf{5671 \text{ watt-hours.}}$$

- (C16): Average daily PV amp-hour production during worst month. Dividing the usable average daily photovoltaic energy during worst month (C15) by battery bus voltage (A2) determines the average daily photovoltaic amp-hour production during the worst month. $(C15) / (A2)$.

$$5671 \text{ watt-hours} / 24 \text{ volts} = \mathbf{236 \text{ amp-hours.}}$$

- (C17): Nominal rated PV module output. The rated PV module output in watts is stated by the manufacturer. Photovoltaic modules are usually priced in terms of the rated module output (\$/watt). For the Siemens Solar M55 module, the rated module power is **53 watts**.

(C18): Nominal array rated output. Multiplying the number of modules to be purchased (C12) by the nominal rated PV module output (C17) determines the nominal rated array output. This number will be used to determine the cost of the photovoltaic array.

$$46 \text{ modules} \times 53 \text{ watts} = 2438 \text{ watts.}$$

D. GENERATOR/BATTERY CHARGER SIZING

- (D1): Generator. The selected generator must meet or exceed peak ac power demand. The generator **Onan 5.0CCK-3CR** was selected for this application.
- (D2): Peak generator output power. The peak generator output power is determined by the manufacturer's data for the selected generator. Figure 6.12 shows that the peak generator output for the Onan 5.0CCK-3CR is **5000 watts**.

MODEL SELECTION and RATING TABLE

MODEL NUMBER	ELECTRICAL DETAILS				GENERAL UTILITY RATING			ENGINE	
	VOLTS	HERTZ	PHASE	WIRE	KW	KVA and PF	AMP	RPM	STARTING
5.0CCK-3CP*	120/240	60	1	4	5.0	5.0 at 1.0 PF	21.0	1800	Manual
5.0CCK-3CR*	120/240	60	1	4	5.0	5.0 at 1.0 PF	21.0	1800	Remote
5.0CCK-4R	120/208	60	3	4	5.0	5.0 at 1.0 PF	14.0	1800	Remote
5.0CCK/5DR**	120/240	60	3	4	5.0	5.0 at 1.0 PF	12.0	1800	Remote
5.0CCK-4XR***	277/480	60	3	4	5.0	5.0 at 1.0 PF	6.0	1800	Remote
4.2CCK-53BR	110/220	50	1	4	4.2	4.2 at 1.0 PF	19.1	1500	Remote
4.2CCK-53CR*	120/240	50	1	4	4.2	4.2 at 1.0 PF	17.2	1500	Remote
4.2CCK-55DR**	120/240	50	3	4	4.2	4.2 at 1.0 PF	10.1	1500	Remote
4.2CCK-57R	220/380	50	3	4	4.2	4.2 at 1.0 PF	6.4	1500	Remote

Figure 6.12 Onan generator specifications

- (D3): Battery charger. The battery charger converts ac power from the generator to dc power for charging the batteries. The battery charger is selected so that the maximum battery charger input ac power is nearly equal to but less than (D2), and the charger dc voltage is the same as the nominal battery bus voltage (A2). The battery charger **Photron P-24150** was selected for this application.
- (D4): Battery charger maximum charge rate. This figure is obtained from the manufacturer's data for the battery charger selected in (D3). The manufacturer's data given in figure 6.13 shows that the maximum charge rate for the Photron P-24150 is **150 amps**.

TABLE I: BATTERY CHARGER SPECIFICATIONS

MODEL NUMBER	OUTPUT DATA					INPUT DATA					PHYSICAL DATA	
	DC VOLTS		DC AMPS	DC WATTS		AC AMPS (max)			AC WATTS		CABINET STYLE	WT. IN LBS
	(nominal)	(max.)	(avg.)	(max.)	(avg.)	120V	240V	480V	(max.)	(avg.)		
P-2460	24	60	39	1,440	1,073	15.4	7.7	—	1,848	1,386	I	78
P-2470	24	70	46	1,680	1,265	18.0	9.0	—	2,160	1,620	I	86
P-2490	24	90	59	2,160	1,623	23.3	11.6	5.8	2,784	2,088	I	99
P-24105	24	105	68	2,520	1,870	27.0	13.5	6.8	3,240	2,430	I	110
P-24115	24	115	75	2,760	2,063	29.6	14.8	7.4	3,552	2,664	II	127
P-24125	24	125	81	3,000	2,228	32.2	16.1	8.1	3,864	2,898	II	137
P-24150	24	150	98	3,600	2,695	—	19.4	9.7	4,656	3,492	II	146
P-24170	24	170	111	4,080	3,053	—	22.0	11.0	5,280	3,960	II	158
P-24200	24	200	130	4,800	3,575	—	25.8	12.9	6,192	4,644	II	170
P-24240	24	240	156	5,760	4,290	—	31.0	15.5	7,440	5,580	II	183
P-24270	24	270	176	6,480	4,840	—	35.0	17.5	8,400	6,300	II	195

Figure 6.13 Photron battery charger specifications

- (D5): Battery charger maximum ac input. This figure is obtained from manufacturer's data shown in figure 6.13. The maximum ac input is **4656 watts**.
- (D6): Battery charger average ac input power. This figure is also obtained from manufacturer's data shown in figure 6.13. The average ac input power for the Photron P-24150 is **3492 watts**.
- (D7): Battery charger average dc output power. This figure is obtained from manufacturer's data as shown in figure 6.13. The average dc output power is **2695 watts**.
- (D8): Battery charger average efficiency. Dividing the battery charger's average dc output power (D7) by its average ac input power (D6) determines the battery charger average efficiency. (D7) / (D6).

$$2695 \text{ watts} / 3492 \text{ watts} = 0.77.$$

- (D9): Generator turn-on point [BSOC]. The generator turn-on point is determined by subtracting the average daily depth of discharge (B10) from 1.0. Then, from this number subtract 0.05. $[1.0 - (B10)] - 0.05$.

$$[1.0 - 0.47] - 0.05 = 0.48.$$

- (D10): Average daily PV energy deficit during worst month. Subtracting the usable average daily photovoltaic energy during the worst month (C15) from the total energy demand per day (A9) determines the average daily photovoltaic energy deficit during the worst month. $(A9) - (C15)$.

$$7463 \text{ watt-hours} - 5671 \text{ watt-hours} = 1792 \text{ watt-hours}.$$

- (D11): Average daily PV amp-hour deficit during worst month. The average daily photovoltaic amp-hour deficit during the worst month is determined by dividing the average daily photovoltaic energy deficit during the worst month (D10) by the battery bus voltage (A2). $(D10) / (A2)$.

$$1792 \text{ watt-hours} / 24 \text{ volts} = \mathbf{75 \text{ amp-hours.}}$$

- (D12): Fraction of battery capacity supplied to the battery from generator/battery charger during worst month. This figure is determined by dividing the average daily photovoltaic amp-hour deficit during the worst month (D11) by the total battery amp-hour capacity (B8). $(D11) / (B8)$.

$$75 \text{ amp-hours} / 500 \text{ amp-hours} = \mathbf{0.15.}$$

- (D13): Generator/battery charger turn-off point [BSOC]. The battery state of charge at which point the generator turns off is determined by subtracting the average daily depth of discharge (B10) from 1.0, and then adding this quantity to the fraction of battery capacity supplied to the battery from generator/battery charger during the worst month (D12). $[1.0 - (B10)] + (D12)$.

$$[1.0 - 0.47] + 0.15 = \mathbf{0.68.}$$

- (D14): Number of months in which peak sun hours per day at design tilt are less than design peak sun hours (C6). For this application there are **4 months**.
- (D15): Number of months in which generator/battery charger backup is required daily. This number is equal to the number of months in which peak sun hours per day at design tilt are less than design peak sun hours (D14). For this application, there are **4 months**.
- (D16): Required generator/battery charger amp-hour production during charging cycle. The total amount of charge developed by the generator/battery charger is determined by first subtracting the generator turn-on point (D9) from the generator turn-off point (D13). This number is then multiplied by the total battery amp-hour capacity (B8) and divided by 0.85. $\frac{(D13) - (D9) \times (B8)}{0.85}$.

$$\frac{[0.68 - 0.48] \times 500}{0.85} = \mathbf{118 \text{ amp-hours.}}$$

- (D17): Average yearly generator/battery charger amp-hour production. The average number of amp-hours the generator/battery charger produces in one year is determined by first dividing the required number of months in which generator/

battery charger backup is required daily (D15) by 12. Then, this number is multiplied by 365. This total is then multiplied by the required generator/battery charger amp-hour production during charging cycle (D16).
 $[(D15) / 12] \times 365 \times (D16)$.

$$[4 / 12] \times 365 \times 118 = \mathbf{14357 \text{ amp-hours.}}$$

(D18): Battery charger average charge rate. This value is estimated from battery charger literature between turn-on and turn-off [BSOC]. For this application the battery charger average charge rate is **95 amps**.

(D19): Average generator/battery charge on-time during charging cycle. The length of time the generator is on per cycle is determined by dividing the required generator/battery charger amp-hour production during charging cycle (D16) by the battery charger average charge rate (D18). $(D16) / (D18)$.

$$118 / 95 = \mathbf{1.24 \text{ hours.}}$$

(D20): Average yearly generator/battery charger on-time. This figure is determined by dividing the average yearly generator/battery charger amp-hour production (D17) by the battery charger average charge rate (D18). $(D17) / (D18)$.

$$14357 / 95 = \mathbf{151 \text{ hours.}}$$

(D21): Average generator ac output power. The generator's average ac output power is determined by first multiplying the battery charger average charge rate (D18) by the battery bus voltage (A2) and then dividing this number by the battery charger average efficiency. $[(D18) \times (A2)] / (D8)$.

$$[95 \times 24] / 0.77 = \mathbf{2961 \text{ watts.}}$$

(D22): Average yearly generator energy production. This figure is determined by first multiplying the average generator/battery charger on-time (D20) by the average generator ac output power (D21) and then dividing this number by 1000.
 $[(D20) \times (D21)] / 1000$.

$$[151 \times 2961] / 1000 = \mathbf{447 \text{ kilowatt-hours.}}$$

(D23): Average generator load. The fraction of generator peak ac output is determined by dividing the average generator ac output power (D21) by the peak generator output power (D2). $(D21) / (D2)$.

$$2961 / 5000 = \mathbf{0.59.}$$

6.5 Example 4: Sizing a Photovoltaic Water Pumping System

The following example illustrates a systematic methodology for designing a stand-alone direct-coupled photovoltaic water pumping system. Typically, direct-coupled systems are only practical when centrifugal pumps are used. Positive displacement pumps usually require a maximum power point tracker or operation from batteries to perform effectively. For pumping systems generating from batteries, the procedure is the same as for stand-alone photovoltaic systems with battery storage once the wattage and time of operation for the pump-ins for load is determined.

The application presented calls for a direct-coupled pumping system capable of delivering 4000 gallons of water per day in the Orlando, Florida, vicinity. A submersible pump is to be used at a depth of 65 feet below ground level. The water table level is assumed to be 40 feet below ground level on the average. The pump is required to lift the water to a height of 60 feet above ground level for storage, thus eliminating the need for battery storage. Steel pipe with an inside diameter of 1 inch is to be used. Figure 6.14 illustrates this pumping example.

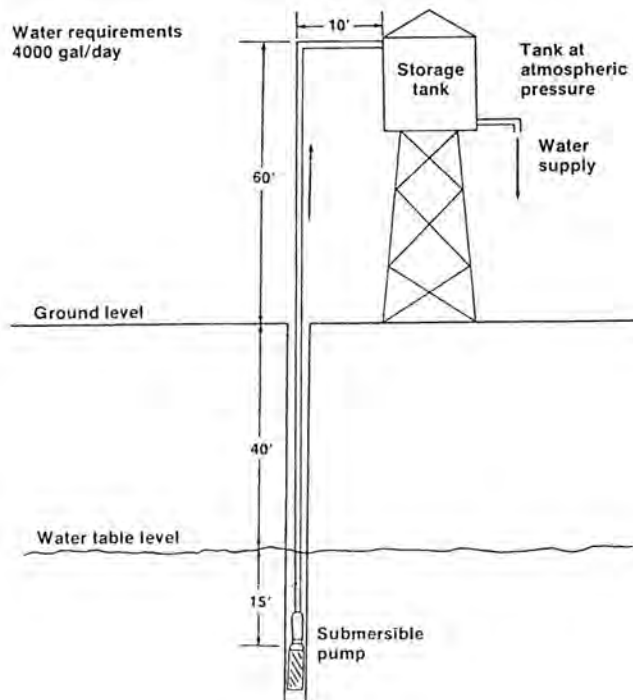


Figure 6.14 Pump system illustration

The following is the completed sizing worksheet used for this application. Detailed explanations of each step follow the worksheet.

Photovoltaic Water Pumping System Design WORKSHEET

Design period December Design tilt 40°
Design location Orlando, FL Latitude 28.55°N

Insolation Availability

P1 Daily insolation = 4.24 [kWh/(m²-day)]
P2 Usable insolation = P1 4.24 x derating factor 0.95 = 4.03 [kWh/(m²-day)]
P3 Peak sun hours available = P2 = 4.03 (hrs/day)

Pumping Flow Requirements

P4 Daily quantity of water required = 4000 (gal/day)
P5 Peak flow rate = P4 4000 / (P3 4.03 x 60) = 16.5 (gal/min)
P6 Pipe inside diameter = 1 (in) Type Steel
P7 Peak velocity = P5 16.5 / (P6 1)² x .408 = 6.73 (ft/s)

Pumping Head Requirements

Static Head

P8 Suction lift (or Head) * = -15 (ft)
P9 Discharge head = 115 (ft)
P10 Pressure head = 0 (PSIG) x 2.31 = 0 (ft)
P11 Total static head = P8 -15 + P9 115 + P10 0 = 100 (ft)

Dynamic Head

P12 Velocity head = (P7 6.73)² x 0.0155 = 0.7 (ft)

Friction Head		Equivalent		Equivalent	
Pipe Fitting	Quantity		Length Factor		Length
<u>90°</u>	<u>1</u>	x	<u>2.7</u>	=	<u>2.7</u> (ft)
		x		=	(ft)
		x		=	(ft)
		x		=	(ft)
		x		=	(ft)

Actual pipe length = 125 (ft)

P13 Total equivalent length = 127.7 (ft)

P14 Friction head = P13 127.7 / 100 x loss per 100 ft 17.8 = 22.7 (ft)

P15 Total dynamic head = P12 0.7 + P14 22.7 = 23.4 (ft)

P16 Total system head = P11 100 + P15 23.4 = 123.4 (ft)

* Enter a negative number for suction head.

Pumping Energy Requirements

P17 Hydraulic energy =

$$P16 \underline{124} \text{ (ft)} \times P4 \underline{4000} \text{ (gal/day)} \times 0.0031 = \underline{1538} \text{ (Wh/day)}$$

P18 Hydraulic power =

$$P5 \underline{16.5} \text{ (gal/min)} \times P16 \underline{124} \text{ (ft)} \times 0.188 = \underline{385} \text{ (watts)}$$

Pump Selection

$$\text{Flow rate} = P5 \underline{16.5} \text{ (gal/min)}$$

$$\text{Total system head} = P16 \underline{124} \text{ (ft)}$$

Select a pump/motor combination capable of meeting flow and head requirements with high efficiency.

$$\text{Pump/motor model} \underline{\text{Jacuzzi SJ1-D10}}$$

$$\text{Efficiency} \underline{44} \text{ (\%)}$$

$$P19 \text{ Motor voltage} = \underline{55} \text{ (volts)}$$

$$P20 \text{ Electric power} = \underline{920} \text{ (watts)}$$

$$P21 \text{ Daily electrical energy} = P20 \underline{920} \times P3 \underline{4.03} = \underline{3708} \text{ (Wh/day)}$$

Photovoltaic Array Sizing

$$\text{Selected PV Module} \underline{\text{Solarex SX-146}}$$

Standard tests conditions (STC): 1 kW/m², 25°C

$$M1 \text{ Module voltage at max power (STC)} \underline{18} \text{ (volts)}$$

$$M2 \text{ Module current at max power (STC)} \underline{2.67} \text{ (amps)}$$

$$M3 \text{ Module guaranteed power output at 1 kW/m}^2 \text{ (STC) or (M1} \times \text{M2)} \underline{46} \text{ (watts)}$$

$$M4 \text{ Total energy demand} = P21 \underline{3708} \text{ (Wh/day)}$$

$$M5 \text{ Impedance mismatch and non-linear effects for direct coupled systems} = (0.7 - 0.9) \underline{0.9}$$

$$M6 \text{ Required array output} = M4 / M5 \underline{4120} \text{ (Wh/day)}$$

$$M7 \text{ PV module operating voltage} = M1 \times (1.1 - 1.2) \underline{21.6} \text{ (volts)}$$

$$M8 \text{ Daily energy output per module} = M3 \times P3 \underline{185} \text{ (Wh/day)}$$

$$M9 \text{ Temperature derating factor} = (0.80 - 0.90) \underline{0.90}$$

$$M10 \text{ Derated module energy output} = M8 \times M9 \underline{166} \text{ (Wh/day)}$$

$$M11 \text{ Number of modules to meet daily energy requirements} = M6 / M10 \underline{25} \text{ (modules)}$$

$$M12 \text{ Number of modules per string rounded to the closest integer} \\ = P19 / M7 \underline{3} \text{ (modules)}$$

$$M13 \text{ Number of strings in parallel rounded to the closest integer} \\ = M11 / M12 \underline{8} \text{ (strings)}$$

$$M14 \text{ Total number of modules required} = M12 \times M13 \underline{24} \text{ (modules)}$$

INSOLATION AVAILABILITY

The location of the application is Orlando, Florida, which is at 28.55° North latitude. Assuming a constant load, the array is designed to meet the average daily load during the worst insolation month. For December in Orlando, an average tilt of 40° from horizontal is nearly optimum.

Design Period: December

Design Tilt: 40°

Design Location: Orlando, FL

Latitude: 28.55° North

P1: Daily Insolation. The amount of insolation occurring at the design location (Orlando, FL) during the design period (December) at design tilt (40°) is obtained from daily insolation data shown in figure 6.15. The daily insolation for this application is **4.24 kWh/(m²-day)**.

City	Tilt	Insolation (kWh/m ² /day)												Annual
		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	
Orlando, FL Latitude 28.55	Horizontal	3.14	3.92	4.99	5.99	6.27	5.78	5.68	5.28	4.72	4.11	3.46	2.92	4.69
	15	3.75	4.43	5.30	6.05	6.10	5.54	5.49	5.24	4.89	4.53	4.06	3.56	4.91
	20	3.92	4.56	5.36	6.01	5.99	5.41	5.37	5.18	4.90	4.63	4.23	3.74	4.94
	25	4.07	4.67	5.39	5.95	5.85	5.26	5.23	5.10	4.89	4.70	4.37	3.90	4.95
	30	4.19	4.75	5.39	5.85	5.67	5.07	5.06	4.99	4.86	4.75	4.49	4.04	4.93
	35	4.29	4.80	5.36	5.72	5.47	4.87	4.87	4.85	4.79	4.77	4.58	4.15	4.88
	40	4.37	4.82	5.31	5.56	5.24	4.63	4.66	4.69	4.71	4.76	4.64	4.24	4.80

Figure 6.15 Insolation data

P2: Usable insolation. Pump/motors directly-coupled to a photovoltaic array require a minimum current before starting. Because the irradiance on the photovoltaic array must reach a threshold before the pump starts, some of the insolation (integrated irradiance) is not usable. Figure 6.16 illustrates pump/motor turn-on and turn-off points and the resulting unusable insolation.

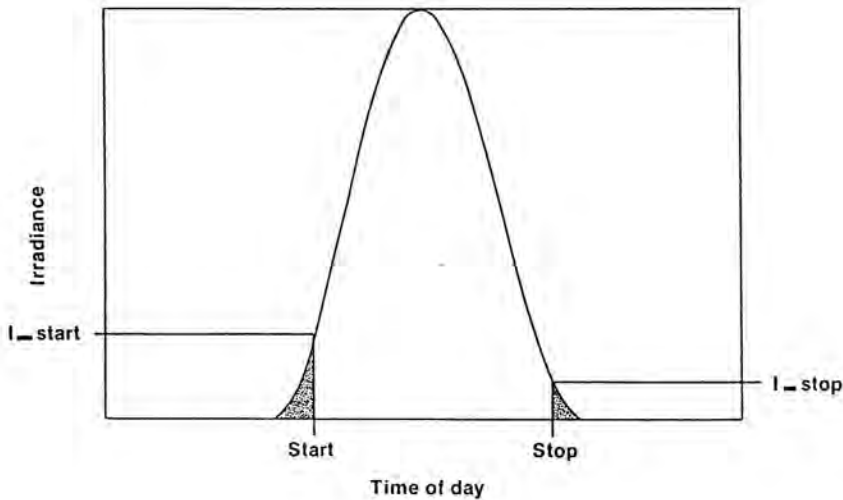


Figure 6.16 Photovoltaic pumping start/stop characteristics

The approximate amount of insolation that is usable per day is determined by multiplying the daily insolation (P1) by a derating factor. This derating factor is an estimated value determined by comparing pump turn-on and turn-off points with the performance for a given photovoltaic array. For this application a derating factor of 0.95 is used.

$$\text{Usable insolation} = 4.24 \times 0.95 = \mathbf{4.03 \text{ kWh/(m}^2\text{-day)}}.$$

- P3: Peak sun hours available. The peak sun hours available are numerically equal to the amount of insolation that is usable per day (P2).

$$(P2) = \mathbf{4.03 \text{ hrs/day}}.$$

PUMPING FLOW REQUIREMENTS

- P4: Daily quantity of water required. This quantity is determined by the pumping system application. For this application the amount of water required per day is **4000 gallons**.

- P5: Peak flow rate. The peak velocity at which water is delivered by the pump, assuming that the daily quantity of water is pumped with the sun at peak intensity during the usable peak sun hours, is determined by dividing the daily quantity of water required (P4) by the usable peak sun hours (P3). (This measurement is converted from gal/hr to gal/min by multiplying usable sun hours by 60.)

$$\text{Peak flow rate} = \frac{4000}{4.08 \times 60} = 16.5 \text{ gal/min.}$$

- P6: Pipe inside diameter. The inside diameter of the pipe size used in this application is **1 inch**, and the pipe is made of steel.

- P7: Peak velocity. To determine the peak flow velocity of the water moving through pipe, the peak flow rate (P5) is divided by the inside pipe diameter squared. This number is then multiplied by a conversion factor of 0.408 to convert to ft/sec.

$$\text{Peak velocity} = \frac{16.5}{(1)^2} \times .408 = 6.73 \text{ ft/sec.}$$

PUMPING HEAD REQUIREMENTS

STATIC HEAD

- P8: Suction lift (or head). Suction lift is the vertical distance (ft) from the surface of the water source to the center of the pump. Figure 6.17 illustrates the pump configuration. Because the pump is located 15 feet below water level the suction lift is a negative value. This negative value is referred to as a suction head.

$$\text{Suction head} = 15 \text{ ft (or suction lift} = -15 \text{ ft).}$$

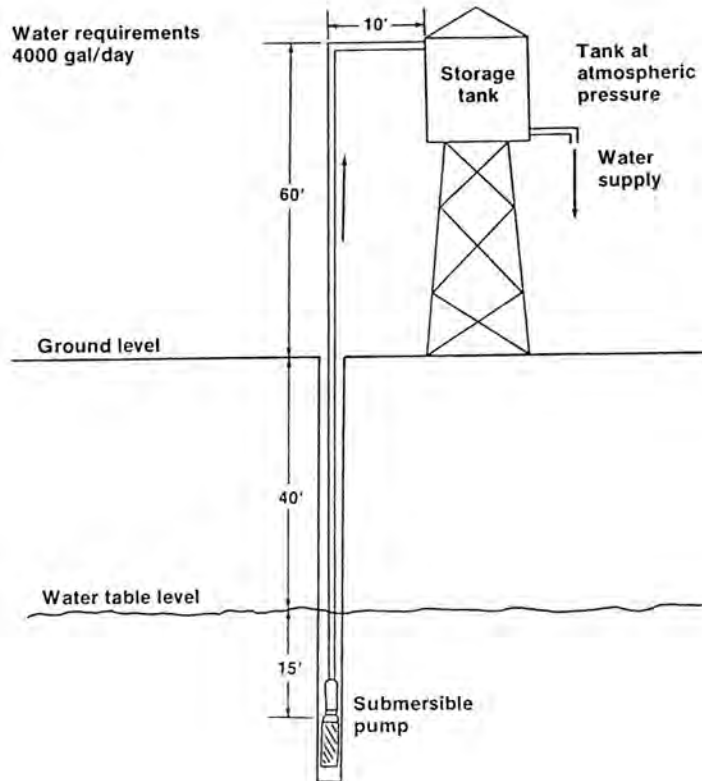


Figure 6.17 System sized in example

- P9: Discharge head. Discharge head is the total vertical distance (ft) from the center of the pump to the point of free discharge. As illustrated in figure 6.17 the vertical distance from the center of the pump to the water table is 15 ft. The vertical distance from the water table to ground level is 40 ft, and the vertical distance from ground level to the storage tank is 60 ft.

$$\text{Discharge Head} = 15 \text{ ft} + 40 \text{ ft} + 60 \text{ ft} = \mathbf{115 \text{ ft.}}$$

- P10: Pressure head. If a final discharge pressure higher than atmospheric pressure is desired, the pump must be able to supply the extra needed energy. The pressure head is the equivalent feet of head required to provide this pressure. A factor of 2.31 is used to convert units of psig to ft. Since the tank in this application is at atmospheric pressure, the pressure head is 0.

- P11: Static head. The measure of the total head required to lift the water to a desired level and to store it in a tank at a prescribed pressure is the sum of the suction lift or head (P8), the discharge head (P9), and the pressure head (P10).

$$\text{Total static head} = -15 \text{ ft} + 115 \text{ ft} + 0 \text{ ft} = \mathbf{100 \text{ ft.}}$$

DYNAMIC HEAD

- P12: Velocity head. The equivalent head that a pump must supply to move the fluid through pipe at a given velocity is determined by squaring the peak velocity (P7) and multiplying this number by the conversion factor 0.0155 to convert to ft. This number is usually small and can often be neglected in PV water pumping systems.

$$\text{Velocity head} = (6.73)^2 \times 0.0155 = \mathbf{0.7 \text{ ft.}}$$

- P13: Total equivalent length. In addition to the energy required to lift and store the water, energy is also required to overcome losses due to pipe friction. Friction head is the head required to overcome these energy losses that occur as a fluid flows through the pipe.

In this application there is one 90° fitting of 1 inch diameter. The equivalent length factor of this fitting (obtained from the chart shown in figure 6.18) is 2.7.

Size of Fitting, Inches	½"	¾"	1"	1¼"	1½"	2"	2½"	3"	4"	5"	6"	8"	10"
90° Ell	1.5	2.0	2.7	3.5	4.3	5.5	6.5	8.0	10.0	14.0	15	20	25
45° Ell	0.8	1.0	1.3	1.7	2.0	2.5	3.0	3.8	5.0	6.3	7.1	9.4	12
Long Sweep Ell	1.0	1.4	1.7	2.3	2.7	3.5	4.2	5.2	7.0	9.0	11.0	14.0	
Close Return Bend	3.6	5.0	6.0	8.3	10.0	13.0	15.0	18.0	24.0	31.0	37.0	39.0	
Tee—Straight Run	1	2	2	3	3	4	5						
Tee—Side Inlet or Outlet	3.3	4.5	5.7	7.6	9.0	12.0	14.0	17.0	22.0	27.0	31.0	40.0	
Globe Valve Open	17.0	22.0	27.0	36.0	43.0	55.0	67.0	82.0	110.0	140.0	160.0	220.0	
Angle Valve Open	8.4	12.0	15.0	18.0	22.0	28.0	33.0	42.0	58.0	70.0	83.0	110.0	
Gate Valve—Fully Open	0.4	0.5	0.6	0.8	1.0	1.2	1.4	1.7	2.3	2.9	3.5	4.5	
Check Valve (Swing)	4	5	7	9	11	13	16	20	26	33	39	52	65
Check Valve (Spring)	4	6	8	12	14	19	23	32	43	58			

Figure 6.18 Equivalent number of feet of straight pipe for different fittings

Multiplying the equivalent length factor for each fitting type by the quantity of that type determines the equivalent length.

$$\text{Equivalent length} = 1 \times 2.7 = 2.7 \text{ ft.}$$

Actual pipe length. The actual length of straight pipe used in this application is **125 ft.**

The total equivalent length of pipe for the application is determined by adding the equivalent lengths of the fittings to the actual pipe length.

$$2.7 \text{ ft.} + 125 \text{ ft.} = 127.7 \text{ ft.}$$

- P14: **Friction head.** The equivalent head required to overcome the loss of energy that occurs as fluid flows through a pipe is determined by dividing the total equivalent pipe length (P13) by 100 and multiplying this number by the friction loss per 100 ft. Friction loss per 100 ft is dependent on the type and diameter of piping used and, for this application, is obtained by interpolating the flow rate on the chart shown in figure 6.19.

$$\text{Friction Head} = \frac{127.7}{100} \times 17.8 = 22.7 \text{ ft.}$$

GPM	GPH	3/8"		1/2"		3/4"		1"		1 1/4"		1 1/2"		2"	
		FL	Lbs.	FL	Lbs.	FL	Lbs.	FL	Lbs.	FL	Lbs.	FL	Lbs.	FL	Lbs.
1	60	4.30	1.85	1.86	.80	.26	.11								
2	120	15.00	6.45	4.78	2.06	1.21	.52	.38	.16						
3	180	31.80	13.67	10.00	4.30	2.50	1.08	.77	.33						
4	240	54.90	23.61	17.10	7.35	4.21	1.81	1.30	.56	.34	.15				
5	300	83.50	35.91	25.80	11.09	6.32	2.72	1.93	.83	.51	.22	.24	.10		
6	360			36.50	15.70	8.87	3.81	2.68	1.15	.70	.30	.33	.14	.10	.04
7	420			48.70	20.94	11.80	5.07	3.56	1.53	.93	.40	.44	.19	.13	.06
8	480			62.70	26.96	15.00	6.45	4.54	1.95	1.18	.51	.56	.24	.17	.07
9	540					18.80	8.08	5.65	2.43	1.46	.63	.69	.30	.21	.09
10	600					23.00	9.89	6.86	2.95	1.77	.76	.83	.36	.25	.11
12	720					32.60	14.02	9.62	4.14	2.48	1.07	1.16	.50	.34	.15
15	900					49.70	21.37	14.70	6.32	3.74	1.61	1.75	.75	.52	.22
20	1,200					86.10	37.02	25.10	10.79	6.34	2.73	2.94	1.26	.87	.37
25	1,500							38.60	16.60	9.65	4.15	4.48	1.93	1.30	.56
30	1,800							54.60	23.48	13.60	5.85	6.26	2.69	1.82	.78
35	2,100							73.40	31.56	18.20	7.83	8.37	3.60	2.42	1.04

16.5
gpm {

} = 17.8 ft
friction
head

Figure 6.19 Friction loss per 100 ft of steel pipe

- P15: Total dynamic head. The measure of pressure required to move liquid at a given velocity and to overcome effects due to friction is determined by adding the velocity head (P12) with the friction head (P14).

$$\text{Total dynamic head} = 0.7 + 22.7 = \mathbf{23.4 \text{ ft.}}$$

- P16: Total system head. The total system head is the sum of the total static head and total dynamic head. The system head and the flow rate determine the power requirements for pumping. The total system head is determined by adding the total static head (P11) to the total dynamic head (P15).

$$\text{Total system head} = 100 + 23.4 = \text{approx. } \mathbf{124 \text{ ft.}}$$

The system head vs. flow rate profile has now been determined, and is a function of the piping and flow rate only, independent of the pump motor. The system head vs. flow rate profile may be represented graphically in figure 6.20.

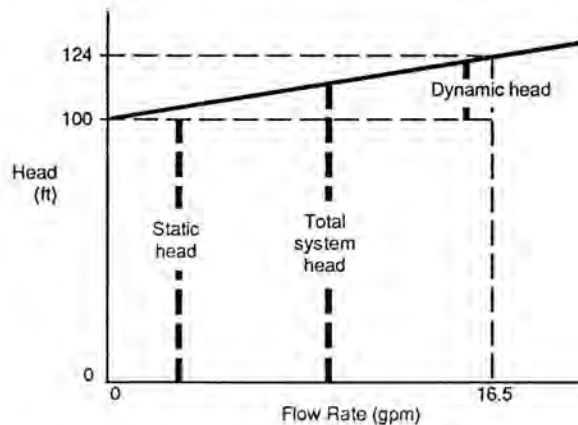


Figure 6.20 System head vs. flow rate

PUMPING ENERGY REQUIREMENTS

- P17: Hydraulic energy. The mechanical energy required to deliver a prescribed volume of water at a given head is determined by multiplying the total system head (P16) by the daily quantity of water required per day (P4). This figure is multiplied by the factor 0.0031 to convert units to watt-hours per day.

$$\text{Hydraulic energy} = 124 \text{ ft} \times 4000 \text{ gal/day} \times 0.0031 = \mathbf{1538 \text{ watt-hours/day.}}$$

- P18: Hydraulic power. This figure is determined by multiplying the peak flow rate (P5) by the total system head (P16). This quantity is then multiplied by the factor 0.188 to convert units to watts.

$$\text{Hydraulic power} = 1.65 \text{ gal/min} \times 124 \text{ ft} \times 0.188 = \mathbf{385 \text{ watts.}}$$

PUMP SELECTION

The criterion for pump selection for any pumping application is that the pump/motor combination be capable of meeting flow and head requirements with high efficiency.

The pump/motor selected for this application is the **Jacuzzi SJ1-D10**. At the prescribed peak flow conditions (i.e., total head of 124 ft and a peak flow rate of 16.5 gpm), this pump has an efficiency of approximately **44%**. Other operating conditions may be determined by superimposing the system head vs. flow rate profile on the pump motor head vs. flow rate curves.

- P19: Motor voltage. The motor voltage at the design operating point is determined by interpolating the manufacturer's data in figure 6.21.

$$\text{Motor voltage} = \mathbf{55 \text{ volts (approximately).}}$$

- P20: Electric power. The electric power required to drive the pump motor is also obtained from figure 6.21 with the lower set of curves representing electric power input vs. flow rate. For a peak flow rate of 16.5 gpm at approximately 55 volts, one can interpolate between the 45V and 60V curves (using the lower family of curves) to estimate the motor electric power input.

$$\text{Electric power} = \mathbf{920 \text{ watts (approximately).}}$$

- P21: Daily electrical energy. The amount of electrical energy required to provide the daily water requirements at a given head is determined by multiplying the electric pump power (P20) times the peak sun hours available (P3).

$$\text{Daily electric energy} = 920 \text{ watts} \times 4.03 \text{ hrs/day} = \mathbf{3708 \text{ watt-hours/day.}}$$

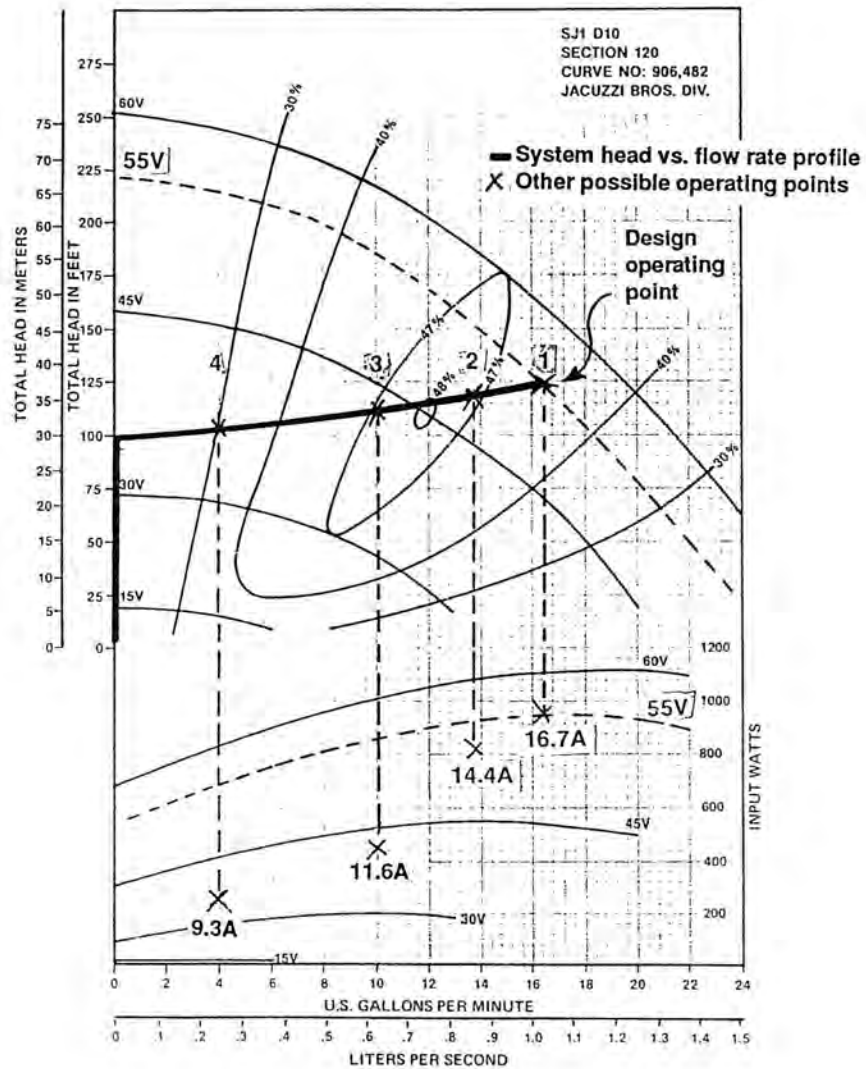


Figure 6.21 Efficiency graph for Jacuzzi SJ1 D10 pump

PHOTOVOLTAIC ARRAY SIZING

A Solarex photovoltaic module, model **SX-146**, was selected for this application. Figure 6.22 provides the manufacturer's specifications for the SX-146 module.

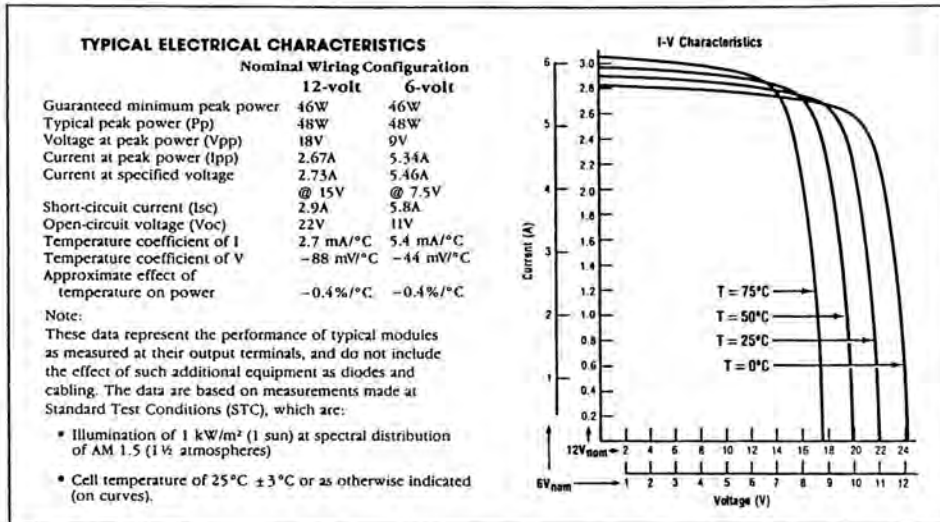


Figure 6.22 Solarex SX-146 module specifications

- M1: Module voltage at max power (STC). The photovoltaic module voltage is obtained from the manufacturer's specifications, as in figure 6.22. The voltage at maximum power for the SX-146 is **18 volts**.
- M2: Module current at max power (STC). The photovoltaic module current at maximum power is also obtained from the manufacturer's specifications. Current for the SX-146 at maximum power is **2.67 amps**.
- M3: Module guaranteed power output at 1 kW/m² (STC). Module guaranteed power output at standard test conditions is obtained from the manufacturer's specifications shown in figure 6.22. The guaranteed power output for this module, indicated by the manufacturer's specification data, is **46 watts**.
- M4: Total energy demand. The total energy demand that the photovoltaic array must meet is equal to the daily electrical energy required by the pump/motor to provide the daily quantity of water at a given head (P21).

Total energy demand = **3708 watt-hours/day**.

- M5: Impedance mismatch and nonlinear effects for direct-coupled systems (0.7 - 0.9). Because the modules do not operate at the maximum power point throughout the day, a derating factor is used to adjust the energy demand. In addition, the pump/motor may not operate at the design efficiency for all irradiance levels. For this application a factor of **0.9** is used.

- M6: Required array output. The required array output is the adjusted total energy demand. To determine the required array output, the total energy demand (M4) is divided by the derating factor (M5).

$$\text{Required Array Output} = \\ 3708 \text{ watt-hours/day} / 0.9 = \mathbf{4120 \text{ watt-hours/day.}}$$

- M7: PV module operating voltage. The module voltage at maximum power (M1) is multiplied by an adjustment factor (between 1.1 - 1.2) to establish a module operating voltage that is, on an I-V curve, to the right of the maximum power voltage. This is necessary to ensure that the pump/motor load line intersects the maximum power locus on the PV array family of I-V curves somewhere between 700 and 800 W/m². A derating factor of 1.2 is used for this application.

$$\text{PV module operating voltage} = 18 \text{ volts} \times 1.2 = \mathbf{21.6 \text{ volts.}}$$

- M8: Daily energy output per module. The daily energy output per module at STC is determined by multiplying the guaranteed module power at 1kW/m² (M3) times the peak sun hours available (P3).

$$\text{Daily energy output per module} = \\ 46 \text{ watts} \times 4.03 \text{ hr/day} = \mathbf{185 \text{ watt-hours/day.}}$$

- M9: Temperature derating factor. A temperature derating factor (between 0.80 - 0.90) is used to compensate for the difference between actual operating conditions and standard test conditions. For this application a temperature derating factor of 0.90 is used.

- M10: Derated module energy output. The derated module energy output is determined by multiplying the daily energy output per module (M8) times the temperature derating factor (M9).

$$\text{Derated module energy output} = \\ 185 \text{ watt-hour/day} \times 0.90 = \mathbf{166 \text{ watt-hours/day.}}$$

- M11: Number of modules to meet daily energy requirements. To determine the number of modules needed to meet the daily energy requirements, the required array output (M6) is divided by the derated module energy output (M10).

$$\text{Number of modules to meet daily energy requirements} = \\ 4120 \text{ watt-hours/day} / 166 \text{ watt-hours/day} = \mathbf{25 \text{ modules.}}$$

- M12: Number of modules per string. To determine the number of modules needed for each string, the motor voltage (P19) is divided by the photovoltaic module operating voltage (M7). This number is then rounded to the nearest integer.

$$\text{Number of modules per string} = 55 \text{ volts} / 2 \text{ volts} = \mathbf{3 \text{ modules.}}$$

- M13: Number of strings in parallel. The number of strings in parallel required to supply the needed energy is determined by dividing the number of modules needed to meet the daily energy requirements (M11) by the number of modules per string (M12). This number is rounded to the nearest integer.

$$\text{Number of strings in parallel} = 25 \text{ modules} / 3 \text{ modules} = \mathbf{8 \text{ strings.}}$$

- M14: Total number of modules required. The total number of modules required for this application is determined by multiplying the number of modules per string (M12) by the number of strings in parallel (M13).

$$\text{Total number of modules required} = 3 \text{ modules} \times 8 \text{ strings} = \mathbf{24 \text{ modules.}}$$

Since the optimal array configuration (current vs. voltage characteristic) for a direct-coupled photovoltaic system is determined by an iterative process, it helps to check the results of the preceding sizing example. To do this, it is necessary to develop a family of I-V curves for the array at different sunlight levels from manufacturers' data. For the 3 series by 8 parallel SX-146 array in the example, the family of I-V curves at 50°C is shown in figure 6.23.

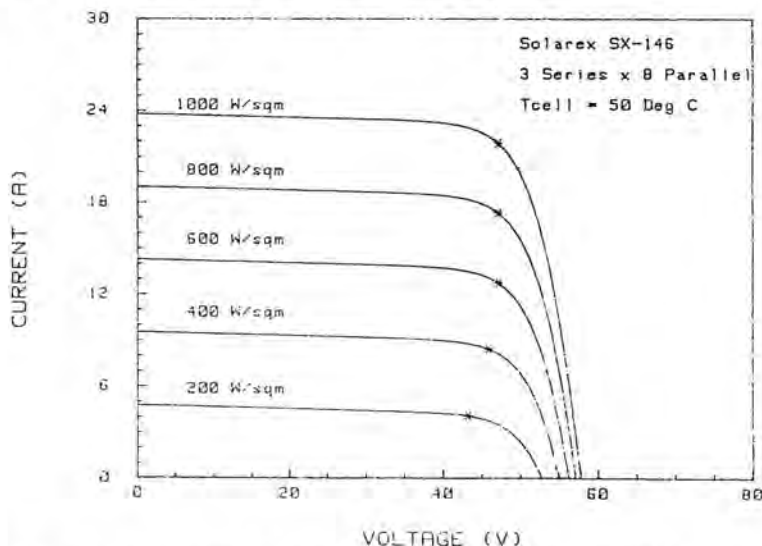


Figure 6.23 Family of I-V curves at 50°C for SX-146 array

To examine the matching of the pump/motor with the PV array, it is necessary to develop an I-V (current-voltage) load line for the pump/motor load. This is readily accomplished by determining the current and voltage for the pump motor at various points on the system's head vs. flow rate profile (from figure 6.21).

These current-voltage operating points for the pump/motor may then be plotted on the family of PV array I-V curves. By fitting a curve to the pump/motor current-voltage points, one can examine the closeness of the match between the pump/motor load line and the PV array locus of maximum power points. A properly designed system will have an intersection of the pump/motor I-V load line and PV array locus of maximum power points between 700 and 800 W/m² sunlight as shown in figure 6.24.

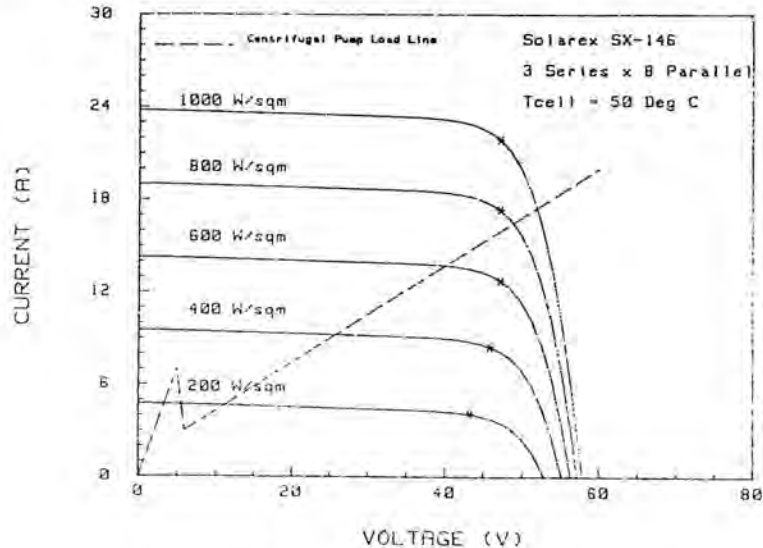


Figure 6.24 I-V curves and load line intersection for a properly designed system

At this point, the designer can take hourly average sunlight data for a typical design day and predict the PV array I-V curve for each hour. With the I-V load line for the pump/motor, the intersection with the PV array I-V curve determines the average operating point for that hour.

The flow rate can then be determined at that point and totaled over the hours in the day for the different PV array I-V curves determined from the design day insolation. Alternative PV array series parallel configuration and module types may be examined in this way to determine the optimal design for the given system head vs. flow rate profile and daily water requirement.

Exercises

1. Carefully review Example 1: Sizing a Stand-alone Photovoltaic System on pages 6-2 through 6-11. Referring to the steps in the sizing process (i.e., A1-A12, B1-B10, C1-C14), suggest energy conserving changes that should be considered in order to reduce the number of batteries, number of photovoltaic modules, and associated cost of the system.
2. Using the same electrical appliances for the same number of hours per day, redo Example 1 but for a residence located at Tonopah, Nevada. How do the calculated number of batteries and photovoltaic modules compare with those for Tallahassee? What is the design month and array tilt angle for Tonopah? (Note: Use the same batteries and modules as in Example 1.)
3. Carefully review Example 2: Sizing a Stand-alone Engine Generator System on pages 6-12 through 6-21. Based on your review, would you recommend: a) no battery storage, b) smaller battery capacity, or c) larger battery capacity? Discuss the tradeoffs.
4. List two advantages of the hybrid photovoltaic-generator system discussed in Example 3 beginning on page 6-22.
5. Carefully review Example 4: Sizing a Photovoltaic Water Pumping System beginning on page 6-36.



Electrical Design

7

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Objectives

For a given application, do the following:

- 1) Specify the wire types and sizes.*
- 2) Specify the terminations and connections.*
- 3) Specify the overcurrent protection devices.*
- 4) Specify the disconnect requirements and devices.*
- 5) Specify the grounding strategy and paths.*
- 6) Specify the protection diodes.*
- 7) Specify lightning and surge protection.*
- 8) Specify the instrumentation for monitoring system operation and performance.*
- 9) Produce an electrical design that meets prescribed electrical codes.*

Key Words

*Wiring terminations
Splice connections
Terminals
Plug/receptacle connectors
Conductors
Combiner panel
Overcurrent protection
Fuses
Circuit breakers
Grounding*

*Current path
Junction box
Heat sink
Disconnects
Switches
Protection diodes
Lightning protection
Direct strike interception
Surge arrestors*

7.1 Design Guidelines and Considerations

When selecting components and designing the electrical layout of photovoltaic systems, several issues must be considered. These issues include safety, compliance with electrical codes, wiring strategies, the types and sizing of conductors, terminations, overcurrent protection and disconnect devices, grounding, protection diodes, surge protection and instrumentation.

Perhaps the most important aspect of designing PV systems is to make them safe, reliable and easy to maintain. Any PV system designer, equipment manufacturer, or installer should have thorough knowledge of electrical codes and a full understanding of engineering principles and hazards associated with electrical and photovoltaic power systems. Common problem areas in the electrical design of PV systems are:

- Insufficient ampacity and insulation for conductors
- Unsafe wiring methods
- Lack of, or improper placement of overcurrent protection and disconnect devices
- Use of unlisted equipment, or improper application of listed equipment (ac in dc use)
- Lack of or improper system grounding
- Unsafe battery installation and use.

7.1.1 Differences Between PV and Conventional Electrical Systems

Unlike conventional ac electrical systems which generally have only one electrical supply, photovoltaic systems typically have two or more dispersed sources of energy. In addition to the PV array, other energy sources such as batteries, engine or wind turbine generators, and the utility interface with grid-interactive inverters or battery chargers need to be considered in the system electrical design. A few of the important differences that should be noted between PV and conventional ac electrical systems are:

- PV electrical systems have dc circuits which require different type and sizes of conductors than ac circuits, and electrical equipment (such as overcurrent protection and disconnect devices) must have proper dc ratings and listings.
- PV electrical systems have dispersed energy sources. Special disconnect means are required to isolate components. For example, fuses may require disconnecting from circuits on both sides, rather than one.

- Energy flows in PV systems may be bi-directional, such as a battery subsystem, grid-interactive power conditioner, or a stand-alone inverter with a battery charger.
- PV systems sometimes require an interface with the conventional ac utility-grid.
- The maximum current in a PV array is short-circuit limited. If an electrical problem occurs in the system, the current may be too low for standard fault-detection devices to recognize.

7.1.2 PV Systems and the National Electrical Code

The National Electrical Code (NEC) guides the electrical system designer and installer on safe and reliable practices for the United States. The primary purpose of the NEC is the practical safeguarding of persons and property from hazards arising from the use of electricity. It applies to almost all PV systems, including those operating below 50 volts, ac or dc. The NEC is not intended as a design specification nor an instruction manual for untrained persons [90-1]. The National Fire Protection Association updates the NEC every three years. Throughout this section, articles in the NEC are referenced by numbers in brackets.

Designers, installers and dealers of PV systems and equipment should become familiar with the requirements of the NEC, including the methods and standards associated with the design and installation of electrical power systems. For most PV applications, the electrical wiring, including connection to photovoltaic power system components, must be completed by a licensed electrician and inspected by a designated local authority for compliance with the NEC. In some cases more stringent local codes may apply; in some rural or developing areas there may be none at all.

The NEC covers nearly all electrical systems, including stand-alone and grid connected PV systems. The NEC also covers PV applications for billboard lighting, recreational vehicles and other remote applications. The NEC does not apply to automobiles, railway cars, boats or on utility-owned properties. Neither does it apply to consumer electronics and other self-contained electronic devices which have no external wiring or electrical contacts.

Article 690 addresses safety standards for the installation of PV systems and was added to the NEC in 1984. While Article 690 specifically deals with PV power systems, many other articles of the code may also apply to specific PV system installations. The system designer/installer should be familiar with all portions of the NEC that pertain to PV systems. Table 7.1 lists the articles from the NEC that are applicable to PV systems, depending on the specific design.

7.1.3 Equipment Listing

In general, the NEC requires that all conductors, overcurrent protection and disconnect devices, terminations, grounding equipment and other electrical hardware be listed by a nationally recognized testing laboratory. Some electrical components of PV systems, such as wiring, overcurrent protection and disconnect devices are listed. However, there are many other components commonly used in PV systems, such as charge controllers, inverters, and other devices that do not have applicable listings. While many of these components meet or exceed applicable ratings for their use, low volume production often does not justify the costs associated with their testing and listing by a recognized laboratory. As the industry grows, there has been an increasing trend among PV component manufacturers to have their equipment listed. A few of the nationally recognized testing laboratories include Underwriters Laboratory (UL), Factory Mutual Research and ETL Testing Laboratories.

Of the many PV module manufacturers, only a few offer modules with a recognized listing. UL standard 1703 is applicable to PV modules, and is required by the NEC for PV modules mounted on the roofs of dwellings.

7.1.4 Electrical Code Compliance

Many PV systems installed today may not be in compliance with the NEC, and as a result may constitute a hazard to people and property. Some reasons for this lack of compliance with the NEC are:

- Many PV designers and installers are unaware of the dangers associated with low-voltage dc electrical power systems, and have little experience with the interface of PV systems with conventional residential or commercial electrical systems.
- Electrical inspectors have not had significant experience dealing with direct current and PV power systems.
- The electrical equipment industry does not widely distribute listed equipment suitable for use in dc circuits meeting NEC requirements.
- PV equipment manufacturers, such as those who make modules, charge controllers and inverters have generally been unable to afford the costs associated with the testing and listing of their hardware by approved laboratories.
- Many publications imply that PV systems are easily designed, installed and maintained by untrained personnel.

Table 7.1 - National Electric Code Articles Applicable to Photovoltaic Systems

Article	Title
90	Introduction
100 *	Definitions
110 *	Requirements for Electrical Installations
200	Use and Identification of Electrical Conductors
210 *	Branch Circuits
220	Branch-Circuit and Feeder Calculations
230-F *	Service Equipment -Disconnecting Means
240 *	Overcurrent Protection
250 *	Grounding
280	Surge Arrestors
300	Wiring Methods
310	Conductors for General Wiring
331	Electrical Nonmetallic Tubing
336	Nonmetallic-Sheathed Cable Types NM and NMC
338	Service-Entrance Cable Types SE and USE
339 *	Underground Feeder & Branch Circuit Cable Type UF
348	Electrical Metallic Tubing
370	Boxes and Fittings
373	Cabinets and Cutout Boxes
384	Switchboards and Panelboards
422	Appliances
445	Generators
450 *	Transformers and Transformer Vaults
480 *	Storage Batteries
551	Recreational Vehicles, Parks
690	Solar Photovoltaic Systems
702	Optional Standby Systems
705 *	Interconnected Electric Power Production Sources
720	Circuits & Equipment Operating at less than 50 V

* Denotes articles referenced from Article 690

7.1.5 Electrical Inspection

As the first step in the electrical design process, the local inspector should be informed of the type and the extent of the PV installation, and determine whether there are any local code requirements that differ from those outlined by the NEC. Early communication with the local inspector will help ensure that the design meets local code requirements with the least amount of effort expended, and that the system will be completed and inspected in a timely manner.

Many local inspectors work with conventional electrical systems and have little experience with photovoltaics. They need sufficient time to evaluate the aspects of PV systems that differ from conventional electrical systems. Some NEC requirements may be interpreted differently by different inspectors and acceptable methods may vary. In general, electrical inspectors expect equipment used in electrical systems to be listed and/or tested by a recognized organization.

7.2 Conductors and Wiring Methods

Conductors, or the wiring used in electrical systems, comes in a variety of types, sizes and ratings for different applications. In the design of PV systems, it is important that the proper conductor sizes and ratings be used for a safe and reliable electrical system. In general, conductors are rated for their ampacity or current handling capability, resistance, temperature rating and electrical insulation.

Copper conductors are recommended for all photovoltaic system wiring. Aluminum conductors may be used in some circumstances, but are not recommended and require different sizing than copper conductors. Conductors can be either single-strand or multi-strand; the multi-stranded is easier to install due to its greater flexibility.

7.2.1 Conductor Insulation Types

All conductors, with the exception of some grounding conductors, have an exterior insulation which protects the wire from coming into contact with personnel or equipment. Many types of conductor insulation are available and rated or listed for a variety of applications and locations. When choosing a conductor, the insulation type dictates the ampacity rating at operating temperatures. If exposed to sunlight, conductors must be specified as sunlight resistant. Refer to NEC Articles 300, 310, 336 through 339, and 690-31 for information on wiring methods and types. Table 7.2 presents some of the wire types commonly used in PV systems.

Table 7.2 Conductors used in PV Systems

PV Application	Wire Type
Array Wiring	UF, USE (specify sunlight resistant)
BOS Interconnects	UF, SE (direct burial), THHN (only in conduit)
Interior Exposed	NM, NMC, UF (multi-conductor)
Battery Interconnects	Battery cables, welding cables

Type UF (Underground Feeder, Sunlight Resistant), Type SE (Service Entrance) or Type USE (Underground Service Entrance) are permitted for PV module and panel interconnect wiring. These types are sunlight, high temperature and moisture resistant, and provide long-term reliability required for module connections. Many types such as THHN and THWN are suited for wet and high temperature environments, but are not sunlight resistant, must be enclosed in conduit, and are not acceptable for exposed PV array wiring.

Conductor Locations: The ampacity and temperature derating for conductors depends on their location. When individual conductors are enclosed in conduit they should be rated for temperatures of at least 60°C. NEC Tables 310-69 through 310-84 list the types, number and ampacities of conductors which are buried, enclosed in conduit, or in free air. Except for PV module interconnections, single conductor wiring is not permitted unless enclosed in conduit. Interior exposed cable runs are only permissible with sheathed type cables such as NM, NMC and UF.

Conductor Color Codes: For grounded systems, the insulation on grounded conductors must be white or grey; if it is marked with white tape at the termination point it may be any color except green. Conductors used for module frame and equipment grounding must be bare wire or have green colored insulation. In two-wire negative-grounded PV systems, the positive conductor can be red (or any color with red markings except green or white), and the negative grounded conductor must be white.

7.3 Conductor Sizing

Conductors are sized in PV systems for both their ampacity and voltage drop ratings. Conductor sizes in the U.S. are specified by American Wire Gage (AWG): the higher the gage, the smaller the conductor. Internationally, conductor diameters are generally specified in millimeters.

The NEC requires that conductors used in PV systems operating below 50 volts shall be no

smaller than No.12 American Wire Gage (AWG) [Article 720-4]. In most cases however, higher currents in low voltage dc systems often dictates the use of much larger wire for ampacity or voltage drop limitations. For branch circuits supplying more than one appliance, the conductors may be no smaller than 10 AWG [720-4].

Ampacity: The current-handling capability of a conductor (ampacity) is governed by the wire gage, the temperature rating of the conductor, the ambient temperature, and whether the conductor is installed in free air, conduit, or buried. Tables 310-16 to 310-19 of the NEC give ampacities of conductors for a range of wire gages and operating conditions. Correction factors are given for derating the conductors for operation at elevated temperatures. Depending on its operating temperature, the nominal ampacity rating of a conductor may require derating by 50 percent or more. Temperature derating factors are also given in NEC Tables 310-16 and 310-17.

Example: A No. 10 AWG USE single-conductor cable has an insulation rating of 90°C and an ampacity of 40 amps in ambient temperatures of 26-30°C. When the same conductor is used for module interconnect wiring and may experience temperatures of 61-70°C, its temperature derated ampacity is reduced to 23.2 amps.

Voltage Drop: Often in low voltage dc PV systems, a conductor's ampacity rating may be adequate but, the voltage drop may be unacceptable due to the length of the wire run. As well as wasting energy, voltage drop may affect the operation of battery charge controllers and accuracy of their battery voltage regulation set points. Based on Ohm's law, the voltage drop in a conductor is primarily a function of the current and the overall resistance. Higher operating temperatures increase conductor resistance, and must be accounted for in voltage drop calculations.

The resistance of conductors is generally expressed in ohms per 1000 feet (kft) length. Table 8 in the NEC gives properties of conductors including resistance. When calculating voltage drops, the round trip distance between must be used and must be:

$$\text{Voltage Drop} = \text{Operating Current} \times \text{Resistance per Unit Length} \times \text{Length}$$

(where Length = the total length of conductor (roundtrip) in the circuit)

Increasing the current flow in a conductor, or increasing the length of the same gage conductor, results in an increase in voltage drop. For low-voltage battery-charging systems in particular, a significant portion of the PV array energy may be wasted unless the conductors are sized to minimize the voltage drop. Voltage drop from the modules to the batteries should be 3 percent or less of the system voltage. For calculating the voltage drop, resistance values from Table 8 of the NEC (Chapter 9) may be used.

7.3.1 PV Circuit Conductors

The output of photovoltaic modules is short-circuit current limited, and is generally limited to no more than 150 percent of the typical peak operating current, depending on the array fill factor and irradiance enhancements from clouds or snow. To prevent conductors from overheating, they should be sized to carry at least 1.25 times the rated short-circuit current plus enhancements, taking into account appropriate temperature deratings.

The rated short-circuit current is calculated by adding the short-circuit current ratings of the modules (at an irradiance of 1000 W/m^2) or PV source-circuits (integral building blocks of the array) connected in parallel. In a series-first wiring scheme, where the individual parallel strings terminate in a junction or combiner box, the individual string conductors need only be capable of carrying 125 percent of the maximum expected short-circuit current for one module.

All ungrounded conductors from the PV array and source circuits shall be protected by overcurrent devices. Since the PV array is short-circuit current limited, these devices actually protect the array conductors from battery or power conditioner system short-circuits. In systems with parallel sets of series-connected modules, overcurrent protection on individual array source circuits protects conductors in one string in the event of a failure in either the string or blocking diode.

7.3.2 Load Circuit Conductors

On the load distribution circuits of a PV electrical system, the conductors for individual and branch circuits (for either ac or dc loads) should be sized to carry at least 1.25 times their rated load current. As discussed above for the PV circuit conductors, if the wire runs are long, the voltage drop limitations in the dc load circuits may determine the conductor size. For dc load circuits, a three to four percent maximum voltage drop limit is recommended to ensure loads receive acceptable voltages.

7.3.3 Inverter Circuit Conductors

When an inverter is used to supply ac loads or appliances, it draws sizable dc currents from the battery bank, depending on the inverter input and output voltages. For example, an inverter with a 12-volt dc input supplying a 120-volt, 120-watt electrical load will draw in excess of 10 amps dc for what amounts to a one-ampere ac load at 120 volts. Furthermore, inverters may draw surge currents 4 to 10 times the rated current when starting some motor loads. The NEC requires that conductors connecting an inverter to a battery bank be sized to handle 125 percent of the maximum steady-state circuit current at the inverter-rated output power, which is determined by the inverter efficiency, power factor, and nominal input and output voltages. For ac electrical loads with low power factor, the dc current may be considerably higher than what would be expected with higher power factor or resistive loads.

Most well designed PV systems use inverter cables several times the required size (based on ampacity) to minimize voltage drops and improve the overall circuit efficiency. When the conductors are oversized, the equipment grounding conductor must also be oversized accordingly.

7.4 Terminations and Connections

The number and quality of electrical terminations in photovoltaic power systems are critical issues, particularly with regard to the potential for high resistance 'hot spots' in low voltage dc subsystems. In general, it is recommended to liberally coat all terminations in PV systems with an anti-corrosion grease, particularly in cases of dissimilar termination materials and in marine environments. The methods and types of terminations between conductors and components in PV systems varies widely, but can generally be classified into the categories listed below.

Crimped Terminals: Useful for securing a conductor to a ring or spade type terminal, in order to facilitate connection to a screw, post, or stud and nut type terminals. These types of connections are prone to developing high resistance over time, and should be crimped with a heavy-duty electrician's crimping tool, soldered and protected from the weather. The use of high-grade UL listed terminals is suggested over unlisted automotive or electronic grade items.

Binding Post Terminals: Often called box type pressure terminals, these terminations accept a bare wire and secure it by pressure exerted by a screw. This is a preferred type of connection as it eliminates the one extra connection required with crimped terminals. These terminations may need to be retightened periodically to ensure a good connection. Many PV modules have this type of terminal in their junction box.

Twist-On Wire Splices: Often called wire nits, these connections have proved less than reliable in low-voltage PV systems, frequently corroding and developing high resistance hot spots.

Plug and Receptacle Type Connectors: Often plug and receptacle type connectors are used to interconnect PV system components, particularly on some PV modules. Advantages of plug/receptacle connectors include: rapid connections with no tools; they may be polarized and non-interchangeable between the positive and negative circuits; and they protect live parts. The disadvantage of some plug/receptacle connectors is the possible buildup of ohmic resistance due to corrosion over time. Other types have o-ring gaskets which improve the sealing of these connections when used outdoors. When using plug/receptacle connectors for electrical load connections, the NEC requires that the plug/receptacle be of the proper type for ac or dc circuits. In general, plug/receptacle type connectors are not recommended for primary electrical system connections in accessible locations. An important consideration in the use of plug/receptacle connectors is that they have the appropriate current and voltage

ratings and are listed with a recognized laboratory.

Junction Boxes: Any connection between conductors in an outdoor location must be done within a rainproof junction box such as NEMA style 3R, and any box penetrations such as screw holes should be sealed with silicone. These types of terminations are typically used when connecting array source circuits to primary conductors leading to the remainder of the PV system.

Module and Array Connections

The specific arrangement of series and parallel modules varies with the current-voltage characteristics of the modules used in the array and the overall array current-voltage requirements. In general, modules are first wired in series strings to achieve the voltage requirements. Next the series strings are connected in parallel to achieve the desired current output. Where several series strings are connected in parallel, a terminal block or bus bar arrangement must be used so that one series string or source circuit can be disconnected without disconnecting the grounded conductor of other source circuits. This bus bar prevents a "daisy chain" connection of modules as shown in Figure 7.1.

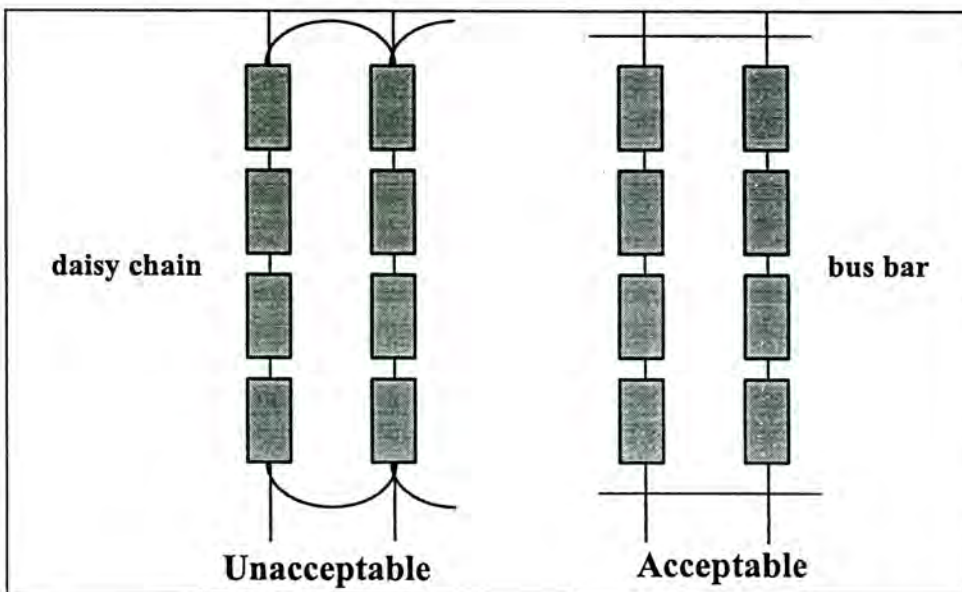


Figure 7.1 Module interconnect methods

7.4.1. Array Series and Parallel Wiring Strategies

When wiring an array, many designers recommend first building series strings to the desired array output voltage. The series strings can then be connected in parallel to obtain the desired output power. The advantages of wiring in series first include:

- easier array expansion
- easier replacement of individual modules
- smaller switches and components required
- smaller wires needed for the longest runs
- more convenient access for diagnostics and troubleshooting
- minimum wiring material (reducing both labor and cost).

For large utility-size arrays, modules are often wired in parallel first in order to minimize array losses due to module mismatch and row-to-row shading. The parallel groups of modules are then connected in series to obtain the high source-circuit voltages.

7.4.1.1 PV Modules and Array

Conduit is generally not required for wiring connections to and between PV modules but may be required or advisable in certain circumstances. If conduit is not used, appropriate strain reliefs must be used on all wiring. In general, PV modules are equipped with a junction box that provides a weather tight electrical connection to the module and the circuit, and may also include space for installation of a bypass diode. Many types of junction boxes have built-in strain reliefs or knock-out accesses suited for the installation of conduit or strain-reliefs. Under most circumstances, the wiring from the array to the primary junction box must be enclosed in rigid metallic or nonmetallic conduit.

The NEC requires that certain electrical information *must* appear on every PV module. This includes polarity of terminals or leads, maximum overcurrent device rating for module protection rated V_{oc} , V_{op} , I_{sc} , I_{op} , P_{mp} , and maximum system voltage. At present, only a few of the many photovoltaic module manufacturers have had their products listed with a nationally recognized testing laboratory.

The NEC also requires that a disconnect device be installed to disable portions of the array or the entire array. While the array may be short-circuited, most often a disconnect is used to open-circuit the array or subarrays.

7.5 Overcurrent Protection

Overcurrent devices, such as fuses or circuit breakers, are placed in an electrical circuit to protect the conductors and loads from overheating and creating a fire hazard under fault or overload conditions. Every ungrounded conductor must be protected by an overcurrent

device, and the overcurrent device must be located to provide protection from all sources of power [240-20, 690-9]. The exception to this is that if the PV array is the only source of power to the load, as in a direct-coupled system configuration. In this case no overcurrent devices are necessary if the ampacity of the conductor is greater than 1.25 times the rated short-circuit current of the PV array [690-8].

Fuses and circuit breakers used in PV system dc circuits must have appropriate ratings for dc application. Typical automotive fuses do not have dc ratings or dc listing with recognized laboratories, and should not be used in PV systems. They are also generally rated for low voltages, and have no interrupt rating.

7.5.1 Selection Criteria for Overcurrent Protection

The current rating of the overprotection devices should always be equal to, or less than, the ampacity ratings for the conductors in that circuit. Under no circumstances should the rating of overcurrent protection devices exceed the ampacity of the circuit conductors. Special attention should be paid to properly select dc-rated overcurrent protection devices for dc circuits, as they must meet different requirements than ac powered ones.

The maximum open-circuit voltage of the PV array determines the voltage rating for overprotection devices in dc systems [690-7]. The maximum array open-circuit voltage rating is calculated by adding the open-circuit voltage of the individual modules connected in series. If the expected winter operating temperatures are quite low, the voltage rating should be increased to reflect the increase in open-circuit voltage at the lower operating temperatures. For example, the open-circuit voltage of crystalline silicon modules increases about 0.4% per degree Centigrade that the operating temperature is lowered. If the winter operating temperature is 20°C lower than the temperature for which the PV modules were rated, the voltage rating of the PV system and component ratings must be increased by 10 percent.

If fuses are used for the overprotection device, a switch on each side of the fuse is required to disconnect the fuse from all sources of power [690-16]. This permits the safe replacement of failed fuses.

PV electrical systems may experience many transient or surge currents either from lightning or electrical load surges. The use of inverse-time circuit breakers or time-delay fuses should eliminate nuisance overcurrent faults when there is no real threat to conductors or safety.

Ampere Interrupting Rating: All listed overcurrent protection devices are rated for their Ampere Interrupting Rating (AIR) which is the design current limit at which the device will reliably operate. The AIR is not generally important for array source-circuits as long as the conductors have been properly sized. However, battery circuits have a short-circuit current potential of several thousand amps, and protection devices must have an appropriate AIR

limit exceeding this value. A disastrous battery explosion or fire may occur if an overcurrent protection device fails under a battery short-circuit current condition.

7.6 Disconnect Requirements

The designer must provide the ability to electrically disconnect or isolate the major PV system components from all other equipment in the system [690-15]. Only manually operated switches or circuit breakers are approved for disconnect means [690-17]. Similar to overcurrent protection devices, disconnect switches and circuit breakers are rated for either dc or ac application, current ratings and AIR limit.

A switch or circuit breaker must also be used to disconnect all the current-carrying conductors of the PV array source-circuits from all the other conductors [690-13]. In ungrounded 12- or 24- volt dc systems, both the positive and negative conductors from the array must have disconnects, increasing disconnect costs. Only small, self-contained PV systems with no external contacts or use-serviceable parts may be designed without disconnects.

In general, untrained personnel may operate PV system disconnect switches as long as they have a simple, comprehensible layout and the switches are properly labeled. A maximum of six switches or six circuit breakers (either can be used) are allowed for disconnecting [230-71]. Required disconnects should be grouped, marked and readily accessible [230-72, 690-15]. For specific information on disconnecting requirements refer to NEC Articles 690-13 through 690-18.

Each piece of equipment in a PV system shall have disconnect switches or circuit breakers to isolate it from all sources of power. When properly rated and located, circuit breakers can serve as both disconnect and overcurrent protection devices, and often prove less costly than separate disconnects and fuses.

Batteries can deliver thousands of amperes under short circuit conditions, potentially causing explosions, fires, burns, shock and equipment damage. For these reasons, proper dc rated overcurrent and disconnect protection devices are required on all PV battery systems. Fuses or circuit breakers used for overcurrent protection must not only be able to operate properly under 'normal' high currents resulting from load problems, but also operate under battery short-circuit conditions. The interrupt ampere rating (AIR) for overcurrent devices must be considered with regard to the battery system, or the device could fail with disastrous results. For ungrounded systems, disconnects are required on both the positive and negative conductors leading to and from the battery. For grounded systems, disconnect and overcurrent protection are only required on the ungrounded conductor.

7.7 Grounding

The connection of an electrical system with the ground provides a low-impedance path (i.e., through a conductor) from the grounded point in a system to the earth, where electrical charge can dissipate safely. Grounding is one of the fundamental preventive measures included in the design of an electrical system for avoiding hazardous conditions to persons and property. Equipment grounding and system grounding prevent shock hazards, stabilize system voltage-to-ground, and facilitate operation of overcurrent devices under fault conditions. Figure 7.2 shows that the equipment ground wire is designed to provide a lower impedance conductor path to ground than alternative paths through the body.

A fault (or short-circuit) can develop between the cells and the metal frame in a current-producing photovoltaic array, presenting a potential hazard to anyone coming in contact with the frame. Consequently, it is important that all metal frames and other metal support structures be properly grounded to a common ground.

Article 100 of the NEC defines *grounding* as a connection to the *earth*. Grounding in electrical systems is used to enhance personnel safety and to minimize the effects of lightning and other surges on equipment.

A *grounded conductor* is a system conductor that normally carries current and is grounded. Normally, the negative of a two-conductor PV system is grounded. A grounding conductor does not normally carry current, and is used to connect the exposed metal portions of equipment to the grounding system, or to connect the grounded conductor to the grounding system.

For two-wire PV systems (including stand-alone and grid-connected systems) operating above 50 volts, one dc conductor should be grounded. In a three wire system, the neutral or center tap of the dc subsystem shall be grounded. The *grounding conductor* shall not be smaller than No.8 AWG or the largest conductor supplied by the system [250-93]. The grounding conductor for the dc portion of PV systems should be connected to the PV array source circuits as close to the modules as possible [690-43]. Disconnect switches must not open-circuit the grounded conductor at any time.

Charge Controllers and Grounding: In a grounded stand-alone PV system, it is important that the charge controller does not perform any switching or regulation functions in the circuit leg of the grounded conductor. This often presents a problem for charge controllers which regulate the array or load by negative leg switching. Under these circumstances, all of the grounding conductors may not be at the same potential when the charge controller is regulating.

In general, connecting the grounding conductor to the PV system on the battery side of the charge controller at a point where the system conductors are the largest size will provide the

best system grounding. In order to prevent potentially hazardous ground loops and current flows through uninsulated conductors, it is imperative that no more than one grounding connection be made to the grounded negative conductor of a PV system.

Equipment Grounding: All non-current-carrying exposed metallic parts of junction boxes, PV module frames, equipment and appliances in the entire PV electrical and load distribution system should be grounded, regardless of the system operating voltage [690-43]. The equipment grounding conductor must be sized in relation to the overcurrent protection devices in that circuit. If the current-carrying conductors have been oversized to compensate for voltage drops, the size of the equipment-grounding conductor must also be increased.

Inverter AC Output Circuits: The NEC requires that both the green equipment ground as well as the white neutral conductor be grounded. If these grounds are made at a common point at the inverter, then plug-in devices will be properly grounded and can be used safely. When using inverters or auxiliary generators in PV systems, it is recommended that these devices be hard wired into the load distribution center. To avoid parallel grounding paths they should not have an internal connection between the neutral and grounding conductors.

Grounding Electrodes: Most PV systems require a grounding electrode, also known as a grounding rod. It must be a corrosion-resistant rod, a minimum of 5/8 inch in diameter and driven a minimum of 8 feet into the earth. In some cases, direct connection to water or well pipes may suffice for the grounding electrode. Common ground rods are made of copper-clad steel connected to grounding conductors with clamps. The resistance of the ground can be measured with an earth potential tester or a megger meter. These instruments impose a high voltage between the system grounding electrode and a reference electrode, and measure the current flow to calculate the resistance. Resistance of a good ground will typically be less than a few ohms. Soil conditions may affect the quality of the ground; deeper ground rods may be required to lower the resistance.

Connections and conductor clamps to the grounding electrode should be inspected and tightened periodically to ensure a good ground over time. If more than one grounding electrode is used to increase protection from lightning induced surges, the secondary grounding electrode should be located as close as possible to the PV array and connected to the module and array frames. To prevent ground loops and safety hazards, there should be only be one point in the system where the grounding electrode conductor is attached to the grounded conductor in the PV system.

The dc system grounding electrode shall be in common with or be bonded to the ac system grounding electrode. Furthermore, the grounded conductor and equipment ground in a system must be tied to the same common point. If a grounding conductor is used in a PV system, it should be the first conductor to make and the last conductor to break the circuit during any disconnect procedures. According to current UL standards, electrical equipment such as inverters must have the current-carrying conductors electrically isolated from the

chassis. However, for some electrical equipment, the chassis is connected to the negative circuit and creates problems with ground loops in PV systems. Under these circumstances, the grounding point for the system is the negative terminal of the equipment having a chassis ground.

This same common ground should be used for grounding the electrical circuit. Figure 7.2 illustrates why metal frames and other metal hardware should be grounded for safety.

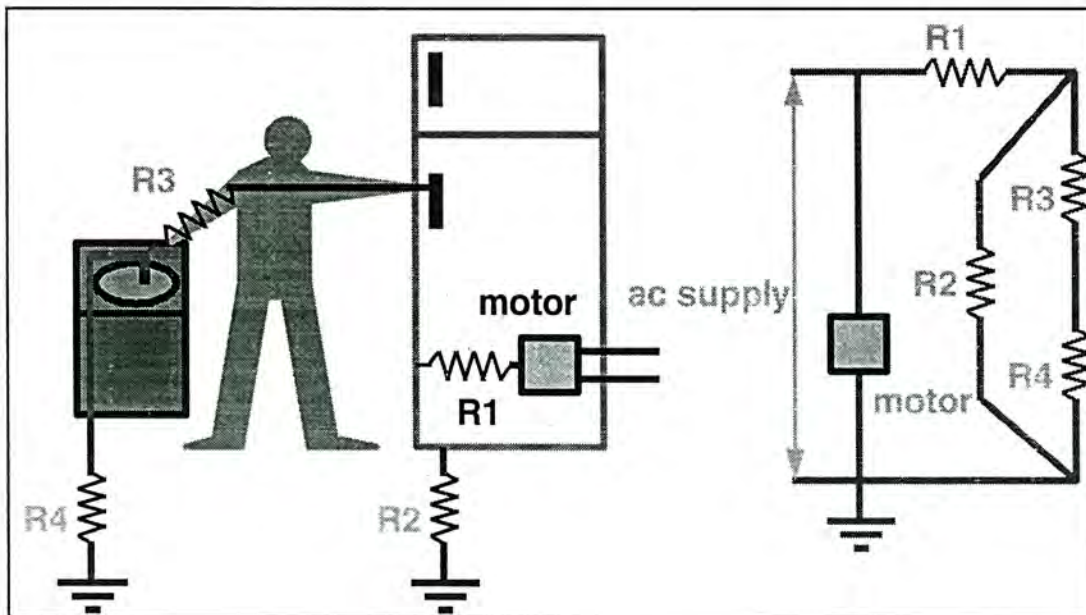


Figure 7.2 Traditional grounding equipment

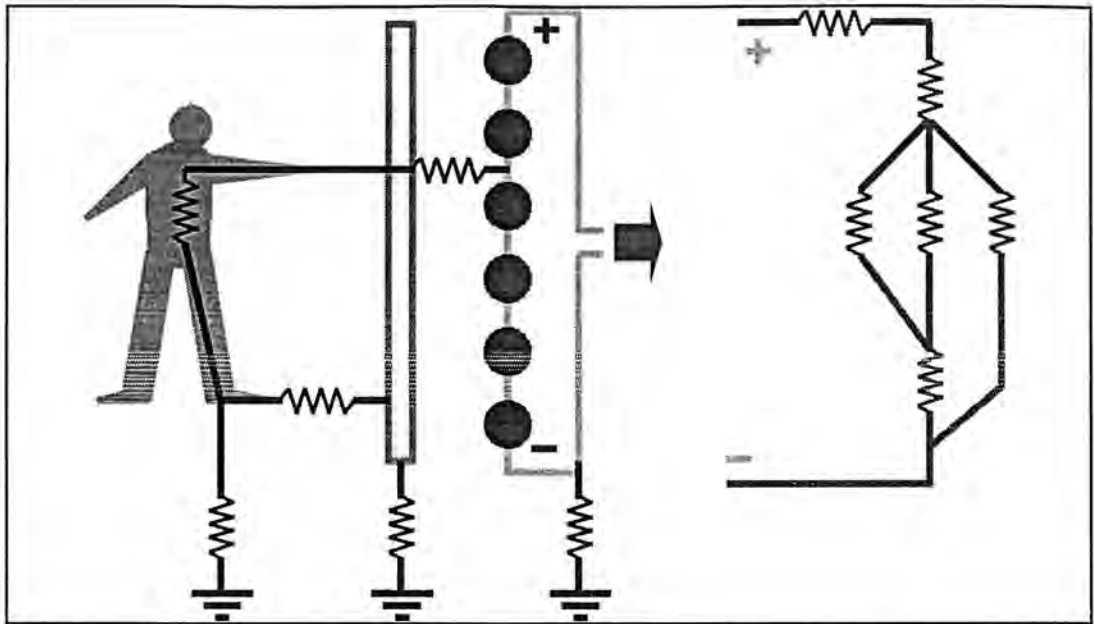


Figure 7.3 Grounding and safety in a photovoltaic system

7.7.1 Code Requirements

If the rated open-circuit voltage of the PV system is 50 volts or less, none of the conductors are required to be grounded. For systems over 50 volts, one conductor of a two-wire system must be grounded. Three-wire systems over 50 volts require the neutral conductor to be grounded [690-41]. Regardless of system voltage, all non-current-carrying metal parts (support structures, junction boxes, equipment, appliances, etc.) must be grounded [690-43, 250 E].

For information on electrical grounding requirements refer to:

NEC Art. 250: Grounding

NEC Art. 690: Solar photovoltaic systems; Part E Grounding.

7.7.2 Current Leakage to Ground

If a current path develops between the cells and module frame, or from a terminal in a junction box to ground, valuable current is lost and a safety hazard exists. By alternately measuring the current between the positive terminal and ground and between the negative terminal and ground one can estimate the location of the leakage path in a module comprised of series-connected cells.

7.7.3 Ground-Fault Protection

If PV arrays are mounted on the roofs of dwellings, Article 690-5 requires ground-fault detection, interruption and an array disablement (GFID) device for fire protection. Currently, no commercial equipment exists for this purpose but some is under development. Ideally, a GFID device would automatically sense excess ground-fault currents, interrupt the currents, open the circuit between the array and load, and short the PV array or subarray.

7.8 Protection Diodes

Diodes permit current flow in only one direction and prevent hot-spot heating.

7.8.1 Bypass Diodes

Bypass diodes are used to minimize power losses from shading or cell failures by providing bypass routes for current (they are not normally in operation). The NEC recommends one diode per 12-18 series cells. Bypass diodes are usually but not always supplied with modules. If the modules are all in parallel, such as a 12-volt battery charging system, bypass diodes are not needed. Bypass diodes do not require heat sinking unless they are expected to carry high current levels from parallel substrings.

Figure 7.5 shows the high power dissipation that occurs in a module that is forced to carry the current produced by three parallel substrings when no bypass diodes are available.

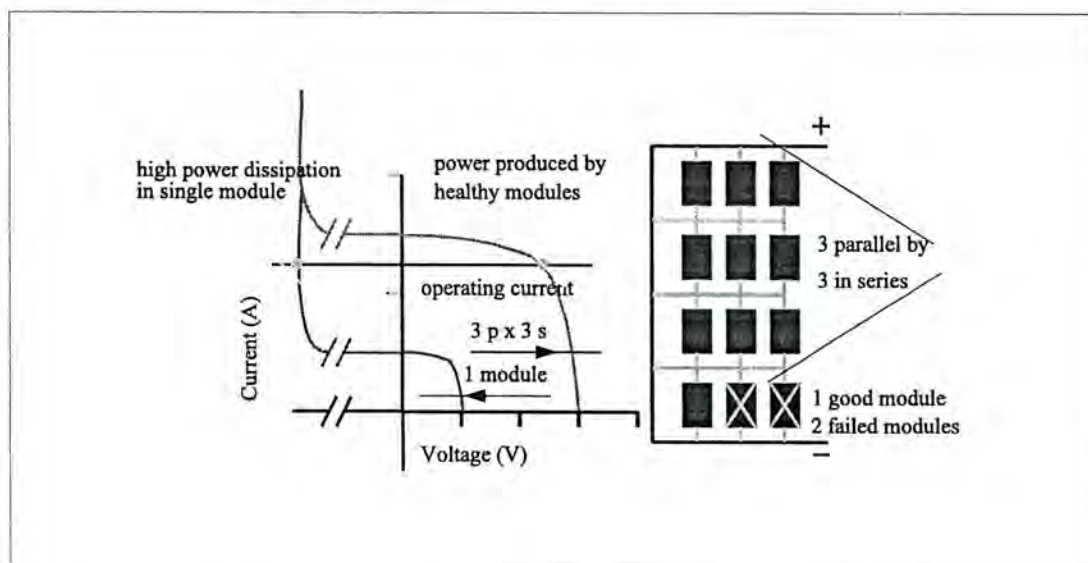


Figure 7.5 Power dissipation in array with failures and no bypass diodes

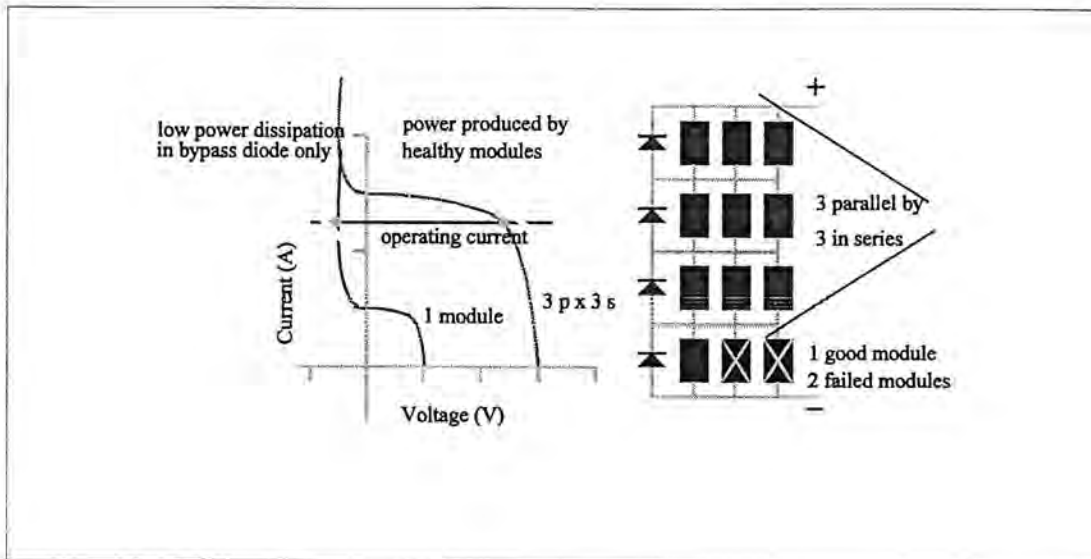


Figure 7.6 Power dissipation in array with failures and bypass diodes

7.8.2 Blocking Diodes

Blocking diodes prevent reverse current flow through the modules. For battery charging systems, a blocking diode may be used to prevent the reverse current flow from the battery to the array during the night. Some charge controllers have a feature that accomplishes the same thing, thereby eliminating the need for the blocking diode and improving the system efficiency. The voltage drop across the blocking diode is 0.4 to 0.7 volts (depending on diode type). This represents a 3 to 6 percent loss in energy for a 12-volt system. The energy loss is proportionately less for higher voltage systems.

For large systems with multiple strings, blocking diodes should be installed on the individual strings instead of using one for the whole array. If one of the strings develops a fault, this prevents the current flow from the other strings from entering the faulted string and damaging the modules.

Because they are normally in operation, blocking diodes require appropriate heat-sinking. The current rating and voltage tolerance of blocking diodes should be:

Current rating: $1.5 \times \text{rated } I_{sc}$

Voltage tolerance: $1.5 \times \text{rated } V_{oc}$

7.9 Lightning Protection

Lightning protection can be provided by one or more of three basic methods: direct strike interception, proper equipment grounding, and terminal protection (surge arrestors). Direct strike interception (i.e., the use of lightning rods) is not generally warranted for lightning protection of a photovoltaic system due to high cost.

7.9.1 Equipment Grounding

Equipment grounding refers to providing ground wire connection between the non-current-carrying metal parts (support structure, junction boxes, equipment, appliances, etc). Grounding one of the conductors will also help to shunt current surges away from the system components. Refer to Section 7.7 for more information on grounding.

7.9.2 Surge Arrestors

Surge arrestors are a means of protecting equipment, conductors, and the structure which contains them from the high-energy voltage surges that can arise in power lines or other conductors due to a nearby lightning strike. Surge arrestors will not provide protection from a direct strike.

An important characteristic of the surge arrestor is that it acts as an open-circuit (high impedance) device until the voltage across it rises above its rated threshold breakdown voltage. At this voltage the surge arrestor provides a low impedance path to ground for the dissipation of the surge energy.

Surge arrestors have three ratings: breakdown voltage, current, and the maximum energy they can dissipate. For a photovoltaic installation, the breakdown voltage should be greater than the maximum expected open-circuit voltage of the array, so that the device will activate only in the event of an extreme voltage surge. The higher the surge arrestor's current rating, the larger the surge it can handle. A typical device also contains a rating for the maximum energy in joules which it can dissipate. The higher this rating, the more protection the surge arrestor will provide for the circuits it protects. Surge arrestors are located on both positive and negative leads of each string. Surge arrestors should be placed on the array side of the blocking diodes and other BOS components (an important point that is often overlooked), and at the input and output of the inverter, if applicable. Additional guidelines for the installation and connection of surge arrestors is contained in the NEC article 280.

7.10 Instrumentation

7.10.1 Test Points

Properly located test points allow for easy measurement of the PV system operating parameters, and easy diagnostics of system performance. Test points that enable the measurement of the PV array output (i.e., current and voltage) and the battery voltage and current should be included in the system design. For some systems, a less complicated approach may be warranted. A simple digital voltmeter can be used to measure voltages at any point in the electrical circuit, as well as voltage drops across current shunts. If no current shunts are installed, a dc/ac hall-effect current gun can be clamped around the wire to measure the current in a circuit.

7.10.2 Data Acquisition Systems

For more detailed information than that derived from instantaneous measurements at test points, some type of data collection and storage system may be included in larger PV systems. Overall efficiencies as well as the voltage and current operating profiles of the PV array, battery and load can be closely monitored by measuring system operating parameters over time. Other variables that may be measured include insolation and the temperatures of the array and battery. Some battery and system controllers manufactured for PV systems may have the ability to store selected operating data, however most designs will require an auxiliary data acquisition system. Integration of the measurement points within the electrical system is important when using a data acquisition system. This not only helps avoid interruptions in performance, but also prevents grounding loops which may lead to measurement errors and safety problems. Because data acquisition systems are often the least reliable part of the system, data needs should be well defined before selecting the simplest and lowest cost system that meets those needs.

7.10.3 Other Monitoring

Other types of instrumentation and monitoring may be required in the electrical design of PV systems to measure energy flows and to facilitate routine performance checks. In utility-interactive systems, two induction watt-hour meters are usually required by the utility to record energy flows to and from the utility grid. A third watt-hour meter is recommended to measure photovoltaic system ac energy at the power conditioner output. This extra meter not only measures photovoltaic system output, but also calculates the electrical loads. Ampere-hour meters are often used to record the dc energy flow from the PV array and into or out of the battery and (perhaps) to the loads. If one ampere-hour meter is used, the suggested location would be on the battery source-circuit to measure net battery ampere-hours.

References

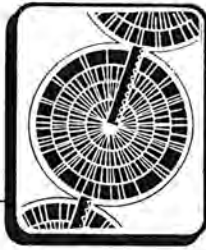
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National Electrical Code -1993, Quincy, MA: National Fire Protection Association, 1989.

Exercises

1. List the six article numbers and names in the National Electric Code (NEC) that apply to photovoltaic systems.
2. List at least three problems to be avoided with wiring terminations.
3. What are the two common conductor materials used in wiring? Which material is recommended?
4. In selecting wiring, list three items that should be specified for the wire insulation.
5. For photovoltaic systems, selecting the conductor size is based on two considerations. What are they? Which one of these two is not as important of a concern for utility-supplied 120-volt alternating current systems?
6. List two devices used for overcurrent protection.
7. List two disconnect devices used for isolating major components of the photovoltaic system.
8. What is the primary reason for electrical grounding? Explain the difference between a grounded conductor and a grounding conductor. For a low voltage PV system (i.e., less than 50 volts), is a grounded conductor required?
9. List the two types of protection diodes and explain the purpose of each.
10. List three ways to protect against lightning strikes.
11. If the instrumentation for your photovoltaic system is limited to measuring only two quantities, which two would you select?
12. Sketch an electrical wiring diagram for Example 1 in Section 6, showing the relative locations of all electrical components. (Note: It is not necessary to draw each of the array strings; just show two or three as representative.)



Mechanical Design and Building Integration

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Mechanical Design and Building Integration

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Objectives

- 1) *Compare the relative magnitudes of the following structural loads: dead loads, live loads, wind loads, and snow loads*
- 2) *Identify the advantages and disadvantages of standoff mounting, rack mounting, direct mounting and integral mounting.*
- 3) *For a given application, compute the design wind load for a PV array.*
- 4) *For a given application, produce a mechanical design that avoids shading, is structurally sound, meets prescribed building codes, minimizes material degradation, and is aesthetically appropriate for the site.*

Key Words

*Structural loads
Irradiance enhancement
Mounting configurations
Standoff mount
Rack mount*

*Integral mount
Direct mount
Weather sealing
Safety
Aesthetics*

8.1 Design Guidelines

The mechanical design of a photovoltaic array addresses three areas: the strength requirements, the material requirements, and the array mounting system design.

8.2 Strength Requirements

The photovoltaic array support structure must meet the local building codes. If the array is mounted on the roof of the building, the roof strength must also meet the local building codes for the additional load imposed by the photovoltaic array. Loads are of the following types: dead loads, live loads, snow loads, and wind loads.

8.2.1 Structural Loads. Dead loads act downward and consist of the weight of the photovoltaic modules and the mounting hardware (approximately 5 pounds per square foot).

Live loads are the loads experienced during maintenance type activities. Generally these loads are small (3 psf) when compared with the wind loads (24 to 55 psf), and they may be ignored if it is assumed that maintenance activities will not be performed when it is extremely windy.

Snow loads can also increase the structural requirements. This is particularly evident in mountainous regions of the country with high annual snowfalls. Mounting the array further off the ground and at steeper tilt angles helps to minimize snow accumulations.

Wind loads are typically the highest of the load types. The array support structure should be designed to withstand the wind loads in combination with the dead loads, and snow loads if applicable.

8.2.2 Design Wind Load. Wind loads are region specific and the local building code is the authority on the design wind speed used. Typically, figures such as figure 8.1 are included in the building code manuals for determining the design wind speed. With the design wind speed selected, a design wind load that acts normal to the array surface is calculated using the method outlined by the local building code.

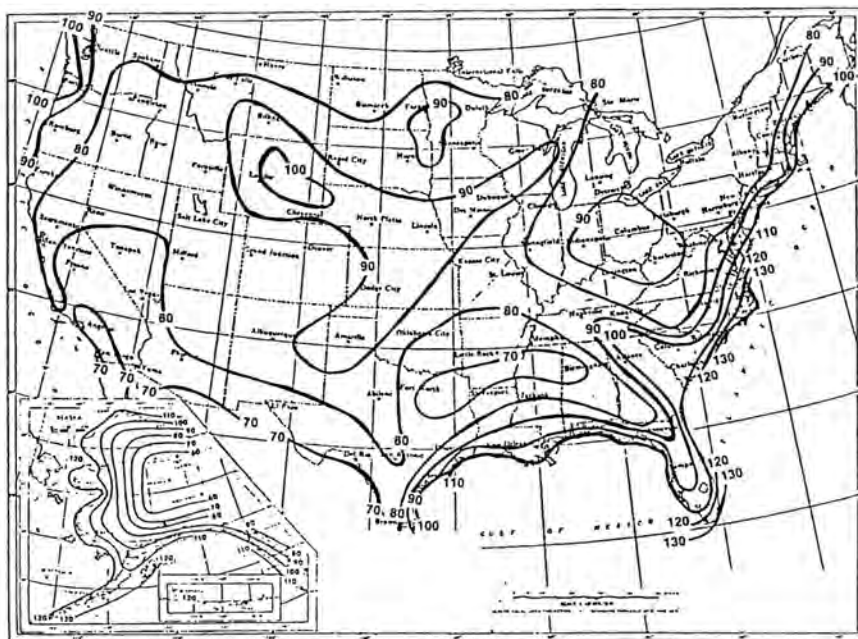


Figure 8.1 Design wind speeds in miles per hour

This method may be of the form:

$$\text{Design Wind Load (psf)} = \text{Velocity Pressure} \times \text{Force Coefficient} \times \text{Use Factor}$$

Where,

- The **velocity pressure** is a function of the design wind speed and the height of the array above the ground. A higher pressure is used for an increased wind speed or array height.
- The **force coefficient** depends on the tilt of the array or roof. Wind forces are minimized for an array tilt angle of about 20 degrees from the horizontal, and they become a maximum for an array tilt angle of 90 degrees (vertical). Large wind forces also occur for array tilt angles of from 10 to 15 degrees. The array acts as an efficient airfoil for these angles.
- The **use factor** depends on the consequence of a failure. A higher factor is used if the damage would be extensive, or if personnel injury would result.

8.3 Material Requirements

Materials used must be of adequate strength and must not be adversely affected by their environment.

8.3.1 Mounting Hardware Strength. Mounting hardware must support all loads and should maintain their strength over the array lifetime. Note that corrosion degrades the strength of the mounting hardware over time. Note also that the wind loading requirements for the array (including the mounting hardware) vary with location and code jurisdiction.

8.3.2 Environmental Compatibility. In designing a photovoltaic system it is important that all exposed materials, such as module frames, junction boxes, terminations, wiring, mounting hardware (including beams, brackets, nuts, bolts, etc.) and sealants, be selected so as to be compatible with expected temperature, humidity, wind, rain and salt environments at the site. In particular, it is important to avoid the use of dissimilar metals and to select the proper type and size of wiring. It is especially important that exposed wiring be properly protected from ultraviolet radiation, moisture and salt. Aluminum hardware should not be in direct contact with concrete because the lye in the concrete will corrode the aluminum.

8.3.3 Recommended Hardware. The following hardware has proven itself for use in photovoltaic systems.

- Structural Members – Hot-dip galvanized steel per the specifications of ASTM A123 or ASTM A527. Corrosion resistant aluminum, type 6061 and 6063.
- Fasteners – Stainless steel, cadmium or zinc plated, or hot-dip galvanized steel per ASTM A123. Avoid the use of poor quality fasteners that will corrode and make maintenance activities difficult, or that might result in a structural failure.
- Weather Sealants – Sunlight and weather resistant, long life.

8.4 Array Mounting System Design

Objectives when designing an array mounting configuration include:

- Minimizing installation costs
- Providing ready accessibility

- Maximizing array performance
- Providing sufficient strength, environmental compatibility, and weather tightness
- Eliminating safety hazards
- Designing the array mounting so it is aesthetically pleasing.

8.4.1 Installation Considerations. Developing an installation plan and implementing the following suggestions can minimize array installation costs.

- Use preassembled and prewired panels to reduce on site labor.
- Use a minimum number of attachment points and roof penetrations.
- Carefully select locations of nuts, bolts, screws, etc.
- Use captive fasteners as appropriate.
- Limit the number of workers required and the need for special tools and equipment.

8.4.2 Accessibility Needs. There are several times during which array accessibility is needed: installation, maintenance, repair and replacement. By providing adequate accessibility, labor costs can usually be reduced and safety enhanced.

8.4.3 Maximizing Array Performance. To maximize array performance, potential shading problems should be eliminated in the site selection process. The array operating temperatures should be kept as low as possible to maximize the array output and system life using simple, passive techniques. Irradiance enhancement from tracking the sun may also be considered when designing an array mounting configuration.

8.4.3.1 Shading Considerations. Even slight shading can significantly affect array performance. Keeping the array active area clean and entirely free of shading from structures and vegetation throughout the year will help maximize power output. When specifying the array mounting configuration and location, determine the sun paths for the site in order to identify potential shading of the array during the different seasons of the year. For the maximum energy production, shading should not be permitted on any part of the array between one and one half hours after sunrise and one and one half hours before sunset. If some shading cannot be avoided, consider alternative array layouts and wiring strategies.

8.4.3.2 Array Cooling. Array cooling improves efficiency, increases reliability and extends the lifetime of the array. JPL found that by cooling an array 10°C, the lifetime of the modules doubled. When designing the array mounting configuration, use passive techniques to promote cooling airflow over the back surface of the array. Table 8.1 compares how different module mounting configurations affect operating temperatures. The installed normal operating cell temperatures (INOCT) are temperatures to be expected in service for a given mounting configuration and the manufacturer's stated normal operating cell temperature (NOCT). INOCT is lowest for rack mounted panels because both sides of the panel have unrestricted airflow. Direct mounted panels have only one side of the panel exposed to the ambient air; consequently, INOCT is the highest for this configuration.

Table 8.1 Installed normal operating cell temperature

Rack Mount	INOCT = NOCT - 3°C								
Direct Mount	INOCT = NOCT + 18°C								
Standoff and Integral Mount	INOCT = NOCT + X <table> <tr> <th>W (inches)</th><th>X (°C)</th></tr> <tr> <td>1</td><td>11</td></tr> <tr> <td>3</td><td>2</td></tr> <tr> <td>6</td><td>-1</td></tr> </table> Where W is the standoff, entrance, or exit height or width, whichever is less. Add 4°C if channeled.	W (inches)	X (°C)	1	11	3	2	6	-1
W (inches)	X (°C)								
1	11								
3	2								
6	-1								

Source: SAND85-0330

8.4.3.3 Irradiance Enhancement. Irradiance can be enhanced by optimizing the array orientation and tilt, sun tracking in various modes, and concentrating. For roof-mounted arrays and ground-mounted arrays with a fixed tilt, the array should face within twenty degrees of south to capture the maximum amount of insolation. For optimum annual performance, tilt the array at an angle from the horizontal equal to the site latitude. A tilt angle of site latitude plus 15 degrees will optimize winter performance, while a tilt angle of site latitude minus 15 degrees will optimize summer performance. Sun tracking and concentrating do not generally apply to roof-mounted arrays.

8.4.4 Roof-Mounted Arrays. There are four generic roof mounting schemes: standoff, rack, integral and direct. All array mounting designs should provide for ready access in case maintenance or repair is required.

8.4.4.1 Standoff Mounting. Standoff arrays are mounted above and parallel to the roof surface as illustrated in figure 8.2.

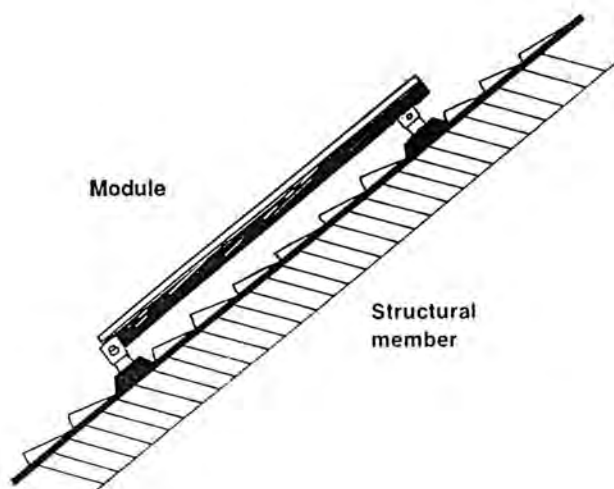


Figure 8.2 Standoff mount

Standoff mounts work well in both new and retrofit applications for buildings with sloping roofs. When installing a standoff mounted array, affix panels or subarrays to the roof using point connections (usually at corners of the panels or subarrays). Keep the number of point connections and roof penetrations to a minimum. Maintain at least three inches between the roof and the bottom of the module frame.

Lag screws that penetrate the roof rafters three to four inches may be used to fasten the standoffs to the roof. Because the rafter spacing may be different than the required standoff spacing (due to module and panel sizes), two other recommended methods are shown in figure 8.3.

To reduce corrosion, avoid to the extent possible the use of dissimilar materials in the framing, mounting and grounding materials. Electrically ground the module frames and mounting hardware.

Hinged subarrays provide easy access for maintenance and repair. Because the primary mechanism of standoff array cooling is convection from the front and back module surfaces, design module frames and mounting hardware to enhance airflow under the array.

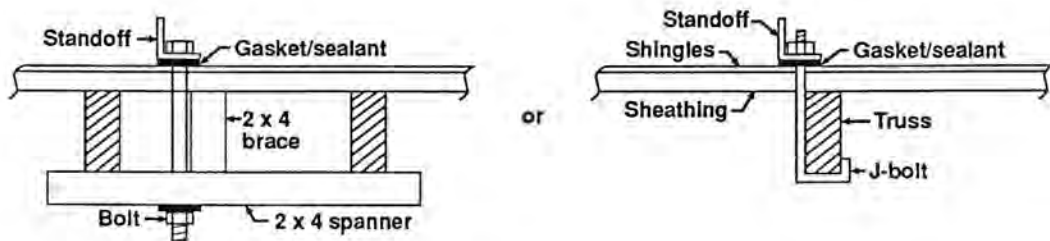


Figure 8.3 Securing standoffs to the roof

Design considerations for standoff mounting are:

- Designs that allow for both lateral and vertical airflow can be expected to lower operating temperatures.
- Designs that induce pressure differences between air inlet and exit regions can be expected to lower operating temperatures due to increased airflow.
- Arrays with a higher ratio of lateral to vertical dimension may operate at lower temperatures than those with lower aspect ratios.
- Standoff mounts can significantly reduce heat gain in attics.

8.4.4.2 Rack Mounting. Rack mounted arrays are above and tilted at a non-zero angle to the roof, as illustrated in figure 8.4. Rack mounts are recommended for flat roofs and roofs with a slope of 2 in 12 or less. Rack mounts are usually subjected to higher structural loads, incur higher costs for mounting hardware, and are less attractive than standoff mounts. However, for the same array area, the total energy output is often somewhat higher because of optimized orientation and lower average operating temperatures.

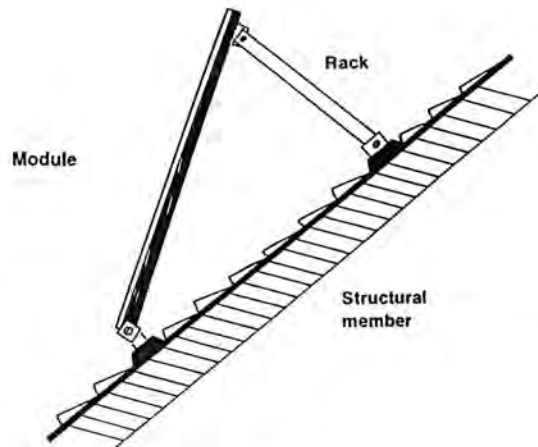


Figure 8.4 Rack mount

The mounting structure is usually attached to the roof substructure using point connections. To reduce corrosion, avoid to the extent possible the use of dissimilar metals in the framing, mounting and grounding materials when installing a rack mounted array.

Rack arrays typically run relatively cool compared to other mounts and they can reduce heat gain through roofs. Because the primary mechanism of rack array cooling is convection from the front and back of the module surfaces, cooling can possibly be enhanced by locating the rack to take advantage of natural air channels and reducing obstructions to air flow, such as screens, grates, and walls.

8.4.4.3 Integral Mounting. For integral arrays, the array replaces conventional roofing material as illustrated in figure 8.5. Integral mounting often increases the array installation labor costs and it is difficult to weatherseal. Only experienced installers should consider this method.

Because integral mounted arrays replace conventional roofing material they become a significant architectural feature of a building and can be aesthetically very pleasing. It is recommended that only thoroughly tested and proven designs be used because of possible serious water leakage.

Modules in integral mounts are often individually framed in a structural support, usually on all four sides. For a given total array area, the larger the size of the individual modules used, the smaller the total linear dimension of framing required. Structural framing of the modules should be designed to allow for thermal expansion and contraction of array materials.

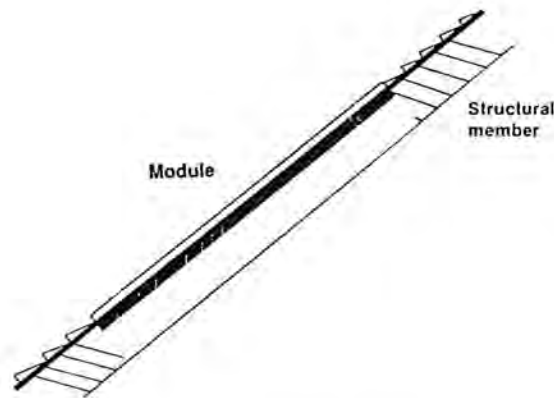


Figure 8.5 Integral mount

Dimensional tolerances must be carefully considered and are typically much tighter than for standoff or rack mounts. If commercial curtain-wall glazing techniques are used, larger modules are preferable to smaller modules.

Lack of PV array accessibility can be a major problem for buildings with beamed-cathedral ceilings, whereas integral arrays mounted over conventional attics usually provide ready access to the back side of the modules for maintenance and repair.

Arrays with a higher ratio of lateral-to-vertical dimension may operate at lower temperatures than those with lower aspect ratios. Module structures that inhibit airflow can be expected to produce higher operating temperatures. Therefore, only designs that offer minimal restriction to airflow should be used. Operating temperatures of modules over beamed-cathedral ceilings depends heavily on sufficient airflow over the back surface of the array. Integral mounts may be expected to increase the heat gain through roofs.

Array cooling inlet flow is affected by overhang, soffit and upper wall design. Module framing structures, air inlets and exits, and attic/ceiling configurations should be designed to enhance air flow along the back surface of the modules. Active cooling of the arrays is not recommended.

8.4.4.4 Direct Mounting. In direct mounting, the array is affixed directly to the roofing material, with little airspace between the module and roof. Figure 8.6 illustrates a direct mounted array.

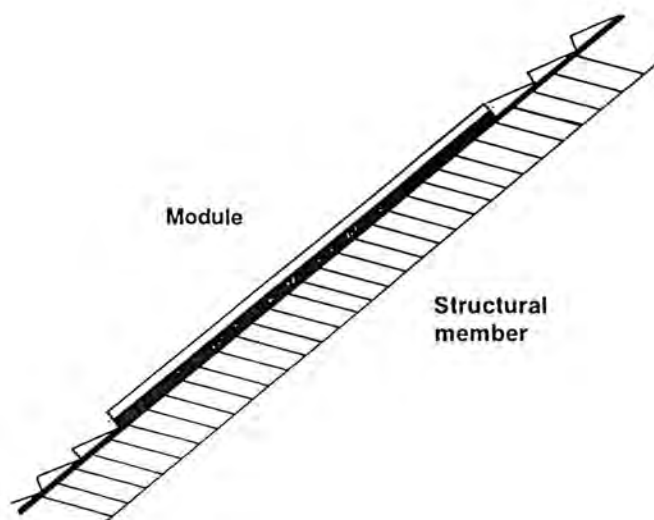


Figure 8.6 Direct mount

Experimental results with direct mounts to date have been discouraging. Array operating temperatures have been much higher than for other mounting techniques, resulting in poorer performance and severe degradation of the modules. The use of direct mounting may prove desirable for new thin film modules that are not as sensitive to operating temperature, but it is not recommended for conventional crystalline silicon modules.

8.4.5 Ground-Mounted Arrays. Ground-mounted arrays are supported by racks, poles, or tracking stands. These arrays must be strongly secured to the ground to resist uplifting caused by wind loads. All ground mounted arrays run relatively cool because good airflow is possible over both the front and back surfaces of the modules. This cooling can be enhanced by minimizing obstructions to air flow such as shrubbery and fences.

8.4.5.1 Rack Mounting. Rack mounting is commonly used for mounting arrays on the ground. It uses simple structural hardware, such as angles and channels, and it is adaptable for both small and large PV arrays. Most PV module manufacturers and PV equipment suppliers offer hardware for rack mounting PV arrays on the ground. Figure 8.7 is an example of a low cost rack-mounted array design developed by Battelle Columbus Laboratories.

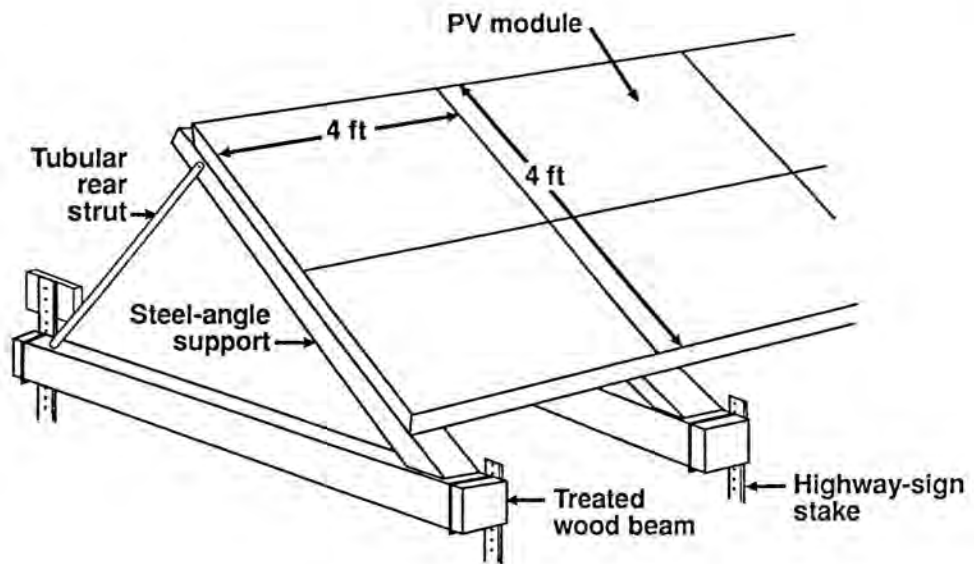


Figure 8.7 Battelle Columbus Laboratories design

8.4.5.2 Pole Mounting. If the array is only a few modules, it can be mounted on a pole as shown in figure 8.8. Depending on the number of modules and their height above the ground, the pole may need to be set in concrete to resist the overturning moment during windy conditions. Among others, outdoor lighting is a good application for pole-mounted arrays.



Figure 8.8 Pole mount

8.4.5.3 Tracker Stand Mounting. Because tracking arrays have the ability to receive more sunlight over the day than stationary arrays, their modules produce more energy. The value of a tracking array depends on whether the additional energy produced offsets its added cost and complexity. There are two types of trackers: active and passive. Active trackers use electric motors and gear drives to direct the array at the sun, and they may track in either one or two axes. The tracking direction is determined by a computer calculating the sun's position, or with sun-seeking sensors.

Passive trackers normally track in only one axis and they use a fluid such as freon that vaporizes and expands when it is heated by the sun. The expanding fluid causes the tracker to pivot towards the sun as the weight of the freon shifts from one side of the tracker to the other. An alternative design uses the freon to operate a hydraulic cylinder and linkage arrangement. The control of the tracker direction for both designs uses sun shades to regulate the heating of the freon by the sun. A passive tracker is shown in figure 8.9. Compared to a fixed tilt array, these trackers show the greatest energy enhancement in the summer when the days are long. Trackers are less beneficial in the winter when the days are shorter. Typical applications are water pumping where the water demand is higher in the summer than in the winter.

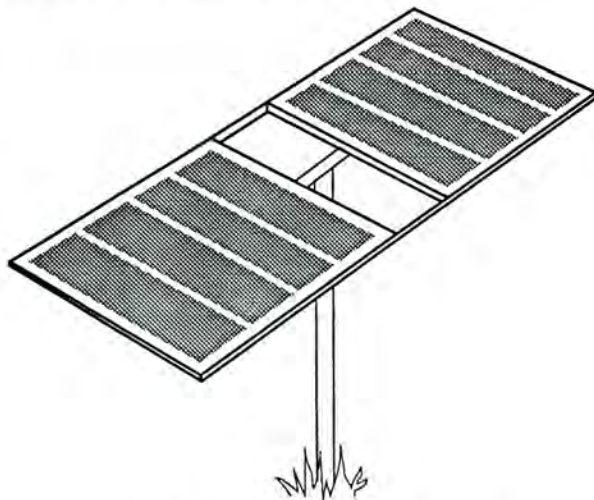


Figure 8.9 Passive tracker

8.4.6 Weathersealing. There are two types of weathersealing: dry and wet. Dry sealing consists of using flashing, hoods, boots, etc. Wet sealants include caulk, roofing cement, tar, etc.

When choosing a sealant, look at the effect of temperature and ultraviolet radiation on the sealant. Other considerations include:

- The number of attachments/penetrations
- Corrosion protection and materials compatibility (avoid the use of dissimilar materials)
- Sealant lifetime and costs.

8.4.7 Safety Considerations. Safety should be considered during installation, maintenance, repair and replacement. Included are fire safety, wiring type, placement and protection, grounding and weather.

Fire safety ratings for roof-mounted arrays are presented in UL Standard 790: Tests for Fire Resistance of Roof Covering Materials. This standard defines three classes of fire safety:

- Class A: Effective against severe fire exposure.
- Class B: Effective against moderate fire exposure.
- Class C: Effective against light fire exposure.

Two tests are used to determine the fire safety classifications: a) spread of flame and b) burning brand. Some modules have received a Class C fire rating.

8.4.8 Aesthetics. It is important that arrays on buildings be aesthetically pleasing by designing them to blend into the building lines and colors. Specifically, the following recommendations are offered:

- Mount the array parallel to the roof if appropriate.
- Use roof dimensions to establish the array aspect ratio.
- Avoid harsh contrasts and patterns.
- Make mounting hardware as inconspicuous as possible.
- Most important, avoid shading even if appearance suffers.

An attractively designed array will be more desirable to prospective buyers (should the house be sold) than an unattractive but functional array.

References:

Venre, Gerard G., *"Photovoltaic System and Building Integration: Design Considerations,"* Fundamentals and Applications of Photovoltaics, Cape Canaveral, FL: Florida Solar Energy Center, 1983, pp. 9-1 through 9-8.

Exercises

1. Of the various types of mechanical forces that act on the photovoltaic array, which one is generally of most concern? Explain.
2. In selecting structural members and materials to support the photovoltaic array, what are the two most important requirements?
3. List five goals in designing the array mounting system.
4. For a fixed-orientation array to be mounted on a south-facing roof, discuss the advantages and disadvantages of each of the four roof-mounting configurations.



Maintenance and Troubleshooting

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Maintenance and Troubleshooting

9

Objectives

- 1) *List the required safety precautions used during system inspection.*
- 2) *List required maintenance and troubleshooting tools and materials.*
- 3) *Describe design features of the PV system instrumentation that facilitate ease of diagnostics and troubleshooting.*

Key Words

*Safety
Inspection
Maintenance*

*Troubleshooting
Tools
Materials*

9.1 Safety

During both maintenance inspections and troubleshooting work, a proper knowledge of safety factors and potential hazards can not be overemphasized. Service personnel should familiarize themselves with the hazards and safety precautions listed below.

9.1.1 Current and Voltage Safety.

- Realize that photovoltaic systems produce current in sufficient amounts to cause bodily injury.
- Check all safety disconnects for proper operation.
- Insure that all metal parts are grounded.
- Cover the modules when working on them during the day (or work on them at night).

9.1.2 Battery Safety.

- Special care must be used when working with and around batteries. When charging, lead acid batteries give off hydrogen gasses which can be highly explosive. Smoking and spark producing activities must be avoided when working around these batteries.
- Extra precaution must be taken when disconnecting wiring from batteries when batteries are charging as this can create sparks and lead to explosions.
- Neutralize lead acid battery acid that gets on the skin with a mixture of baking soda and water.
- Neutralize Ni Cad battery acid that gets on the skin with boric acid or vinegar.
- Insure that a portable eye wash kit is on hand in the event acid is splashed into the eyes. Flush eyes for ten minutes and contact a physician immediately.
- Use eye protection and rubber gloves when working around batteries.
- “Low voltage” batteries can still produce enough short circuit current to cause physical harm.

9.1.3 Tools.

- Use tools which have insulation or tape on the handles or shanks to prevent potential short circuits and electric shocks.
- Insure that brushes used to clean batteries are not spark producing.

9.2 Maintenance

All photovoltaic systems must be inspected and maintained on a regular basis. This preventive maintenance will insure that systems are operating effectively and will in many cases also prevent future problems from occurring.

Maintenance inspections of photovoltaic systems require a minimal amount of time and are quite simple once inspection methodologies and maintenance records are developed. Several of the maintenance inspection procedures can be carried out by the system owner. Nevertheless, the majority of inspection procedures should only be conducted by trained technicians who are familiar with both photovoltaic systems, subsystem components and proper safety procedures. A well maintained system is the best insurance against future problems.

9.2.1 Maintenance Inspection Procedures. Maintenance inspections of a photovoltaic system involve the examination of several subsystem categories. Each should be inspected in an orderly manner. Since some photovoltaic systems operate at high voltages and currents, proper safety procedures must be adhered to. The use of appropriate tools and materials is required for a successful inspection.

9.2.1.1 General Guidelines.

- Inspect system twice per year (Spring and Fall).
- Develop and maintain inspection forms and records.

9.2.1.2 Wiring and Safety Equipment.

- Check all safety disconnects for proper operation.
- Assure that disconnect switches are open during operations that involve wiring.
- Examine wiring connections for corrosion and looseness.
- Inspect wire insulation for degradation.

- Measure voltage drop along wires during normal operation and record current.
- Insure that all metal equipment cases and frames in the system are well grounded (all the way to the grounding object).
- Check the operation of all LEDs, meters, and instrumentation.
- Inspect circuit breakers and fuses.
- Inspect conduit connections for damage and water.

9.2.1.3 Array.

- Conduct a visual check of all modules for delamination, discoloration, cracked or broken cells, excessive dirt or bird droppings.
- Check for shadows and shading in early morning and late afternoon.
- Inspect for excessive vegetation growth around array.
- Insure that modules are well attached to the frame.
- Inspect array frame for corrosion.
- Inspect array frame bolts for tightness and corrosion.
- Inspect wiring connections for corrosion and looseness.
- Inspect junction box seals.
- Inspect junction box for cracks and moisture.
- Examine ventilation paths under modules.
- Make seasonal tilt adjustments as required.

9.2.1.4 Array – Electrical.

- Measure short-circuit current of individual modules.
- Measure open-circuit voltage of individual modules.
- Measure short-circuit current and open-circuit voltage of entire array and array strings.

- For array modules connected in series, shade individual modules to determine the operation of the by-pass diodes.
- For larger systems, shade modules or groups of modules to determine if the operating current decreases a corresponding amount .

9.2.1.5 Batteries (General).

- Inspect battery terminals for corrosion and loose cables.
- Examine battery surface for electrolyte leakage.
- Inspect battery tie downs.
- Insure that batteries are not in direct contact with the floor.
- Check location and attachment of voltage regulator temperature compensation probe, if applicable.
- Inspect battery enclosure box.
- Check battery enclosure ventilation.
- Measure open-circuit battery voltage.
- If battery must remain connected, measure charge or discharge current.

9.2.1.6 Unsealed Batteries.

- Check electrolyte levels.
- Measure specific gravity of cells after full charge.
- Determine state-of-charge.

9.2.1.7 Sealed Batteries.

- Measure open circuit voltage.

9.2.1.8 Electronic Equipment.

- Verify voltage set points of charge controller with regard to battery specifications and system requirements.

- Inspect connections for corrosion and loose wires.
- Listen for unusual noises from charge controller such as relay chatter, etc.
- Insure that charge controller is in a sheltered, clean and well ventilated environment.
- Inspect junction and component boxes for insects, corrosion, etc.

9.2.1.9 Electrical Loads.

- Check for proper operation.
- Ensure that loads are being used as designated.
- Perform any maintenance as required per manufacturers' specifications.

9.2.1.10 Inverters.

- Check inverter stand-by feature.
- Insure that inverter is in a well ventilated, dry, clean and safe environment.

9.3 Troubleshooting

Specific and methodological troubleshooting procedures are required for the accurate determination of photovoltaic system problems and quirky malfunctions. Often, these problems will be discovered during the scheduled maintenance inspections. In the majority of cases, load failure or improper operation will initiate troubleshooting investigations. A thorough operational knowledge of the specific system and the availability of its various components manufacturers' specifications is required prior to attempting to determine the exact cause of system problems.

9.3.1 Troubleshooting Checklists. When the symptoms have been identified, the following checklists can be used to determine the probable causes and the appropriate corrective actions. During the system evaluation, the complete system should be checked to identify any other situations that might lead to future problems.

The checklists listed below were developed by Architectural Energy Corporation, Boulder, CO, for the Naval Facilities Engineering Command (NFECC) and are currently the most comprehensive and concise troubleshooting procedures available. Photovoltaic

systems are difficult to organize because no problem is more important than another. The NFEC checklists provide reference tables for both overall system and specific component problem troubleshooting.

9.3.2. System Troubleshooting.

<u>PROBLEM</u>	<u>REFER TO TABLE</u>
Battery voltage is low	9.1, 9.2, 9.3, 9.4, 9.6
Batteries will not accept a charge	9.1, 9.2, 9.4
Battery voltage is high	9.5, 9.6
Load does not operate at all	9.1, 9.2, 9.7
Load operates poorly	9.1, 9.2, 9.4, 9.6, 9.7
Array voltage is zero	9.1, 9.6, 9.8
Array voltage is low	9.1, 9.8

Table 9.1 Troubleshooting system wiring, switches and fuses

Symptom:	Cause:	Result:	Action:
Load does not operate at all	Switches in the system are turned off or are in the wrong position	Photovoltaic electricity cannot be supplied to loads or batteries	Put all switches in correct position
	System circuit breakers or fuses are blown		Reset circuit breaker or replace fuse*
Load operates poorly or not at all	There is a high voltage drop in the system. Check for undersized or too-long wiring, oversized loads, a ground fault, or a defective diode	Inadequate voltage to charge batteries or operate loads	Increase wire size, reduce load size, find and correct ground faults
	Wiring or connections are loose, broken, burned, or corroded		Repair or replace damaged wiring or connections
	Wiring or connections are short-circuited or have a ground fault		Repair short circuits or ground faults

* Determine why fuses or circuit breakers blew or tripped before replacing or resetting them.

Table 9.2 Troubleshooting loads

Symptom:	Cause:	Result:	Action:
Load does not operate at all	Load is too large for the system or inadequate sun	Shortened battery life, possible damage to loads	Reduce load size or increase array or battery size
	The load is turned off inadvertently. Check for load switches shut off, blown fuses or tripped breakers, tripped motor thermal breaker, or an unplugged line cord	Load does not operate	Repair or replace load* Reset switches
	The load is in poor condition. Check for short circuits in load, a broken load, or an open circuit in the load	Shortened battery life, possible further damage to loads	Repair or replace load. Check load manufacturer for service information
Load operates poorly or not at all	There is inadequate voltage at load. Check for undersized or too-long wiring, oversized loads, or a ground fault	Inadequate voltage to charge batteries or operate loads	Increase wire size, reduce load size, find and correct ground faults
	Wiring or connections are loose, broken, burned, or corroded		Repair or replace damaged wiring
	Small, "phantom" load keeps inverter idling, draining battery		Turn off phantom load or replace it with one not requiring photovoltaic power
	Wiring polarity is reversed	Loads operate backwards or not at all	Correct wiring polarity
* Determine why fuses or circuit breakers blew or tripped before replacing or resetting them.			

Table 9.3 Troubleshooting batteries with low voltage

Symptom:	Cause:	Result:	Action:
No apparent battery defect	Load too large, on too long, or inadequate sun	Battery is always at a low state of charge	Reduce load size or increase system size
	Batteries too cold	A higher voltage is required to reach full charge	Insulate battery enclosure, bury enclosure in ground, move to heated space, install controller with temperature compensation, or repair or replace probe
Low electrolyte level	Overcharging	Loss of battery capacity. See table 9.4 for further information	Add distilled water, unless batteries damaged beyond repair
Battery will not accept a charge	Damaged battery	See table 9.4 for further information	
Voltage below charging resumption setting	Faulty charge controller	Excessive discharge depth. See Table 9.4 for further information	Adjust settings or repair or replace charge controller
Voltage below low voltage disconnect setting	Faulty charge controller	Excessive discharge depth. See table 9.4 for further information	Adjust settings or repair or replace charge controller
Voltage loss overnight even when no loads are on	Faulty blocking diode	Reverse current flow at night discharging batteries	Replace diode
Voltage increasing very slowly, even when no loads are on	Controller not in full charge, stuck in float charge	Inadequate current flow to fully charge batteries	Repair or replace charge controller
Voltage not increasing even when no loads are on and system is charging	Otherwise faulty charge controller	No power from array going into batteries	Repair or replace charge controller
	Switch, circuit breaker, or fuse open, tripped or blown	No power from array going into batteries	Close switch, reset circuit breaker*, or replace fuse*
	Loose, corroded, or broken wiring	Less power from array going into batteries	Repair or replace damaged wiring
	Shaded modules, broken cell, or misoriented modules	Array output reduced	Remove source of shading, replace module, or correct module orientation
Voltage just above charge resumption setting, but controller not charging batteries	Wiring too long or undersized	Voltage reduced	Increase wire size
	Faulty or mispositioned temperature probe or poor connection at "battery sense" terminals on charge controller	Charge controller thinks batteries are cooler than their actual temperature	Repair, replace or reposition probe
Inaccurate charge controller dial	Misadjusted charge controller		Reset controller dial or replace controller

* Determine why fuses or circuit breakers blew or tripped before replacing or resetting them.

Table 9.4 Troubleshooting batteries that will not accept a charge

Symptom:	Cause:	Result:	Action:
No apparent battery defect	Load too large, on too long, or inadequate sun	Battery is always at a low state of charge	Reduce size of load or increase size of system
High water loss	Overcharging	Heat damage to plates and separators	Replace battery, repair or replace charge controller
Electrolyte leakage shorts	Broken/leaking container	Sulfation, lead sulfate	Replace battery
Muddy electrolyte material, shorts between plates	Age	Shedding of plate	Replace battery
Discolored or odorous electrolyte	Contaminated electrolyte	Battery failure	Replace battery
No symptoms other than not accepting a charge*	Undercharging, usually without adding water	Sulfation, possibly lead sulfate shorts between plates	Replace battery
	Left uncharged too long	Sulfation, or plates hard when scratched	Replace battery
	Cracked partition between cells	Discharge between adjacent cells	Replace battery
	Hammering cable connections onto terminal posts	Shorts between terminal post strap and plates, electrolyte leak	Replace battery
	Misaligned plates and separators	Treeing shorts between bottoms of plates	Replace battery
	Plate material carried to top of plates	Mossing shorts between tops of plates	Replace battery
	Shorts between plates and straps	Grid top broken and moved upward to strap, lead rundown from strap to plate	Replace battery
	Overcharging a sulfated plate	Spalling (shedding of chunks of plate material)	Replace battery
	Overcharging	Disintegration of positive plates	Replace battery
	Specific gravity and temperature too high for too long	Soft negative plates	Replace battery
	Too many shallow charging cycles	Cracked negative plates	Replace battery
	Holes in separators	Loose fragment of grid, buckled plates, lumps or dendrites on plate, weak spot in separator, vibration	Replace battery

* Although the battery damage from these causes cannot be seen without taking apart the battery, they are listed here for the sake of completeness. Do not attempt to dismantle batteries!

Table 9.5 Troubleshooting batteries with high voltage

Symptom:	Cause:	Result:	Action:
Voltage over charge termination setting and/or high water loss	Faulty or nonexistent charge controller	Shortened battery life, possible damage to loads	Replace with charge controller with lower charge termination setting
	Battery storage too small for array	Shortened battery life, possible damage to loads and batteries	Install more batteries
	Misadjusted charge controller	Shortened battery life, possible damage to loads and batteries	Adjust charge controller
	Mismatched battery and voltage regulator	Shortened battery life, possible damage to loads and batteries	Replace charge controller, or change setting on adjustable units
	Batteries are cold and charge controller has temperature compensation	Shortened battery life, possible damage to loads	Insulate batteries, or move to warm environment
High water loss	Batteries are too hot	Voltage at which gassing starts is lower than normal	Insulate battery enclosure, and/or provide ventilation
	Infrequent maintenance	Low water levels, battery damage	Shorten maintenance interval
Voltage only slightly above charge termination setting	Faulty or mispositioned temperature probe or poor connection at "battery sense" terminals on charge controller	Charge controller thinks batteries are warmer than their actual temperature	Repair, replace, or reposition probe

Table 9.6 Troubleshooting charge controllers

Symptom:	Cause:	Result:	Action:
Battery voltage below charge resumption setting	Faulty charge resumption function in charge controller	Excessive battery discharge. See table 9.4 for further information	Repair, readjust, or replace charge controller
Battery voltage just below charge resumption setting, but controller not charging batteries	Faulty or mispositioned temperature probe or poor connection at "battery sense" terminals on charge controller	Charge controller thinks batteries are cooler than their actual temperature	Repair, replace, or reposition probe
Battery voltage below low voltage disconnect setting	Faulty low voltage cutoff in charge controller	Excessive battery discharge. See table 9.4 for further information	Repair or replace charge controller
Battery voltage loss overnight even when no loads are on	Faulty blocking diode, no diode, or faulty charge controller	Reverse current flow at night discharging batteries	Replace or add diode, or repair or replace series relay charge controller
	Old or faulty batteries	Batteries self-discharging	Replace batteries
Battery voltage not increasing even when no loads are on and system is charging	Otherwise faulty charge controller	No power from array going into batteries	Repair or replace charge controller
Battery voltage over charge termination setting and/or high water loss	Faulty or nonexistent charge controller	Shortened battery life, possible damage to loads and batteries	Repair or replace charge controller and possibly batteries
	Misadjusted charge controller	Shortened battery life, possible damage to loads and batteries	Repair or replace charge controller and possibly batteries
	Mismatched battery and voltage regulator	Shortened battery life, possible damage to loads and batteries	Change charge controller, or change setting on adjustable units
	Controller always in full charge, never in float charge	Shortened battery life, possible damage to loads	Repair or replace charge controller and possibly batteries
Battery voltage just above charge termination setting, but controller still charging batteries	Faulty or mispositioned temperature probe or poor connection at "battery sense" terminals on charge controller	Charge controller thinks batteries are warmer than their actual temperature	Repair, replace or reposition temperature probe or change charge controller
Buzzing relays	Too few batteries in series	Voltage is low	Reconfigure or add batteries
	Loose or corroded battery connections	High voltage drop	Repair or replace cables
	Low battery voltage	See table 9.3 for more information	Repair or replace batteries

(Table 9.6 continued on page 9-12)

Table 9.6 Troubleshooting charge controllers (continued)

Symptom:	Cause:	Result:	Action:
Erratic controller operation and/or loads being disconnected improperly	Timer not synchronized with actual time of day	Controller turns on and off at wrong times	Either wait until automatic reset next day, or disconnect array, wait 10 seconds, and reconnect array
	Electrical "noise" from inverter	Rapid on and off cycling	Connect inverter directly to batteries, put filters on load
	Low battery voltage	See table 9.3 for more information	Repair or replace batteries
Erratic controller operation and/or improper load disconnection	Faulty or mispositioned temperature probe or poor connection at "battery sense" terminals on charge controller	Charge controller thinks batteries are warmer or cooler than their actual temperature	Repair, reposition, or replace temperature probe or change charge controller
	High surge from load	Battery voltage drops during surge	Use larger wire to load, or add batteries in parallel
	Otherwise faulty charge controller, possibly from lightning damage	Loads disconnected improperly, other erratic operation	Repair or replace charge controller and check system grounding
	Adjustable low voltage disconnect set incorrectly	Loads disconnected improperly	Reset low voltage setting
	Load switch in wrong position on controller	Loads never disconnect	Reset switch to correct position
	Charge controller has no low voltage disconnect feature	Loads never disconnect	If necessary, replace charge controller with one with a low voltage disconnect feature
Fuse to array blows	Array short circuited with batteries still connected	Too much current through charge controller	Disconnect batteries when testing array's short circuit current
	Current output of array too high for charge controller	Too much current through charge controller	Replace charge controller with one with a higher rating
Fuse to load blows	Short circuit in load	Unlimited current	Repair short circuit or replace load
	Current draw of load too high for charge controller	Too much current through charge controller	Reduce load size or increase charge controller size
	Surge current draw of load too high for charge controller	Too much current through charge controller	Reduce load size or increase charge controller size
"Charging" at night	Normal operation for some charge controllers up to two hours after dark	No appreciable energy loss	Check the system later that night
	Timer not synchronized with actual time of day	Controller turns on and off at wrong times	Either wait until automatic reset next day, or disconnect array, wait 10 seconds, and reconnect

Table 9.7 Troubleshooting inverters

Symptom:	Cause:	Result:	Action:
No output from inverter	Switch, fuse, or circuit breaker open, blown, or tripped, or wiring broken or corroded	No power can move through inverter	Close switch, replace or reset fuse* or circuit breaker*, or repair wiring or connections
	Low voltage disconnect on inverter or charge controller open	No power available to inverter	Allow batteries to recharge
	Timer delay on inverter startup from idle	Few second delay after starting load	Wait a few seconds after starting loads
	High battery voltage disconnect on inverter open	Inverter does not start	Connect load to batteries and operate it long enough to bring down battery voltage. Adjust high voltage disconnect on charge controllers
Motors running hot	Square wave inverter used	Harmonics of waveform rejected as heat	Change to dc motors or use inverter with quasi-sine or sinusoidal waveform
Loads operating improperly	Excessive current draw by load	Voltage from inverter too low for load	Reduce size of loads or replace inverter with one of larger capacity
	Square wave inverter used		Change to dc motors or use inverter with quasi-sine or sinusoidal waveform
	Defective inverter		Replace inverter
Motors operating at wrong speeds	Inverter not equipped with frequency control	ac frequency varies with battery voltage	Replace inverter with one equipped with frequency control
Inverter circuit breaker trips	Load operating or surge current too high	Excessive current draw by load	Reduce size of loads or replace inverter with one of larger capacity
Inverter dc circuit breaker trips	Inverter capacitors not charged up on initial startup	Excessive current draw by inverter	Install momentary contact switch and 15 ohm, 50 watt resistor in parallel with the circuit breaker, use it for a few seconds to charge capacitors on first start up
* Determine why fuses or circuit breakers blew or tripped before replacing or resetting them.			

Table 9.8 Troubleshooting arrays

Symptom:	Cause:	Result:	Action:
No current from array	Switches, fuses, or circuit breakers open, blown or tripped, or wiring broken or corroded	No current can flow from array	Close switches, replace fuses*, reset circuit breakers*, repair or replace damaged wiring
Array current low	Some modules shaded		Remove source of shading
	Some array interconnections broken or corroded	Drop in output current	Repair interconnections
	Defective bypass or blocking diodes	Drop in output current	Replace defective diodes
	Some modules damaged or defective	Drop in output current	Replace affected modules
	Full sun not available	Drop in output current	Wait for sunny weather
	Modules dirty	Drop in output current	Wash modules
	Array tilt or orientation incorrect	Drop in output current	Correct tilt and/or orientation
No voltage from array	Switches, fuses, or circuit breakers open, blown or tripped, or wiring broken or corroded	No power can move from array	Close switches, replace fuses*, reset circuit breakers*, repair or replace damaged wiring
Array voltage low	Some modules in series with others disconnected or bypass diodes defective	Drop in array voltage	Repair or replace modules, connections, or diodes
	Wiring from array to balance of system undersized or too long	Drop in array voltage	Replace undersized wiring
* Determine why fuses or circuit breakers blew or tripped before replacing or resetting them.			

9.4 Maintenance Inspection and Troubleshooting Tools

In order to assure that maintenance inspections and troubleshooting procedures are conducted in a prompt and efficient manner service personnel should always have the necessary tools available at the work site. Listed below are the tools that should accompany service personnel to the work site:

- Ammeter (clamp-on)
- Battery terminal cleaner
- Battery terminal clamp remover
- Compass
- Cell water filler
- Cleaning brush (non-sparking)
- Caulking gun
- Container (for mixing solutions)
- Diagonal cutters
- Flashlight
- First aid kit
- Hacksaw
- Hydrometer
- Inclinator
- Insulation meter
- Light meter
- Linesman pliers
- Nutdriver set
- Needlenose pliers
- Paper/pencil
- Rubber gloves
- Safety goggles
- Soldering iron, portable
- Screwdriver set
- Shading material for array
- Solar site analyzer
- Stop watch
- Tape measurer
- Voltage test light
- Thermometer
- Tool pouch
- Utility knife
- Wire strippers
- Volt-Ohm meter

9.5 Maintenance Inspection and Troubleshooting Materials

Listed below are materials that should be on hand whenever a photovoltaic system is being inspected or serviced:

- Cable
- Compound, anti-oxidizing
- Conduit
- Connectors, conduit
- Connectors, crimp
- Fuses
- Grease, wire pulling
- Hardware, mounting
- Inspection checklist
- Log book
- Manufacturer's specifications (if predeterminable)
- Nails
- Nuts, wire
- Oil, standard for loads
- Rags
- Screws, assorted
- Sealant, silicone
- Service log
- Site map
- Soap
- Soda, baking
- Solder, electrical
- Tape, electrical
- Terminals, lug
- Ties, cable
- Water, distilled
- Wire

Reference:

Maintenance and Operation of Photovoltaic Systems, Naval Facilities Engineering Command, NAVFAC MO-405.1, September 1989.



Economic Analysis

10

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Economic Analysis

10

Objectives

Using life cycle cost analysis:

- 1) *Compute the present worth of a stand-alone PV system over the projected system life.*
- 2) *Compute the present worth of a stand-alone engine generator system over a given period.*
- 3) *Compute the present worth of a hybrid PV and engine generator system over a given period.*
- 4) *Compute the present worth of providing conventional electricity by extending the utility grid.*
- 5) *Compare the costs of a stand-alone PV system and three alternatives.*

Key Words

*Life cycle costing
Operating costs
Maintenance costs
Economic assumptions
System life
Inflation rate*

*Discount rate
Real discount rate
Fuel escalation rate
Present worth
Present value
Repair and replacement costs*

10.1 Determining System Cost Effectiveness

Section 6 demonstrates procedures for sizing a number of stand-alone electric generating systems. In order to determine which system type would be the most economic for a specific application, a comparison must be made. This section presents life cycle costing as a method for comparing these various alternatives.

The flow chart in figure 10.1 illustrates the procedure in which the life cycle cost of each alternative system is determined by adding the initial cost and operating costs together. To determine a preference the life cycle costs of the various systems are compared.

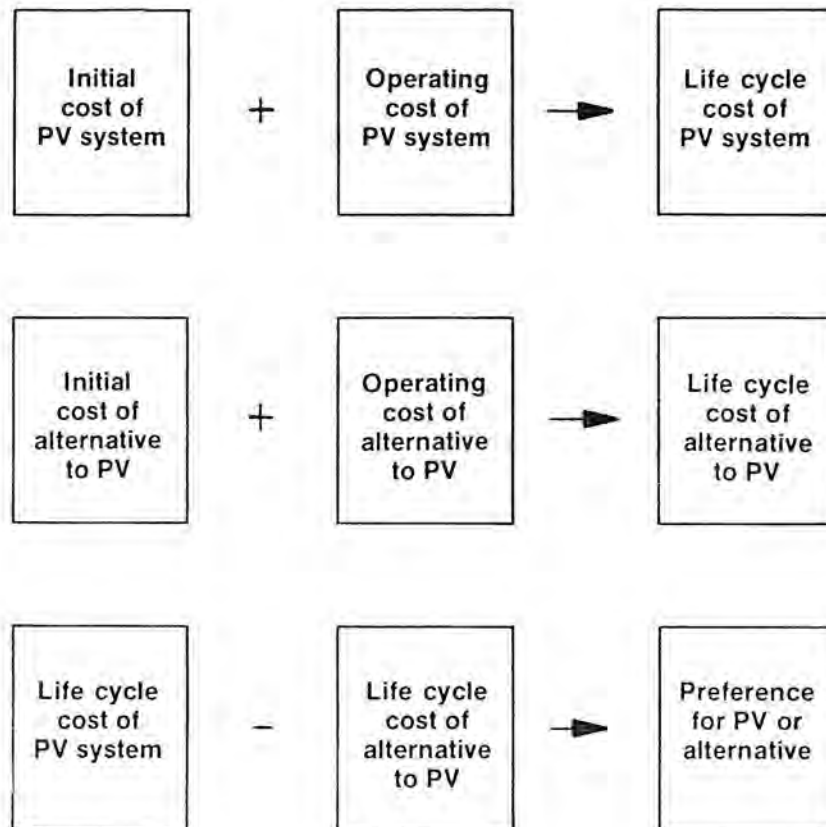


Figure 10.1 Determining photovoltaic system cost effectiveness

10.2 Life Cycle Costing

Life cycle costing is a method of economic evaluation which calculates the total cost of ownership over the life span of the system. Initial cost and all subsequent expected costs are included in this calculation.

The object of life cycle costing is to determine the alternative or combination of alternatives that either 1) provides the greatest expected effectiveness for a given expected cost or 2) provides a given expected effectiveness for the least expected cost.

The value of an electric generating system is time dependent and cannot be determined by examining initial cost. Operating and maintenance costs over the life of the system must also be factored into the decision process. It may be more economically feasible to pay a higher initial cost in order to obtain a lower ownership cost.

The cost analysis examples at the end of this section present completed life cycle costing worksheets for the stand-alone photovoltaic, stand-alone generator and hybrid photovoltaic-generator system examples from Section 6. Each of these alternative systems is sized for the same application.

10.3 Life Cycle Cost Evaluations

Using life cycle costing to distinguish between the effectiveness of various alternatives requires:

- 1) Determining the load of the system being evaluated
- 2) Defining the economic conditions for evaluation (including system life span)
- 3) Determining the present worth of the system (total cost of system including operating, maintenance and replacement costs)
- 4) Performing calculations for competing alternatives
- 5) Comparing the alternatives (present worth (\$) and present value (in \$/kW-hr)).

10.3.1 Determine Load. Complete the sizing procedure presented in Section 6 for the electric generating system being evaluated. This sizing procedure determines the system load.

Note that specific values from the sizing worksheets in Section 6 are used in the cost analysis worksheets in Section 10. For example, in the worksheet "Cost Analysis for Stand-Alone Photovoltaic Systems," (C13) in step F1 refers to (C13) from the Stand-Alone Photovoltaic System sizing worksheet in Section 6. In the worksheet "Cost Analysis for Stand-Alone Generator Systems," (C8) in step F1 and (C14) in step F5 refer to (C8) and (C14) from the Stand-Alone Generator sizing worksheet in Section 6.

10.3.2 Define Economic Assumptions for Evaluation. After determining the load, define the economic assumptions for the life cycle costing evaluation. Economic assumptions are held constant for all of the systems being compared. Economic assumptions include:

- Desired system life
- Inflation rate
- Discount rate
- Real discount rate
- Fuel escalation rate (some cases)
- Current fuel cost (some cases).

10.3.2.1 Desired System Life. The desired system life is the expected lifetime of the system being evaluated (in years).

10.3.2.2 Inflation Rate. The inflation rate is the rate of increase in the amount of money required to purchase the same goods over a period of time.

10.3.2.3 Discount Rate. The discount rate is a percentage used to reduce the value of future dollars in relation to present dollars.

10.3.2.4 Real Discount Rate. The real discount rate is the nominal discount rate minus the inflation rate.

10.3.2.5 Fuel Escalation Rate. The fuel escalation rate is a percentage used to compensate for future increases in the price of fuel.

10.3.2.6 Current Fuel Cost. The current fuel cost is the present price of fuel (including transportation).

10.3.3 Determine Present Worth of System. After the economic assumptions are defined, determine the present worth of each component in the system. The present worth method of analysis compares all expenditures, regardless of when they occur, during a common year. This common year is called the baseline year.

To compare all expenditures during the baseline year all future expenditures are discounted to reflect their time value. Once this discounting is accomplished, all expenditures are weighed on a common basis.

Repair and replacement costs for restoring the entire system to its original performance or condition must be considered when determining the total present worth of the system. For example, if the desired system life of a photovoltaic system is 20 years but the batteries in the system only have a life expectancy of 14 years, the batteries will have to be replaced during the lifetime of the photovoltaic system. These replacement batteries cost money and therefore increase the cost and value of the entire system. The same is true for inverters, battery chargers and generators. The cost of each component adds to the present worth of the system and increases the value of energy in \$/kW-hour.

The total present worth of the system is determined by adding the initial cost of the system to the present worths of all replacements that must be made during the system's lifetime and any operating costs (such as fuel).

10.3.4 Perform Calculations. Complete life cycle cost evaluations for every alternative system being compared.

10.3.5 Compare Alternatives. After completing the life cycle cost analysis for each system, distinguish between the effectiveness of the various stand-alone electric generating systems by comparing the present worth of the system and the present value of energy for each system with the other alternatives.

Table 10.1 compares the results of the previous life cycle costing examples. Each system is compared in terms of present worth, present value (the present value of electricity per kW-hour) and initial investment. A fourth system, the cost of connecting to the utility grid, has been added for this comparison. (The completed life cycle costing worksheet for utility connection is presented in Appendix E.)

Table 10.1 Summary of economic analysis for four electrical power systems

	<u>Present Worth</u>	<u>Present Value</u>	<u>Initial Investment</u>
PV System	\$ 56,458	\$1.04/kW-hour	\$ 43,490
Generator System	\$ 71,034	\$1.30/kW-hour	\$ 13,140
Hybrid System	\$ 38,608	\$.71/kW-hour	\$ 30,346
Utility*	\$268,208	\$4.63/kW-hour	\$264,000

* Assumed \$10.00/ft for utility line installation and connection.

According to this analysis the hybrid system would be the most feasible because even though the initial investment is higher than that for a stand-alone generator system, the present worth and the present value of the hybrid system are lower than the other three alternatives.

References:

- Brown, Robert J., Ph.D., and Rudolph R. Yanuck, P.E., *Introduction to Life Cycle Costing*, Englewood Cliffs, NJ: Prentice-Hall, Inc., 1985, pp. 1-29.
- Root, Doug, *"Understanding Life Cycle Costing,"* Cape Canaveral, FL: Florida Solar Energy Center, 1986, pp. 1-24.

Cost Analysis for Stand-Alone Photovoltaic Systems WORKSHEET

Application Stand-Alone Home 5 miles from Utility Line

E. Economic Conditions for Analysis

E1 Desired system life 70 years
 E2 Inflation rate (decimal) .06
 E3 Discount rate (decimal) .08
 E4 Real discount rate (E3 - E2) .02

F. Present Worth Analysis for PV and BOS

F1 Peak watts of array (C14) 2968 watts
 F2 Cost per peak watt for PV array and BOS, installed 9.00 \$/watt
 F3 Initial cost for PV and BOS (F1 x F2) 26,712 \$
 F4 Expected PV array life 20 years

F5 Replacement Year * Initial Installation	F6 Present Worth
(F4) <u>—</u>	(F3) <u>26,712</u>
(2 x F4) <u>—</u>	(F3 / (1 + E4) ^{F4}) <u>—</u>
(3 x F4) <u>—</u>	(F3 / (1 + E4) ^(2 x F4)) <u>—</u>
	(F3 / (1 + E4) ^(3 x F4)) <u>—</u>

F7 Present worth of PV and BOS (summation of F6) 26,712 \$
 F8 Energy production over desired system life, E1 (A9 x E1 x 365 / 1000) 54,480 kW-hours
 F9 Present value of PV electricity (F7 / F8) ,49 \$/kW-hour

G. Present Worth Analysis for Batteries

G1 Total battery kW-hour capacity (B9) 68.8 kW-hours
 G2 Cost per kW-hour for battery 185.00 \$/kW-hour
 G3 Initial cost for battery (G1 x G2) 12,728 \$
 G4 Expected battery life in cycles 5100 cycles
 G5 Expected battery life in years (G4 / 365) 14 years

* Do not calculate for replacement years greater than or equal to the system life, E1.

** Estimate from battery literature at average daily depth of discharge, B10.

G6	
Replacement Year *	
Initial Installation	
(G5) <u>14</u>	
(2 x G5) <u>-</u>	
(3 x G5) <u>-</u>	
(4 x G5) <u>-</u>	
(5 x G5) <u>-</u>	

G7	
Present Worth	
(G3) <u>12,728</u>	
(G3 / (1 + E4) ^{G5}) <u>9646</u>	
(G3 / (1 + E4) ^(2 x G5)) <u>-</u>	
(G3 / (1 + E4) ^(3 x G5)) <u>-</u>	
(G3 / (1 + E4) ^(4 x G5)) <u>-</u>	
(G3 / (1 + E4) ^(5 x G5)) <u>-</u>	

G8 Present worth of battery (summation of G7)

22,374 \$

G9 Total present worth of PV and batteries (F7 + G8)

49,086 \$

G10 Present value of PV and battery (G9 / F8)

.90 \$/kW-hour

H. Present Worth Analysis of Inverter

H1 Rated power for inverter

5400 watts

H2 Cost per rated watt for inverter

.75 \$/watt

H3 Initial cost for inverter (H1 x H2)

4050 \$

H4 Expected inverter life

10 years

H5	
Replacement Year *	
Initial Installation	
(H4) <u>10</u>	
(2 x H4) <u>-</u>	
(3 x H4) <u>-</u>	
(4 x H4) <u>-</u>	

H6	
Present Worth	
(H3) <u>4050</u>	
(H3 / (1 + E4) ^{H4}) <u>3322</u>	
(H3 / (1 + E4) ^(2 x H4)) <u>-</u>	
(H3 / (1 + E4) ^(3 x H4)) <u>-</u>	
(H3 / (1 + E4) ^(4 x H4)) <u>-</u>	

H7 Present worth of inverter (summation of H6)

7372 \$

H8 Total present worth of PV system (G9 + H7)

56,458 \$

H9 Present value of PV system (H8 / F8)

1.01 kW-hour

H10 Total initial cost for PV system (F3 + G3 + H3)

43,490 \$

* Do not calculate for replacement years greater than or equal to the system life, E1.

Cost Analysis for Stand-Alone Generator Systems WORKSHEET

Application Stand-Alone Home 5 miles from utility line

E. Economic Conditions for Analysis

E1 Desired system life 20 years
 E2 Inflation rate (decimal) .06
 E3 Fuel escalation rate (decimal) .07
 E4 Discount rate (decimal) .08
 E5 Real discount rate (E4 - E2) .02
 E6 Current fuel cost including transportation 1.20 \$/gal

F. Present Worth Analysis for Generator

F1 Peak generator output (C8) 7500 watts
 F2 Cost per peak watt for generator, installed .65 \$/watt
 F3 Initial cost for generator (F1 x F2) 4875 \$
 F4 Expected generator life in hours 6500 hours
 F5 Average yearly generator run time (C14) 1898 hours/year
 F6 Expected generator life in years (F4 / F5) 3.4 years

F7
Replacement Year *
Initial Installation

(F6) 3.4
 (2 x F6) 6.8
 (3 x F6) 10.2
 (4 x F6) 13.6

F8
Present Worth

(F3) 4875
 (F3 / (1 + E5)^{F6}) 4558
 (F3 / (1 + E5)^(2 x F6)) 4261
 (F3 / (1 + E5)^(3 x F6)) 3983
 (F3 / (1 + E5)^(4 x F6)) 3724

F9 Present worth of generator alone (summation of F8) 21,401 \$
 F10 Expected yearly maintenance cost for generator 250 \$/year
 F11 Present worth of annual maintenance over system life, E1

$$F10 \times \left(\frac{((1 + E5)^{E1} - 1)}{(E5 \times (1 + E5)^{E1})} \right) \quad \underline{4090} \text{ \$}$$

F12 Average generator load (fraction of peak ac output), (C17) 0.29
 F13 Estimated generator fuel consumption at average load, F12 .78 gal/hour
 F14 Annual generator fuel consumption (F5 x F13) 1480 gal/year

* Do not calculate for replacement years greater than or equal to the system life, E1.

F15 Present worth of fuel over sytem life

$$F14 \times E6 \times \left(\frac{1 + E3}{E4 - E3} \right) \times \left(1 - \left(\frac{1 + E3}{1 + E4} \right)^{E1} \right)$$

32,261 \$

F16 Present worth of generator (F9 + F11 + F15)

53,912 \$

F17 Generator energy production over desired system life
(A9 x 365 x E1 / 1000)

54,480 kW-hours

F18 Present value of generaor (F16 / F17)

.90 \$/kW-hour

G. Present Worth Analysis for Batteries

G1 Total battery kW-hour capacity (B9)

15 kW-hours

G2 Cost per kW-hour for battery, installed

185 \$/kW-hour

G3 Initial cost for battery (G1 x G2)

2775 \$

G4 Expected battery life in cycles **

3100 cycles

G5 Expected battery life in years (G4 / 365)

8.5 years

	G6 Replacement Year *
	Initial Installation
(G5)	<u>8.5</u>
(2 x G5)	<u>17</u>
(3 x G5)	<u>-</u>
(4 x G5)	<u>-</u>
(5 x G5)	<u>-</u>

	G7 Present Worth
(G3)	<u>2775</u>
(G3 / (1 + E5) ^{G5})	<u>2345</u>
(G3 / (1 + E5) ^(2 x G5))	<u>1982</u>
(G3 / (1 + E5) ^(3 x G5))	<u>-</u>
(G3 / (1 + E5) ^(4 x G5))	<u>-</u>
(G3 / (1 + E5) ^(5 x G5))	<u>-</u>

G8 Present worth of battery (summation of G7)

7102 \$

G9 Total present worth of generator and battery (F16 + G8)

61,041 \$

G10 Present value of generator and battery (G9 / F17)

1.12 \$/kW-hour

H. Present Worth Analysis for Battery Charger

H1 Rated power for battery charger (C2)

4800 watts

H2 Cost per rated watt for battery charger

.30 \$/watt

H3 Initial cost for battery charger (H1 x H2)

1440 \$

H4 Expected battery charger life

10 years

	H5 Replacement Year *
	Initial Installation
(H4)	<u>10</u>
(2 x H4)	<u>-</u>
(3 x H4)	<u>-</u>
(4 x H4)	<u>-</u>

	H6 Present Worth
(H3)	<u>1440</u>
(H3 / (1 + E5) ^{H4})	<u>1181</u>
(H3 / (1 + E5) ^(2 x H4))	<u>-</u>
(H3 / (1 + E5) ^(3 x H4))	<u>-</u>
(H3 / (1 + E5) ^(4 x H4))	<u>-</u>

* Do not calculate for replacement years greater than or equal to the system life, F1.

** Estimate from battery literature at average daily depth of discharge, B10.

- H7 Present worth of battery charger (summation of H6) 2621 \$
- H8 Total present worth of generator, batteries and battery charger (H7 + G9) 63,668 \$
- H9 Total present value for generator, batteries and battery charger (H8 / F17) 1.17 \$/kW-hour

I. Present Worth Analysis of Inverter

- I1 Rated inverter power output 5400 watts
- I2 Cost per rated watt for inverter .75 \$/watt
- I3 Initial cost for inverter (I1 x I2) 4050 \$
- I4 Expected inverter life 10 years

	I5 Replacement Year *
	Initial Installation
(I4)	<u>10</u>
(2 x I4)	<u>-</u>
(3 x I4)	<u>-</u>
(4 x I4)	<u>-</u>

	I6 Present Worth
(I3)	<u>4050</u>
(I3 / (1 + E5) ^{I4})	<u>3322</u>
(I3 / (1 + E5) ^(2 x I4))	<u>-</u>
(I3 / (1 + E5) ^(3 x I4))	<u>-</u>
(I3 / (1 + E5) ^(4 x I4))	<u>-</u>

- I7 Present worth of inverter (summation of I6) 7372 \$
- I8 Present worth of generator system (I7 + H8) 71,034 \$
- I9 Present value of generator system (I8 / F17) 1.30 \$/kW-hour
- I10 Total initial cost for generator system (F3 + G3 + H3 + I3) 13,140 \$

* Do not calculate for replacement years greater than or equal to the system life, E1.

Cost Analysis for Stand-Alone Hybrid Photovoltaic-Generator Systems WORKSHEET

Application Stand-Alone Home 5 miles from utility line

F. Economic Conditions for Analysis

F1	Desired system life	<u>20</u> years
F2	Inflation rate (decimal)	<u>.06</u>
F3	Fuel escalation rate (decimal)	<u>.07</u>
F4	Discount rate (decimal)	<u>.08</u>
F5	Real discount rate (F4 - F2)	<u>.02</u>
F6	Current fuel cost including transportation	<u>1.20</u> \$/gal

G. Present Worth Analysis for PV and BOS

G1	Peak watts of array (from PV array sizing, C13)	<u>2194</u> watts
G2	Cost per peak watt for PV array and BOS, installed	<u>9.60</u> \$/watt
G3	Initial cost for PV and BOS (G1 x G2)	<u>19746</u> \$
G4	Expected PV array life	<u>20</u> years

G5 Replacement Year * Initial Installation	G6 Present Worth
(G3) <u>—</u>	(G3) <u>19746</u>
(G4) <u>—</u>	(G3 / (1 + F5) ^{G4}) <u>—</u>
(2 x G4) <u>—</u>	(G3 / (1 + F5) ^(2 x G4)) <u>—</u>
(3 x G4) <u>—</u>	(G3 / (1 + F5) ^(3 x G4)) <u>—</u>

G7	Present worth of PV and BOS (summation of G6)	<u>19746</u> \$
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H. Present Worth Analysis for Generator

H1	Peak generator output (D2)	<u>5000</u> watts
H2	Cost per peak watt for generator, installed	<u>.65</u> \$/watt
H3	Initial cost for generator (H1 x H2)	<u>3250</u> \$
H4	Expected generator life in hours	<u>6000</u> hours
H5	Average yearly generator run-time (D20)	<u>151</u> hours
H6	Expected generator life in years (H4 / H5)	<u>40</u> years

* Do not calculate for replacement years greater than or equal to the system life, F1.

H7	H8
Replacement Year *	Present Worth
Initial Installation	(H3) <u>3250</u>
(H6) <u>-</u>	(H3 / (1 + F5)H6) <u>-</u>
(2 x H6) <u>-</u>	(H3 / (1 + F5)(2 x H6)) <u>-</u>
(3 x H6) <u>-</u>	(H3 / (1 + F5)(3 x H6)) <u>-</u>
H9 Present worth of generator alone (summation of H8)	<u>3250</u> \$
H10 Expected yearly maintenance cost for generator	<u>25</u> \$/year
H11 Present worth of annual maintenance over system life, F1	
$H10 \times \frac{((1 + F5)^{F1} - 1)}{(F5 \times (1 + F5)^{F1})}$	<u>409</u> \$
H12 Average generator load (fraction of peak ac output), (D23)	<u>.59</u>
H13 Estimated generator fuel consumption at average load, H12	<u>.68</u> gal/hour
H14 Average yearly fuel consumption (H5 x H13)	<u>103</u> gal/year
H15 Present worth of fuel over system life	
$H14 \times F6 \times \left(\frac{1 + F3}{F4 - F3} \right) \times \left(1 - \left(\frac{1 + F3}{1 + F4} \right)^{F1} \right)$	<u>2245</u> \$
H16 Present worth of generator (H9 + H11 + H15)	<u>3762</u> \$

I. Present Worth Analysis for Batteries

I1 Total battery kW-hour capacity (B9)	<u>12</u> kW-hours
I2 Cost per kW-hour for battery, installed	<u>185</u> \$/kW-hour
I3 Initial cost for battery (I1 x I2)	<u>2220</u> \$
I4 Expected battery life in cycles **	<u>2800</u> cycles
I5 Expected battery life in years (I4 / 365)	<u>7.7</u> years

I6	I7
Replacement Year *	Present Worth
Initial Installation	(I3) <u>2220</u>
(I5) <u>7.7</u>	(I3 / (1 + F5) ^{I5}) <u>1906</u>
(2 x I5) <u>15.4</u>	(I3 / (1 + F5) ^(2 x I5)) <u>1636</u>
(3 x I5) <u>-</u>	(I3 / (1 + F5) ^(3 x I5)) <u>-</u>
(4 x I5) <u>-</u>	(I3 / (1 + F5) ^(4 x I5)) <u>-</u>
(5 x I5) <u>-</u>	(I3 / (1 + F5) ^(5 x I5)) <u>-</u>
I8 Present worth of battery (summation of I7)	<u>5762</u> \$

* Do not calculate for replacement years greater than or equal to the system life, F1.

** Estimate from battery literature at average daily depth of discharge, B10.

J. Present Worth Analysis for Battery Charger

J1	Rated power for battery charger ($D4 \times A2$)	<u>3600</u> watts
J2	Cost per rated watt for battery charger	<u>.130</u> \$/watt
J3	Initial cost for battery charger ($J1 \times J2$)	<u>1080</u> \$
J4	Expected battery charger life	<u>10</u> years

J5 Replacement Year *	J6 Present Worth
Initial Installation	(J3) <u>1080</u>
(J4) <u>10</u>	(J3 / $(1 + F5)^{J4}$) <u>886</u>
(2 x J4) <u>-</u>	(J3 / $(1 + F5)^{(2 \times J4)}$) <u>-</u>
(3 x J4) <u>-</u>	(J3 / $(1 + F5)^{(3 \times J4)}$) <u>-</u>
(4 x J4) <u>-</u>	(J3 / $(1 + F5)^{(4 \times J4)}$) <u>-</u>

J7	Present worth of battery charger (summation of J6)	<u>1966</u> \$
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K. Present Worth Analysis of Inverter

K1	Rated power for inverter	<u>5400</u> watts
K2	Cost per rated watt for inverter	<u>.75</u> \$/watt
K3	Initial cost for inverter ($K1 \times K2$)	<u>4050</u> \$
K4	Expected inverter life	<u>10</u> years

K5 Replacement Year *	K6 Present Worth
Initial Installation	(K3) <u>4050</u>
(K4) <u>10</u>	(K3 / $(1 + F5)^{K4}$) <u>3322</u>
(2 x K4) <u>-</u>	(K3 / $(1 + F5)^{(2 \times K4)}$) <u>-</u>
(3 x K4) <u>-</u>	(K3 / $(1 + F5)^{(3 \times K4)}$) <u>-</u>
(4 x K4) <u>-</u>	(K3 / $(1 + F5)^{(4 \times K4)}$) <u>-</u>

K7	Present worth of inverter (summation of K6)	<u>7372</u> \$
K8	Present worth of hybrid system ($G7 + H16 + I8 + J7 + K7$)	<u>38608</u> \$
K9	Energy production over desired system life, E1 ($A9 \times F1 \times 365 / 1000$)	<u>54480</u> kW-hour
K10	Present value of hybrid system ($K8 / K9$)	<u>.71</u> \$/kW-hour
K11	Total initial cost for hybrid system ($G3 + H3 + I3 + J3 + K3$)	<u>30346</u> \$

* Do not calculate for replacement years greater than or equal to the system life, F1.

Exercises

1. List six different methods of comparing the economics of photovoltaic systems with other alternatives.
2. Review the cost analysis worksheets in Section 10 and compare the present worth of the four alternatives.
3. Under what (altered) conditions would the stand-alone photovoltaic system be the most economically attractive of the four alternatives? Explain.
4. What other important costs have not been included in the life cycle analyses? Explain.



Photovoltaic Lighting Systems

10a

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Photovoltaic Lighting Systems

10a

Objectives

- 1) *Define basic photometric terms.*
- 2) *Compare the qualities of various lamp types in terms of efficacy, lifetime, lumen maintenance, color rendition, and power range.*
- 3) *Combine the photometric data from multiple sources to get an illuminance map.*
- 4) *Explain the functions of the major components of PV lighting systems.*
- 5) *Identify the advantages and disadvantages of the various control methods for PV lighting systems.*
- 6) *For a given application, list at least three appropriate design and three appropriate performance specifications for a PV lighting system.*

Keywords

*Luminous intensity
Luminous flux
Illuminance
Luminance
Candela
Lumen
Footcandle
Footlambert
Reflection
Transmission
Absorption
Luminous efficacy
Color
Color temperature
Chromaticity
Color rendition*

*Inverse square law
Cosine law
Luminaire
Ballast
Coefficient of utilization
Lamp lumen depreciation
Luminaire dirt depreciation
Incandescent lamps
Fluorescent lamps
High intensity discharge lamps
Mercury vapor lamps
Metal halide lamps
High pressure sodium lamps
Low pressure sodium lamps
Candlepower distribution curves
Isofootcandle diagrams*

10a.1 Introduction

Stand-alone photovoltaic (PV) lighting systems represent a substantial market for the PV industry. With diverse applications, thousands of PV lighting systems are being installed annually world-wide. This section presents an overview of PV lighting systems and considerations for the sizing, design and selection of system components. Basic photometric terminology is defined with application to lighting system design and analysis. General information is provided on lamp and ballast performance characteristics and control techniques typically used in PV lighting systems. A case study illustrates the design of PV lighting systems.

10a.1.2 PV Lighting Applications

PV lighting systems have been designed for a variety of applications, ranging in size from small flashlights, portable lanterns and low-level walkway illumination, to larger systems designed for outdoor lighting or highway guide signs.

Generally, PV lighting systems are most practical when the cost of extending utility service is high, and moderate to low illumination levels are required in areas with low ambient light (areas with higher ambient light require greater illumination to provide sufficient contrast). Table 10a-1 lists common PV lighting system applications.

Table 10a-1. PV Lighting Applications

rechargeable flashlights	traffic signals
portable lanterns	navigational aids
parking lots	aviation aids
street lighting	highway guide signs
parks and recreation areas	billboards
pedestrian paths	warning lights
bus stops/shelters	campus security
message board lights	general area lighting
arrow boards	rural residences
building exteriors	secured areas

10a.2 Lighting System Fundamentals

10a.2.1 Photometric Terminology

An understanding of photometric properties and their application to lighting system

design are an important part of specifying, designing, installing and operating PV lighting systems. Following are definitions of the more important photometric properties, terminology and laws.

Source - Common terminology for a light source, such as a lamp or luminaire.

Luminous Flux (ϕ) - The total luminous power emitted from a source, expressed in units of *lumens* (lm). A lumen is the light flux falling on a surface one square foot in area, every part of which is one foot away from a light source having a luminous intensity of one candela in all directions (Fig. 10a-1). The lumen is a quantity of light flux. It expresses the total output of a source, incident light (light falling on a surface) over a specified area or region, or the amount of light reflected, absorbed or transmitted.

Luminance (L) - Luminance, or photometric *brightness*, represents the light which is *reflected or emitted* from a surface, while the illuminance represents the light flux *incident* on a surface. A surface which uniformly emits or reflects one lumen per square foot (one footcandle) has a luminance in that direction of one *footlambert* (fl). In international units, luminance is expressed in units of *nits*, where one footlambert equals 3.426 nits. For a diffusing reflecting surface, the luminance in footlamberts is equal to the footcandles reflected, multiplied by the reflectance.

Reflection - When a light ray strikes and then is turned back from a surface, it is said to be reflected. Reflections can be either specular or diffuse, depending on the nature of the surface. **Reflectance (ρ)** is defined as the ratio of light reflected from a surface to the incident light. Reflectance is normally expressed as the ratio of the brightness in footlamberts and the illuminance in footcandles.

Transmission - Light rays passing through transparent or translucent materials are said to be transmitted. The nature of the material determines the wavelengths of light transmitted, as well as the angle at which the light is refracted (bent) as it passes through the material. The **transmittance (τ)** is defined as the ratio of light transmitted through a material to the incident light.

Absorption - Light rays which pass through transparent or translucent materials are said to be absorbed if they are not reflected or transmitted. The nature of the material determines the wavelengths of light transmitted as well as the angle at which the light is refracted (bent) as it passes through the material. The **absorptance (α)** is defined as the ratio of light absorbed in a material to the incident light.

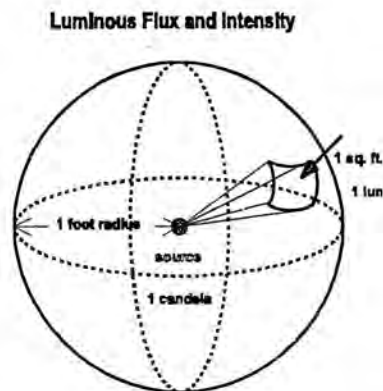


Figure 10a-1

By definition, the sum of the reflectance, transmittance and absorptance equals one:

$$\rho + \tau + \alpha = 1$$

Eqn. 10a-1

Refraction - Light rays that pass obliquely from one medium to another, for example from air through glass, are said to be refracted. The *refractive index* of a material or medium defines the extent to which light rays are refracted when passing through the material.

Luminous Efficacy - A representation of lamp or luminaire efficiency, generally expressed in lumens emitted per watt of power consumed (lm/W). Typical lamp efficacies range from a low of 15 lm/W for some incandescent lamps, up to 180 lm/W for low pressure sodium lamps.

Color - The color of light is determined by its wavelength. The visible spectrum consists of the colors of a rainbow, ranging from violet at one end to red at the other. Wavelengths in the visible spectrum range from about 0.4 to 0.7 μm . Ultra-violet light has wavelengths shorter than 0.4 μm , while infra-red radiation has wavelengths longer than 0.7 μm (1 μm = 1 micrometer).

Color Temperature - Color temperature is a term used to describe the color of a light source by comparing it with the color of a blackbody -- a theoretical complete radiator which emits light with a continuous distribution according to its temperature. The higher the color temperature of a source, the whiter the light source appears. Blue sky has a color temperature of between 10,000 and 30,000 degrees Kelvin (K), fluorescents lamps range between 3,000 and 7,000° K, and incandescent lamps are between 2,000 and 4,000° K. Note that color temperature is not a measure of actual temperature, only a representation of the color of a light source approximating a blackbody.

Chromaticity and Color Rendition - Chromaticity refers to color composition of the light, or the spectral distribution of the light. Chromaticity coordinates give a specific, quantifiable representation of the color of a light source. Color rendition refers to the manner in which a lamp's light output affects color perception.

10a.2.2 Fundamental Equations

Inverse Square Law - The inverse square law states that illumination is inversely proportional to the square of the distance between the source and the surface. In other

words, the illumination two feet away from a source will be one quarter of the illumination one foot away. Similarly, the illumination three feet away from a source will be one ninth of the illumination one foot away. The inverse square law generally applies if the distance at which measurements are taken is a least five times the greatest dimension of the light source. Figure 10a-2 illustrates the inverse square law.

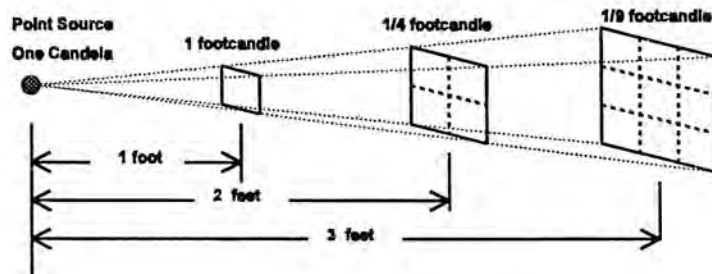


Figure 10a-2: Photometric Inverse Square Law

Cosine Law of Incidence - This law states that the illumination is proportional to the cosine of the angle of incidence, or the angle between the direction of the incident light and perpendicular to the surface. Figure 10a-3 illustrates the cosine law of incidence.

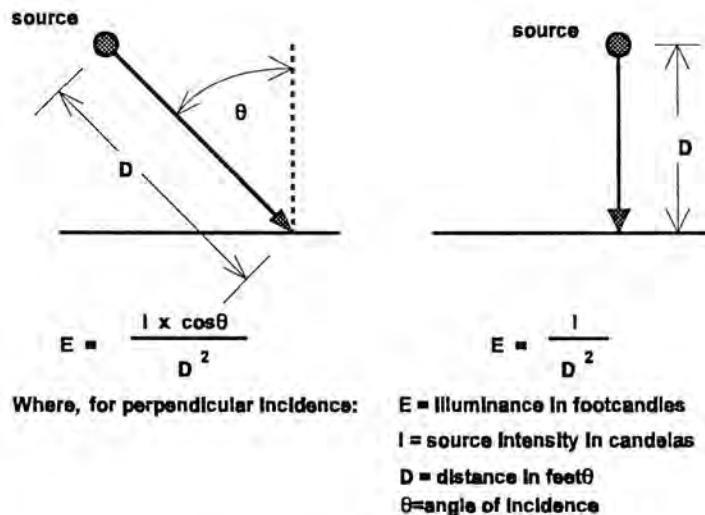


Figure 10a-3: Cosine Law of Incidence

10a.2.3 Instruments and Measurements

Illuminance Meter - A basic photometric instrument, utilizing a light sensitive photovoltaic cell which produces a small current when illuminated. The current output can be calibrated to read directly in units of *footcandles* or *lux*. Color correcting filters are used to approximate the response of the human eye, and cosine correction is often employed to compensate for reflection and other errors at high incidence angles. Illuminance meters are commonly used to measure the light distribution on surfaces in the field.

Luminance Meter - This instrument measures light reflected or emitted from a surface, typically in units of *footlamberts*. The instrument is aimed directly at the test surface, and a photoelectric tube produces a current which is translated to *footlamberts*. Often, luminance measurements are used to quantify the contrast, or brightness difference between an object and its background, for example letters on a sign. Visual acuity depends on maintaining minimum contrast with a focus object and its background.

10a.2.4 Lighting Equipment

A complete lighting system consists of a lamp, socket, fixture or housing, reflectors/diffusers, lenses, ballast controls and power source. In the case of PV lighting systems, the power source is typically a stand-alone PV system with battery storage. Due to the high cost of PV systems, the most efficient lighting system components meeting the application requirements should be selected. The following sections describe basic lighting system components and terminology.

10a.2.4.1 Definitions

Luminaire - A luminaire is a complete lighting unit, including lamps, ballasts, diffusers/lenses, fixture and other components.

Ballast - A device that modifies incoming voltage and current to provide the circuit conditions necessary to start and operate electric discharge lamps. Incandescent lamps do not require a ballast.

Coefficient of Utilization (CU) - The CU rating of a luminaire is defined as the ratio of the light output from the luminaire that strikes the work plane and the light output of the lamps alone. The CU quantifies the efficiency of a lighting installation.

Lamp Lumen Depreciation (LLD) - Sometimes referred to as lumen maintenance, the LLD refers to a lamp's lumen output reduction over its lifetime, generally expressed as a function of time and the initial lamp lumen output. Often the depreciation of lamp lumen

output makes it economical to replace many lamps before they actually burn out.

Luminaire Dirt Depreciation (LDD) - Luminaire dirt depreciation refers to the reduction in light output of a luminaire, as a function of the luminaire design and environmental conditions. Periodic cleaning may be required for particularly dirty applications to maintain minimal levels of illumination.

10a.2.4.2 Light Sources

The choice of a light source is the first decision in lighting system design. Factors to be considered include efficacy, color, lamp life and lamp lumen depreciation. Light sources can be categorized into three groups; incandescent, fluorescent and high intensity discharge (HID). HID lamps are grouped into four major classes: high pressure sodium, metal halide, mercury vapor and low pressure sodium.

Common lamp types used in PV systems include standard and compact fluorescents, and low pressure sodium lamps. Less common in PV systems are high pressure sodium, metal halide and mercury vapor lamps, although these sources are popular for commercial and utility applications. The small variety of low voltage dc ballasts available to power these lamps has limited their application in PV systems. Table 10a-2 lists general characteristics of common lamp types.

Table 10a-2. Light Source Comparison

Lamp Type	Efficacy (lm/W)	Typical Lifetime (hr)	Lumen Maintenance	Color Rendition	Wattage Range
Incandescent	8 - 25	750 - 3,500	Good to Excellent	Good to Excellent	15 - 1500
Fluorescent	40 - 100	6,000 - 24,000	Good to Excellent	Good to Excellent	4 - 215
Mercury Vapor	40 - 60	12,000 - 24,000	Very Good	Poor to Excellent	40 - 1000
Metal Halide	80 - 125	5,000 - 20,000	Good to Excellent	Very Good	70 - 2000
High Pressure Sodium	72 - 140	7,500 - 28,000	Excellent	Good	35 - 1000
Low Pressure Sodium	100 - 180	12,000 - 18,000	Excellent	Poor	18 - 180

Note: Data are for comparison only. Actual lamp specifications vary considerably depending on the design, lamp wattage and manufacturing processes.

Incandescent Lamps - Incandescent lamps are generally constructed with a wire-wound filament, generally tungsten, and enclosed in an evacuated or gas-filled glass bulb. When power is applied, the resistive filament heats to incandescence by the flow of electric current through it. The filament essentially becomes 'white-hot' emitting a continuous spectra of long-wave visible radiation. The higher the temperature of the filament, the greater the portion of emitted energy that lies in the visible spectra.

Types of incandescents include common household bulbs, halogens and other inert gas filament lamps. Initially, the bulbs were evacuated to keep the filament from burning up by removing oxygen. Later, it was discovered that the pressure exerted by an inert gas retards the evaporation of tungsten, allowing higher filament temperatures and higher efficacies.

While incandescent lamps are inexpensive and convenient to use because they do not need a ballast, they generally have low efficacies and short lifetimes compared to electric discharge lamps. For this reason, incandescents are seldom used in PV applications except for short duration or flashing type signals, such as navigational aids.

Fluorescent Lamps - Fluorescent lamps are electric discharge devices which utilize an arc between two cathodes to excite a low pressure mercury vapor, resulting in the emission of ultra-violet (UV) radiation. The UV radiation is absorbed by a phosphor coating on the inside of a glass tube where the radiation is re-emitted at longer, visible wavelengths. The phosphor composition determines the spectral distribution of the light emitted from the lamp. While older fluorescent lamps were limited in their color spectra to primarily blue colors, new rare earth phosphors have allowed designers to achieve a broader and warmer range of colors for fluorescent lamps.

Straight-tube fluorescent lamps with lengths from 6 to 96 inches are common. They are given a "T" designation which refers to the tube diameter in eighths of an inch. For example, a F40-T12 CW lamp designation refers to a 40-watt cool-white fluorescent lamp with a tube diameter of 1½ inches. The length of a fluorescent lamp is related to the power rating, typically about 10 watts per foot. For example, an 18-inch tube is typically rated at 15 watts and a 48-inch tube is rated at 40 watts.

Common fluorescent lamps used in PV lighting systems include the relatively new compact U-tube or PL types. These lamps are popular due to their small size, high efficacy and simple ballast design requirements. Typical power ratings include 5, 7, 9, 13, 24 and 36 watts, although other wattages are available in dual or quad type lamp arrangements. The light output from a 13-watt compact fluorescent is often compared to that of a 60-watt incandescent lamp.

Fluorescent lamps typically convert 20% of the input power to visible light, compared to

incandescents which are less than 10% efficient. In general, the efficacy for larger lamps is higher than for smaller lamps because the power consumed at the electrodes is approximately the same, regardless of the lamp size. This suggests using a few larger lamps rather than many smaller lamps where applicable.

Several starting options have been used for fluorescent lamps. The original fluorescent lamps developed in 1938 were of the preheat type. These required a separate starter to supply a few seconds of current flow through the cathodes to preheat them prior to lamp ignition. When heated, thermionic emission aids in liberation of electrons from the cathode, and allows the lamp arc to initiate at lower voltages. Instant-start lamps rely on ballasts to supply a sufficiently high voltage to strike the arc without the need for preheating. Rapid-start lamps utilize cathode heating windings in the ballast, and start almost as smoothly as the instant start variety; however they are less efficient.

Average rated lamp life is the point at which approximately 50 percent of the lamps in a large test group have burned out and 50 percent remain burning. For fluorescent lamps shorter burn cycles (more frequent starts) shorten life and longer burn cycles (less frequent starts) increase lamp life.

During the first 100 hours of operation, the lumen depreciation for fluorescent lamps may be as much as 10 percent, with a more gradual reduction over the rest of its life. The two principal causes are a gradual deterioration of the phosphor coating and blackening on the inner surface of the bulb from the emissive material discharged by the cathodes.

One disadvantage of fluorescent lamps is that the light output decreases considerably with decreasing lamp temperature. Lower temperatures lower the mercury vapor pressure, which reduces light output and makes the lamp more difficult to start. After the lamp has started, the effective light output depends on what temperature the lamp reaches. When fluorescent lamps are used outdoors, starting may be a problem at low temperatures, and higher starting voltages may be required. Standard ballasts will start lamps reliably down to 50°F. Low temperature ballasts are available for certain lamp types to permit starting well below freezing.

High Intensity Discharge Lamps - High intensity discharge (HID) lamps produce light by an electric arc passing through a vapor or gas, rather than through a wire filament as with incandescents. The arc is created by ionizing a gas inside a quartz tube, and light is produced as the excited gas atoms return to their normal state. The quartz arc tube is enclosed in a larger glass bulb, sometimes coated with phosphors, and acting as a filter for harmful UV radiation. Starting of HID lamps is not instantaneous, and may require several minutes to achieve maximum output depending on the ambient temperature. All HID lamps require a high-reactance transformer or other ballast to limit the arc current.

Mercury Vapor Lamps - Mercury vapor lamps belong to the classification of HID lamps, using mercury as the primary ionizing gas, with a trace of more readily ionized argon to aid in starting. Mercury vapor lamps have a characteristic blue spectral distribution.

Metal Halide Lamps - Another HID lamp and similar in operation to mercury vapor lamps, with the exception that metal iodides are added with the mercury to contribute additional radiation lines to the spectral distribution of the lamp. Metal halides are commonly used indoors and for sign lighting where good color rendition is desired.

High Pressure Sodium Lamps - Classified as HID lamps, high pressure sodium (HPS) lamps use metal sodium as the main ionizing gas in the arc tube. The high gas pressure broadens the otherwise monochromatic radiation spectra of $0.59\ \mu\text{m}$ (yellow light), which is characteristic of low pressure sodium lamps. High pressure sodium lamps have good color rendition and high efficacies.

Low Pressure Sodium Lamps - The low pressure sodium (LPS) lamp is the most efficient light available, with efficacies as high as 200 lumens per watt. The lamp design and construction keep losses to a minimum resulting in high efficacies. In operation, an electrical arc ionizes a low pressure sodium gas, creating a monochromatic $0.59\ \mu\text{m}$ (yellow light) line source. As with other discharge lamps, LPS lamps require a ballast to limit the arc current and supply the minimum open-circuit voltage required for starting the lamp. These lamps are generally used outdoors, where color rendition is not important. LPS lamps are often put to work in PV lighting applications.

10a.2.5 Photometry and Basics of Lighting Design

The design of a lighting system involves consideration of many variables, including the *quantity* and *quality* of illumination required, the purpose or application, and economic factors. *Photometry* refers to the test data which describe characteristics of a luminaire's light output, and is an essential element of lighting design. The most common photometric data are candlepower distribution curves and isofootcandle diagrams.

Quantity of Light - The most obvious measure of a lighting installation is the amount of illumination it provides. The required illumination levels are related to the tasks to be performed under the illumination. Thus critical tasks involving hours of visual work, such as electronics assembly, require high illumination levels on the work plane, while lighting a parking lot requires less.

Table 10a-3 gives recommended values of illumination for various activities.

Table 10a-3. Recommended Illumination Levels (footcandles)

Area/Activity	Range of Illumination	Area/Activity	Range of Illumination
Classroom	50 - 100	Recreation activities	
Reading	20 - 100	tennis	10 - 30
Stairways	20 - 10-20	baseball	15 - 150
Wash rooms	10 - 20	football	20 - 100
Building exteriors	1 - 5	parks	2 - 20
Residences		Roadways	0.6 - 2
general	5 - 10	bus stops	2 - 10
kitchen and bath	20 - 100	billboards, signs	15 - 100
Assembly, inspection		parking lots	0.5 - 4
simple	20 - 50	Storage yards	1 - 20
difficult	100 - 200		
exacting	500 - 1000		

Quality of Light - Adequate quantity of light does not ensure good illumination. Other factors such as glare, diffusion and color are important quality features. Maintaining adequate brightness distributions is equally important as illumination levels. Proper selection of lamp types and luminaires, along with the design of the surrounding area (wall/ceiling color, daylighting, etc.) can generally achieve the quality needed in most lighting situations. Luminaires without diffusers, or with glossy walls, shiny surfaces and low illumination contribute to poor light quality. Good quality illumination helps people perform tasks over prolonged periods.

Candlepower Distribution Curves - Lighting fixtures are designed to distribute light in various ways, depending on the application. This distribution of light from a luminaire can be represented by its *candlepower distribution curve*. These distribution curves are the result of taking candlepower measurements at various angles around a light source or luminaire. The illumination on a surface can be calculated from candlepower distribution data on the source. Where the inverse square law applies, the illumination can be calculated by dividing the candlepower at the required angle by the square of the distance in feet, and multiplying by the cosine of the incidence angle. Figure 10a-4 shows a typical candlepower distribution curve for a street lighting luminaire in the horizontal plane.

Isofootcandle Diagram: An isofootcandle or isolux diagram is a group of curves drawn through points receiving the same amount of illumination on the working surface. Distances on the work plane are represented in multiples of the mounting height to allow translation of the data to other mounting heights. Footcandles for other mounting heights are determined by multiplying the values on the given curves by the ratio of the square of

the present mounting height to the square of the new mounting height. Figure 10a-4 shows a typical isofootcandle diagram.

10a.3 PV Lighting System Sizing and Design

PV lighting systems are a type of stand-alone PV system consisting of a PV module/array which charges a battery during the day while the battery supplies power to a lighting load at night. As with all stand-alone systems the sizing process follows a systematic approach: first, determine the load profile; second, define battery storage requirements; third, size the PV array to meet the load, including losses during the period with the lowest ratio of insolation to load (generally winter). This section presents equations to calculate night hours to aid in the development of load profiles. Insolation to load ratios are also presented for three U.S. cities. These ratios demonstrate the varying sizes of PV systems required to meet an all-night lighting load in different locations at different times of the year. Sizing of the battery and PV array are covered in detail in Chapter 6.

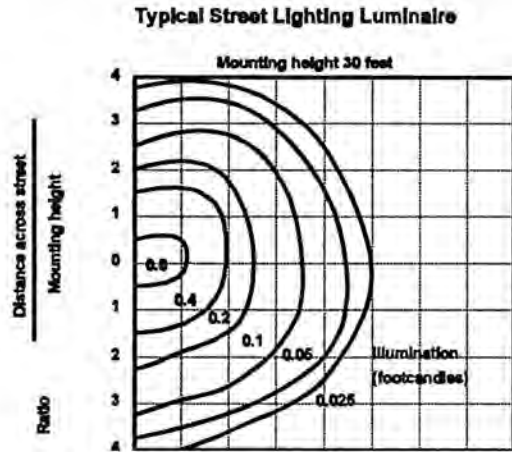


Figure 10a-4: Isofootcandles Diagram

Figure 10a-5 shows a block diagram of a typical PV lighting system.

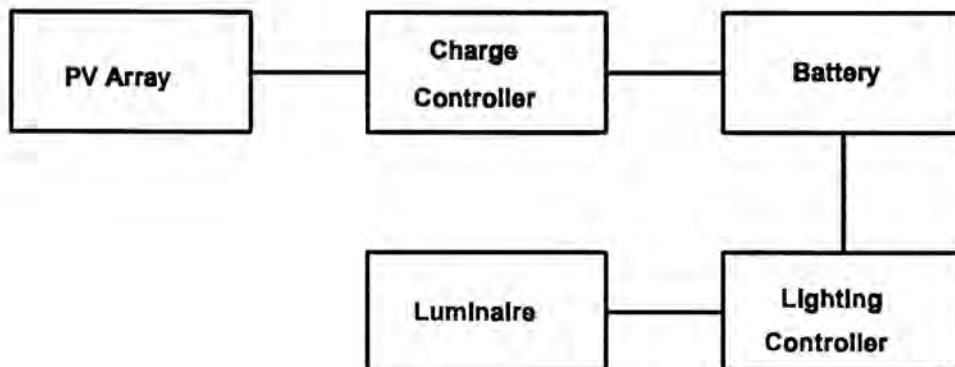


Figure 10a-5: PV Lighting System Block Diagram

10a.3.1 Solar Resource and Load Assessment

For PV lighting systems designed to operate all night, the load varies with the number of night hours: the maximum load occurs on the winter solstice and the minimum load on the summer solstice. Figure 10a-6 shows the number of night hours by month for three U.S. cities at different latitudes. As shown in Figure 10a-6, the higher the latitude the longer the nights in winter and shorter in the summer. At the equator, all days and nights throughout the year are exactly 12 hours, whereas at all other latitudes the days and nights are exactly 12 hours only at the spring and fall equinoxes.

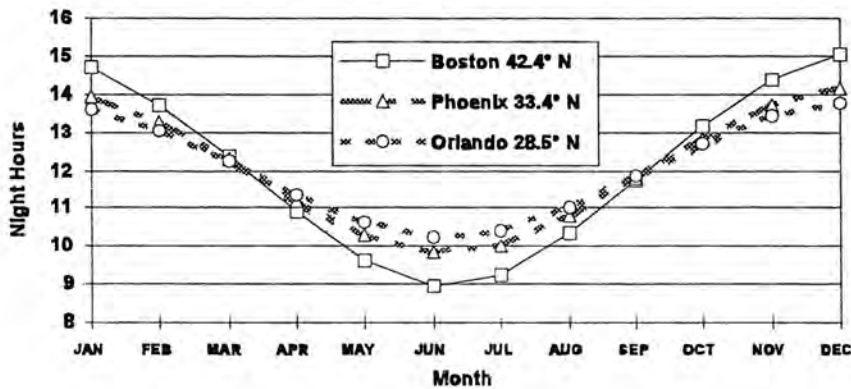


Figure 10a-6: Night Hours for Three U.S. Cities

Equations 10a-2 through 10a-4 give formulas to calculate the night hours for any location as a function of the latitude and time of year.

$$D = \sin^{-1}[0.3975\cos(0.98563(N-173))]$$

Eqn. 10a-2

$$H = \cos^{-1}[-\tan(L)\tan(D)]$$

Eqn. 10a-3

$$T = 2(12-12H/180)$$

Eqn. 10a-4

Where:

D = solar declination (degrees)

N = julian day number (1-365)

H = solar hour angle (degrees)

L = latitude (degrees)

T = night hours (sunset to sunrise)

Figure 10a-7 uses insolation values for south-facing surfaces tilted at the latitude of the city (known as "latitude-tilt surfaces"). These figures are divided by the average monthly night-hours to give insolation to night-hour ratios for Boston, Phoenix and Orlando. By examining this ratio, one can easily identify the critical load periods for different load profiles and array orientations. For example, it can be seen that a PV lighting system designed to operate all night in the winter months would need to be on the order of twice the size in Boston as it would need to be in Orlando to meet the load. However, to meet the load only in the summer, the system sizes for Boston and Orlando would be comparable.

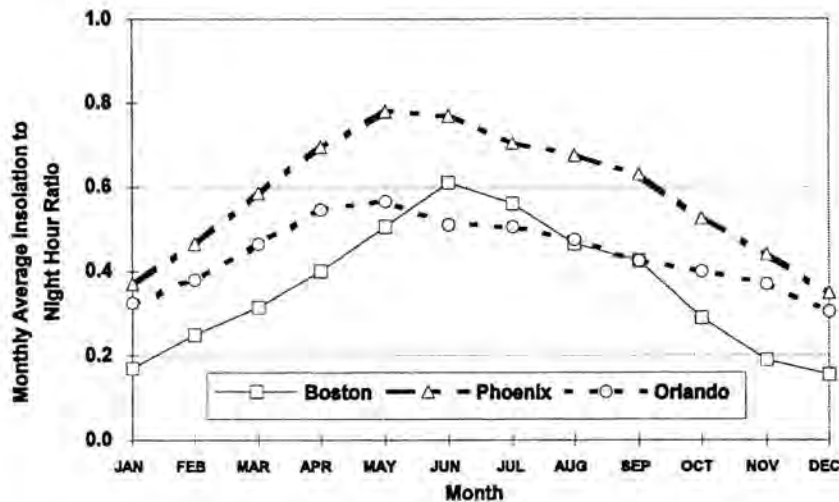


Figure 10a-7: Insolation to Night Hour Ratios for Three U.S. Cities (Latitude Tilt Surfaces)

10a.4

PV Lighting System Component Specification

Currently, various government agencies procure the majority of PV lighting systems. Often the individuals responsible for the procurement have little first hand knowledge of

system design and performance. This section is intended to aid these individuals in identifying specifications for PV lighting systems. In addition, the material presented here may assist PV lighting system manufacturers to tailor their design and performance parameters in product literature for a government procurers.

Warranties: To ensure the long term reliability of PV lighting systems, the buyer may request a warranty from the supplier. Often, warranties are provided by the manufacturers for individual components in the system (e.g. PV modules) and sometimes for the complete system. Warranties for the no-cost replacement of defective components for a nominal period (perhaps 1-2 years) may be requested.

Site Description: Provide the bidder with a description of the intended site for the systems. Include information on the environmental conditions at the site, purpose of the lighting, and any pertinent installation issues (orientation, shading, susceptibility to vandalism, etc.).

Design and Performance Requirements: If they are knowledgeable about the solar resource and PV system the buyer may elect to specify system design parameters. For example, a design insolation value may be specified for the lowest insolation period (typically wintertime) for the array design tilt. Also, high and low ambient temperatures affect the performance of lamps, ballasts, and batteries in PV lighting systems. The buyer may request that the system be designed to start and operate effectively within a specific temperature range, say from -10°C to 35°C .

Performance parameters are generally restricted to the load, although performance of the battery system may be included. For the lighting load, all-night operation may be required, or only a few hours a night may be acceptable. Some systems such as flashing systems used by the transportation departments may be required to operate 24 hours-a-day at a specific flash interval and duration. For systems intended to illuminate surfaces, minimum or average illumination levels over a given area may be specified. For instance, a lighting system may be required to provide an average illuminance of one footcandle over given area with a minimum uniformity of 5:1. Often, PV lighting is used in remote, dark areas, far from the utility grid where lower levels of illumination than conventionally provided may be acceptable. Many PV system manufacturers provide photometric data for their lighting systems for use in lighting analysis software.

For systems intended for use as obstruction lights or flashers, the luminance (brightness) of the light source may be specified. For example, aids to navigation installed on bridge fenders are required by the U.S. Coast Guard to be clearly visible at a distance of 2000 yards on 90% of the nights of the year.

Lamps and Ballasts - Since most PV lighting systems utilize fluorescent or low pressure

sodium lamps rather than less efficient incandescent lamps, ballasts are required. Generally, these are inverter-ballast designs which operate from a dc input voltage (typically 12 or 24 volts) and provide an ac output voltage to the lamp. Several manufacturers produce these low-voltage dc ballasts for the photovoltaic, marine, recreational vehicle and emergency lighting markets.

Knowledge of the design and operational characteristics of low-voltage dc ballasts is essential to the designer of PV lighting systems. These considerations include the effects of voltage, frequency, temperature, and transients on the lamp starting, output and lifetime.

In some cases, ballasts may require heat sinking if they are not highly efficient. To assist in limiting ballast temperature rise, ballasts can be mounted to a metal surface and provided with adequate ventilation. A ballast subjected to higher than nominal voltages will generally operate at increased temperatures, reducing ballast life. Low voltage can cause premature lamp failures as well as unreliable lamp starting and lumen output.

Luminaire Design - In cold climates the buyer may shy away from standard fluorescent lamps due to their problems operating in low temperatures. However, special low temperature fluorescent lamps and ballasts may be specified, or other types of lighting may be used. Where color rendition is important the monochromatic light output of low pressure sodium may not be appropriate.

Fixtures should be appropriately rated for the application, for example outdoor, sunlight resistant, or vandal proof. The National Electrical Code requires that luminaires for wet locations must meet the minimum design requirements covered in Underwriters Laboratories (UL) booklet UL57. Requirements for the lens and fixture construction might include shatter resistance or the use of non-corrosive materials for marine environments. Other considerations for luminaires include ease of lamp and ballast changes, lamp positioning and mechanical strength in high winds.

Photovoltaic Modules and Array - All types of PV modules are acceptable for PV lighting systems, however, for many PV lighting systems, array surface area must be limited due to mechanical and wind load constraints. In these cases, higher efficiency modules may be desirable to minimize area requirements. In special circumstances such as marine lighting applications, modules may have to meet U.S. Coast Guard specifications.

Polycrystalline, crystalline and thin-film PV devices have all been used successfully for PV lighting systems. Due to their lower efficiencies, thin-film devices require greater surface areas and thus have primarily been used for smaller systems or for installations where space is not an issue. The PV module/array may be integrated in the light fixture

for small systems, installed on a pole mount for intermediate sized systems, or mounted to the ground, a roof or independent structure for larger systems.

Batteries - Batteries used in PV lighting systems often experience deep discharge cycles and should be tolerant of this treatment. Either flooded or sealed batteries may be used, the latter having lower maintenance requirements. Catalytic or recombination caps may be specified for flooded lead-acid batteries to reduce water additions where battery maintenance is infrequent, difficult or otherwise expensive.

The specification of the battery subsystem may, for example, require a minimum performance of 1500 cycles to 50% depth of discharge at 25° C. Autonomy (electrical storage) may be specified to meet the load for a given period (typically 3-6 days under no-sun conditions) without exceeding a maximum battery depth of discharge limit (typically 50 to 75%). Refer to the *IEEE Recommended Practice for Installation and Maintenance of Lead-Acid Batteries for Photovoltaic Applications* for additional information (see References).

Control Systems - Several methods may be used to control the load and battery charge in PV lighting systems. Timers, photocells or motion detectors may be used to control the light. The battery charge controller may regulate the light by using a timer or by sensing the array voltage. A battery charge controller should be specified in most PV lighting systems and should include a low voltage load disconnect to protect the battery from excessive discharge. The load disconnect point should not be so high as to reduce load availability by disconnecting the battery before the design lower limit of discharge is reached. Also the load reconnect set point should be sufficiently higher than the load disconnect point to prevent the load from cycling on and off after a disconnect. The charge regulation set points should be appropriate for the battery type. Where temperature extremes are common, compensation may be specified to regulate the battery charge termination voltage.

Light Control Strategies - Depending on the specific application, the designer/buyer may select from among several lighting control strategies for PV lighting systems. Primarily these controls include photocells or array sensing for day/night control and timers to regulate the light operation period. Other applicable controls include infra-red or ultrasonic motion detection, daylight sensing and remote control. In many cases the light control circuit is incorporated in the PV system battery charge controller, although separate components are often used.

Excluding any light control functions, the charge controller (if applicable) plays an important role in the performance of a PV lighting system. Specifically, the low-voltage load disconnect and reconnect set points affect the overall system reliability. A tradeoff exists between maintaining the health of the battery while providing high load

availability. The low-voltage load disconnect defines the lower limit of battery discharge (DOD). Further details on charge controller characteristics in PV systems may be found in Bower, et al., *Performance of Battery Charge Controllers...*; and Dunlop, J., et al., *Performance of Battery Charge Controllers...* (see References).

Spare Parts - The system procurement may specify a supply of spare parts or simply identify sources for the equipment should the need arise. Examples of useful spare components include lamps, ballast, fuses, etc.

Electrical Design - In general, safe and reliable electrical practices should be followed in the design and installation of PV lighting systems. Where applicable, the electrical design of the PV system should follow the requirements of the National Electrical Code.

Conductors in the system should be moisture and sunlight resistant where applicable. Conductor sizes should be no smaller gage than no. 12 AWG. Where possible, it is highly recommended that wiring be protected or enclosed. Fused disconnect switches or circuit breakers capable of isolating the battery from the PV array and the light load from the battery should be provided for the appropriate service (e.g., outdoor applications).

For systems operating above 50 volts, the NEC requires that a current-carrying conductor in the electrical circuit be grounded. While most PV lighting systems are designed to operate at lower voltages, the designer may still elect to ground the array frame, support structure and metallic enclosures. Other desirable features may include transient protection on sensitive system components such as lamp ballasts and charge controllers.

Mechanical Design - Most small, outdoor PV lighting systems ($< 200 W_p$) are designed as self-contained units, often with the PV array mounted on top of a pole just above the light fixture(s). Batteries are generally located at the base of the system due to their weight or underground to insulate from temperature extremes. Considerations in these designs should include tolerance to wind loading on the array surface and the design of a substantial base to counteract the force. Larger systems may use a ground- or roof-mounted array installed to accepted standards.

The construction materials for the system should be suited to their environmental conditions. Module frames, support structures, electrical boxes and enclosures must provide long-term corrosion resistance in the environment. Components fabricated from wood, common unpainted steels or corrosion-prone materials should generally be avoided.

System Documentation - To ensure long-term system performance and reliability of PV systems, it is essential that the designer provide some type of system documentation. This technology is relatively new and maintenance personnel are often not as

knowledgeable about PV systems as they are with more conventional equipment. Too often PV systems lack documentation, resulting in an early retirement for systems with perhaps only minor problems. To enhance the knowledge of users and reliability of the system, the following items may be requested as part of the system documentation:

1. component and system specifications, part lists
2. electrical and mechanical drawings
3. basics of system operation
4. maintenance requirements
5. diagnostics and troubleshooting
6. safety precautions
7. acceptance testing

10a.5 Case Study: PV-Powered Highway Guide Sign Lighting System

In 1988, the Florida Solar Energy Center and the Florida Department of Transportation designed and installed a PV-powered lighting system for an overhead highway guide sign, shown in Figure 10a-8. The highway sign stands on a remote stretch of the BeeLine Expressway, more than five miles from utility service. One of the first systems of this type to be installed in the U.S., this project incorporates many important aspects of PV lighting system design. The following section presents an overview of the project, including the selection of a light source, system sizing, electrical and mechanical design and performance validation.



Figure 10a-8. PV-powered guide sign lighting system.

Characterization of Light Sources and Load Assessment - The first objective in the design process was to select the most efficient lighting system meeting the overall sign illumination requirements. Recommended levels of luminance and illuminance for overhead highway guide signs are given in Table 10a-4 for low, medium and high ambient light levels]. To achieve acceptable contrast with the surrounding background, higher lighting levels are required for signs located in high ambient light areas.

Table 10a-4. Recommended Highway Sign Illumination Levels (AASHTO)

Ambient	Low	Medium	High
Luminance (fl)	7-14	14-28	28-56
Illuminance (fc)	10-20	20-40	40-80

Further lighting design guidelines include maintaining a uniformity of illuminance of no worse than 6:1 over the sign face, with a desired ratio of 4:1. The selected light source should adequately illuminate and preserve the colors on the sign, and should not shadow or obstruct the motorist's view of the sign message. Spill light should be minimized to reduce glare and luminaires should be installed with maintenance considerations in mind.

To help identify the best light source for the job, photometrics and electrical power consumption were measured at several guide sign locations in the field, as well as for a number of representative luminaires in the laboratory. A number of high pressure sodium, fluorescent and mercury vapor lighting systems were evaluated. Illuminance measurements were conducted by dividing the sign area into 3' by 3' square sections and positioning the meter at the center of the sections, parallel to the sign face. Luminance was recorded for the legend and adjacent background surfaces. Where photometric data for luminaires was available, calculations were performed to estimate the illuminance distributions and to compare with actual measurements on the sign surfaces. Results from these tests indicated the lamps that provided the most illuminance per watt of input power were high pressure sodium, followed by fluorescent and then mercury vapor lamps.

To keep the PV system design simple and more efficient, a primary objective was to use only 24-volt dc ballasts to power the lights. Due to the limited availability of dc ballasts to power high pressure sodium lamps and the questionable color rendering properties of the HPS lamps, the tests on dc ballasts focused on the Philips PL36W/84, a 36-watt compact fluorescent lamp, and the Sylvania F032/31K Octron T-8 fluorescent lamp. These are efficient lamps commonly used in PV lighting applications, and dc ballasts to operate these lamps are readily available. Both lamps have high efficacies (approximately 70 lm/W) and consume approximately 40 watts each including the ballast.

In laboratory tests, both the F032 and PL36 lamps started with no problems at low voltage and below freezing temperatures with all ballasts. Photometric test results on several fixture and ballast combinations showed that six of either the F032 or PL36 luminaires would provide adequate illumination, proper contrast and uniformity for the two signs. For all tests, the power consumption for both the F032 and PL36 luminaires

ranged between 38 and 42 watts, or approximately 240 watts total for the six luminaires required for the two signs. The only significant difference between the two lamps was that the F032 lamp could be powered with a low current ballast (265 mA), resulting in up to 24,000 hours lamp life before failure. The ballasts tested for the PL36 lamps use a higher lamp current (430 mA), and typical lamp lifetimes were estimated at 10,000 hours. Based on their expected longer life, the F032 lamps were selected over the PL36 lamps for this application.

Sizing and Load Analysis - After the light source had been selected, the second objective was to develop the load profile and size the PV array and battery accordingly. As discussed previously, the system must be sized to meet the load during the period with the lowest insolation to load ratio: the months of December and January for this site.

Based on Equations 10a-2 through 10a-4, the load varies with the length of the nights. For the given site latitude, the maximum nightly operation time of 13.8 hours occurs on December 21, and a minimum load time of 10.2 hours occurs on June 21. Using the load of 240 watts (six 40 watt luminaires, 3 on each sign) for 13.8 hours per day on December 21 equals a daily energy load of about 3,300 watt-hours, or about 137 ampere-hours at 24 volts dc. To determine the optimal array tilt angle for the design, the average monthly insolation on various south facing tilted surfaces was divided by the average monthly load over a typical year. These results indicated that a south facing 45° tilted array would minimize the overall array size for this application, as well as allow for uniform geometry in the mechanical design of the array installation.

Applying the sizing procedures presented in Section 6 of this manual, and using the December insolation on the array surface of 4 kWh/m²-day, the required array size amounted to about 1,000 watts, or about 20 fifty-watt PV modules. Due to the critical nature of the application, the array size was conservatively increased to 24 modules. To reduce maintenance, a sealed lead-acid battery was selected, comprised of 12 two-volt cells in series (24 volts nominal), with a capacity rating of about 1200 ampere-hours at the nominal system load. This capacity provided sufficient electrical storage (autonomy) to operate the lighting system for over six days with no sunlight during the winter months. In June, the system energy demand is the lowest at about 2,450 watt-hours per day, or 74 percent of the December load. This results in an increase in battery autonomy from six to nine days.

Electrical Design - The control strategy for the system consists of a high-voltage array disconnect to prevent battery over-charging and a low-voltage load disconnect to prevent excessive battery discharge. To control the lighting load, a dc photocell closes the circuit between the lighting load and batteries at dusk and opens the circuit at dawn. An auxiliary or backup control operates the lights by utilizing the PV array as a light sensor.

Due to the long wire runs from the array to the battery and from the battery to the lights, wire sizes were selected to limit the overall voltage drop to less than four percent. Each of the 12 two-module series strings and luminaires were wired separately to minimize the wire sizes needed and to allow for easier troubleshooting if required.

Thirty-foot ground rods were installed on the guide sign structure to minimize the potential for equipment damage from lightning induced effects. The array frames, structure and metallic enclosures were all grounded to a common point. Surge suppressors and fusing were installed on all array source circuits and sensitive system components such as the charge controller and data acquisition unit.

Mechanical Design - The battery bank, combiner box and control components were located in a monolithic concrete equipment enclosure at the south base of the sign structure. Existing techniques employed for luminaire mounting were used to facilitate lamp and ballast replacements.

The photovoltaic array was mounted on the guide sign structure to reduce potential vandalism and shading, however this required special consideration of wind loading effects on the structure. To minimize this load, it was desirable to locate the arrays as close to the ends of the structure as possible without introducing any shading problems between arrays.

Due to the periodic occurrence of irresponsible target shooting directed at highway signs, impact shields fabricated from 1/8 inch aluminum plate were fastened to the back of the PV arrays to provide some measure of protection. To minimize the potential for higher array operating temperatures, the shields were installed in such a way as to allow adequate air circulation over the module back surfaces.

Another concern in the array mechanical design was to determine the minimum required spacing between arrays to prevent shading from the array in front during the winter months when the sun is lower in the sky. Knowledge of the sun's path in the sky over the entire year, as well as the physical dimensions of the array and surrounding obstructions is required to determine shading patterns on arrays. A simple graphic method involving the representation of critical angles on a profile angle protractor can be superimposed on the sun path diagram to determine times that shading will occur. With the given dimensions and tilt angle of the array mounting assemblies, a spacing of 80 inches was required between arrays to eliminate shading in the winter.

Design Summary - Component specifications for the PV guide sign lighting system are given in Table 10a-5.

Table 10a-5. PV Lighting System Specifications

Latitude:	28.45 °N	Battery:	GNB Absolyte II 12-75A27
Longitude:	80.88 °W	Battery Capacity:	1236 Ah
PV Module:	Solarex MSX-60	Lamps:	Sylvania Octron F032
PV Array Area:	13.4 m ²	Ballasts:	Iota 2D-24-F032
PV Array Rating:	1032 W	System Controller:	Integrated Power T-2

Photometric Tests - After installation, photometric measurements were conducted to compare the performance of the lighting system with accepted standards. Illuminance measurements averaged over the two sign faces were 13.5 and 15 footcandles, while the uniformity of illuminance was about 5:1. Luminance measured for the legend (text) was about 12 footlamberts, providing a brightness contrast with the sign background of nearly 8:1. Measurements taken after a three year period before initial lamp replacements showed a decrease in illuminance of only 20 percent, still meeting the recommended illumination levels for overhead highway signs in low ambient light areas (see Table 10a-4).

PV Array Performance - Current vs. voltage measurements (I-V curves) were conducted in the field to compare the actual rating of the PV array with the sum of individual module measurements taken previously. Based on translated field measurements, the PV array rating was determined to be approximately 1050 watts (36 amps at maximum power) at Standard Operating Conditions (SOC) of 1000 W/m² irradiance and 45° C cell temperature. The sum of the 24 individual module measurements corrected to 1 kW/m² irradiance and 45° C cell temperature gave a maximum power rating of 1167 watts with a maximum power current of about 38 amps. The 117-watt difference in these corrected performance measurements gives the magnitude of losses in the PV array source circuits, including wiring, fuses, diodes and module mismatch losses.

To calculate the power losses in wiring, an average length of 160-foot round trip from the array strings to the combiner box was estimated. For the no. 10 AWG stranded wire used in the array source circuits, a resistance of 1.79 ohms per thousand feet gives a source circuit wiring resistance of about 0.3 ohms. At 3 amps per each source circuit (12 parallel strings at 36 amps) this results in a power loss ($P=I^2R$) of 2.7 watts per string, or about 32 watts total. For the germanium blocking diodes, a 0.3 volt drop at 36 amps results in about 11 watts of power loss. Fuses on each of the twelve strings had a 0.4 volt drop resulting in about 15 watts power of loss at 36 amps. The total estimated losses in fuses, diodes and wiring amounts to approximately 58 watts for the PV array source circuits.

While these losses only account for half of the measured difference, the balance may be attributed to module current mismatch in the array and discrepancies between the accuracy of test methods.

Economic Analysis - During the initial phases of the project, the cost of utility service extension was explored. In general, if the utility can expect a 15 percent rate of return on their investment in extending utility service the extension is done at no charge to the customer. For this site, a budgetary estimate was obtained for overhead 7,620 volt service at \$9,000 per mile, or a total of \$45,000. The alternatives were to use a generator or design a PV system to light the signs.

To compare the economics of the PV system, utility service extension and generator, the economic analysis procedures in Section 10 of this manual were used assuming a 30-year PV system lifetime and regular replacement intervals for the battery and luminaires. The initial cost for the PV system was approximately \$20,000, including the PV array, batteries, system controller, luminaires, mechanical components and labor. Nominal costs and replacement intervals were obtained for typical 300-watt gasoline-fueled generators. Table 10a-6 summarizes the results of the economic analysis analyses.

Table 10a-6 Lighting System Economic Comparisons

	Present Cost	Present Cost per kWh	Initial Cost
PV	\$ 20,590	\$ 0.60	\$ 20,000
Generator	\$ 20,340	\$ 0.60	\$ 300
Utility	\$ 47,927	\$ 1.40	\$ 45,000

While the PV and generator systems appear competitive based on the assumptions made for this analysis, in application it is expected the PV system will require less attention and have higher reliability than a generator system. Utility extension costs are obviously prohibitive when compared to the PV and generator options.

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Utility Interconnection Considerations

11

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Utility Interconnection Considerations

11

Objectives

- 1) *Identify the advantages and disadvantages of three different kWh metering options for utility-interactive systems.*
- 2) *Compare safety issues associated with grid-connected PV systems and conventionally powered buildings.*
- 3) *Define power quality and explain its importance from the perspectives of both the homeowner and the utility company.*
- 4) *Describe the functions, selection criteria and power quality considerations of utility-interactive inverters.*
- 5) *For a given example, calculate the power factor.*

Key Words

Interconnection

Distribution box

PURPA

Metering

Single net metering

Dual metering

Simultaneous buy/sell

Isolation devices

Power quality

Frequency

Harmonic distortion

Grid-connected

Power factor

Flicker

ANSI

Utility-interactive inverters

Voltage control

Output frequency

Sinusoidal wave

Waveform

Resonance

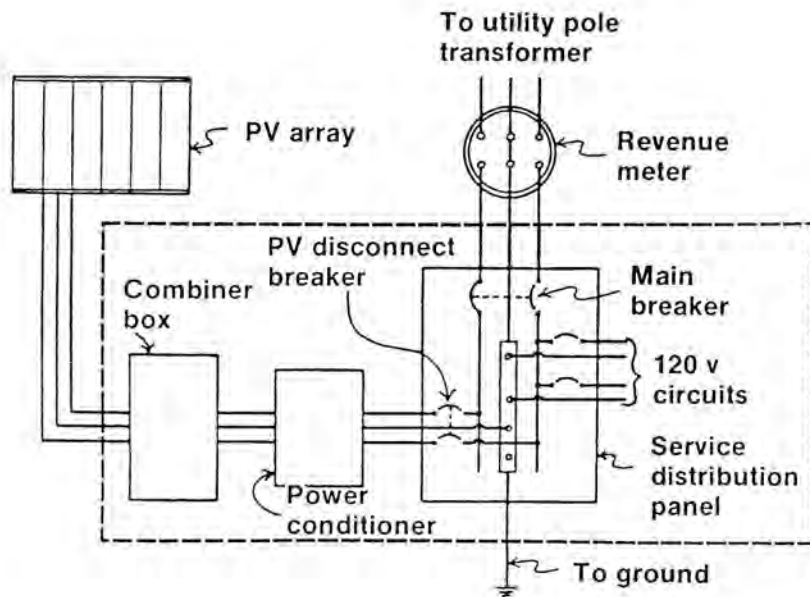
Capacitors

Inductors

11.1 Interconnection Methods

There are three basic ways that photovoltaic generated power can be interconnected to the utility power in a residence. The methods accomplish the same end but vary in the precise location of the connection and in the disconnection-switch geometry.

Figure 11.1 illustrates the first interconnection method, in which the photovoltaic system output is connected into the residence's utility-service distribution box through a 240-volt circuit breaker of appropriate current rating.

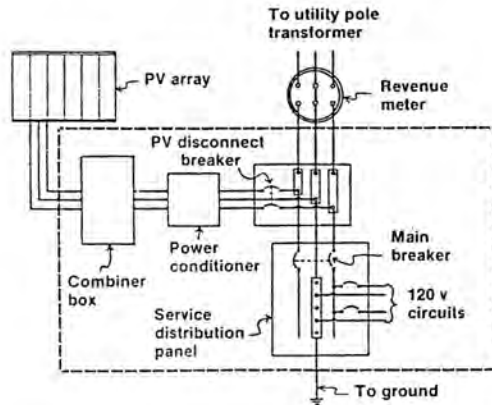


Source: M. Russell

Figure 11.1 Simplest interconnection method for photovoltaic system and utility

In this example, disconnecting the photovoltaic system from the utility and the conductors in the house simply requires switching the photovoltaic system circuit breaker to the off position. This arrangement offers not only simplicity (and low cost) but also convenience, since all disconnects (utility main, photovoltaic system and house circuits) are located on the same panel.

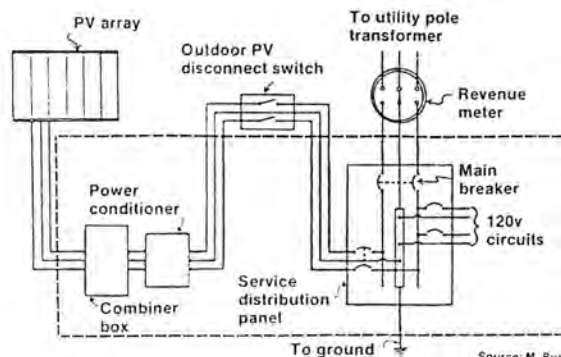
In the second interconnection method, illustrated in figure 11.2, the photovoltaic system output is connected to the incoming utility lines through a circuit breaker in a separate box on the utility side of the main utility service disconnect.



Source: M. Russell

Figure 11.2 Interconnect for photovoltaic system and utility using separate breaker box

The third interconnection method is a variation of the first and includes an outdoor disconnect switch that can be locked in the open position by a utility lineman. This action ensures that the line is not accidentally energized by the photovoltaic system. Figure 11.3 shows the location of the outdoor photovoltaic disconnect switch in the system.



Source: M. Russell

Figure 11.3 Outdoor photovoltaic system disconnect switch

11.2 Planning for Interconnection

While the Public Utilities Regulatory Policy Act (PURPA) requires utilities to interconnect any qualifying facility, it also requires the facility to pay for the cost of interconnection. The technical interconnection requirements imposed by utilities and the cost of these requirements must be considered early in the development of a small power production project. It is best to contact the utility early in the development of small power production projects to establish specific terms and conditions for interconnection. Terms and conditions for interconnection involve:

- Metering options
- Size restrictions on metering options
- Carryover credit on monthly bills
- Buy and sell rates
- Outdoor disconnect requirements
- Insurance requirements
- Interconnection costs.

11.3 Interconnection Issues

Because the utility is ultimately responsible for the power system, a request for interconnection of an independent power production facility to the utility raises several technical and operational issues including: metering, safety, equipment protection, service reliability and power quality.

Essentially, dispersed power-production facilities must 1) be metered to measure the power generated, 2) be safe for the utility customers and linemen, 3) have protection equipment to respond to abnormal conditions and 4) not significantly degrade power quality on the system.

11.3.1 Metering Options. Metering practices are set by contract terms between the producer and the utility. Meters required for a photovoltaic system are the standard accumulating kilowatt-hour meters with which the utility establishes monthly or periodic bills for the residence. A non-photovoltaic residence requires only one meter, which records energy consumed by the loads in the house. For a photovoltaic system the

number of meters required and their placement in the system depends upon the utility's policy on the value of photovoltaic-generated energy relative to utility-supplied energy.

There are three metering methods which may be offered by utilities for monitoring the energy flows associated with the photovoltaic residence: single net metering, dual metering and simultaneous buy/sell metering.

11.3.1.1 Single Net Metering. In single net metering a bidirectional meter is required (although two may be used) and is connected at the point where the utility service enters the house as illustrated in figure 11.4. Electricity flow from the photovoltaic residence back through the meter to the utility causes the meter's reading to decrease, while utility-supplied energy increases the meter reading.

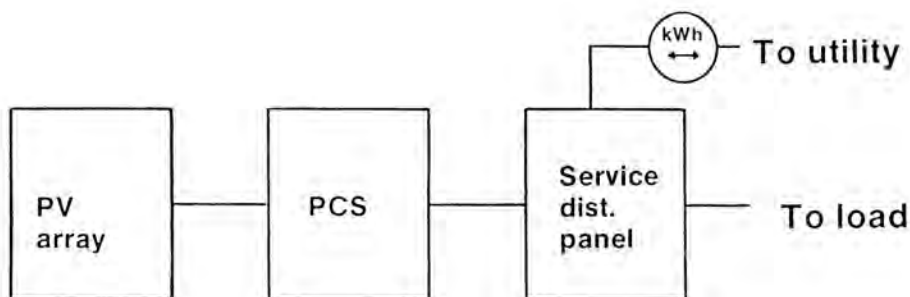


Figure 11.4 Single net metering

Net metering requires that the utility value the energy that the photovoltaic system generates be the same as the energy that the utility supplies to the residence. When this is the case, the buyback ratio (ratio of the price paid by the utility for photovoltaic-generated energy to the price the homeowner pays for utility supplied energy) is one. The meter would read just the same as that in a nonphotovoltaic residence, and the bill would be based upon the net amount of utility energy used over the billing period.

11.3.1.2 Dual Metering. Dual metering permits photovoltaic-generated energy sent back to the utility to be valued differently than the energy supplied to the residence by the utility. Figure 11.5 shows that this arrangement involves the use of two meters.

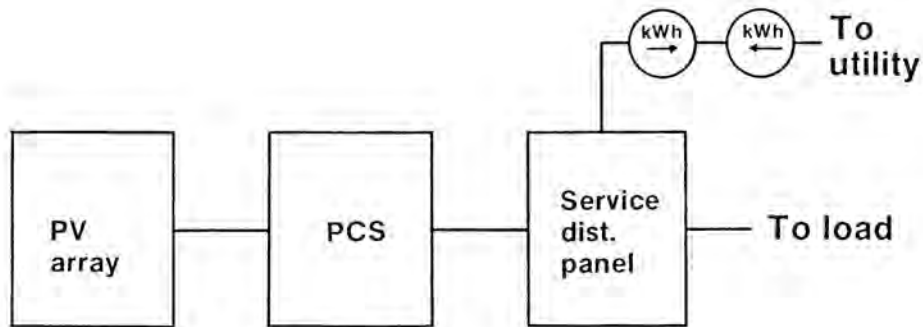
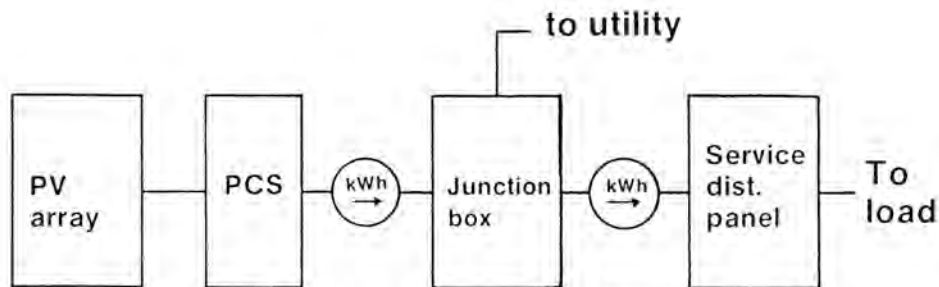


Figure 11.5 Dual metering

The meters are ratcheted so that they can respond to energy flow only in one direction. One of the meters records all utility-supplied energy coming into the residence, and the other records all photovoltaic-generated energy going to the utility. Note that a single-net meter would simply display the difference between these dual meters.

11.3.1.3 Simultaneous Buy/Sell Metering. This option will always be offered as mandated by PURPA. Simultaneous buy/sell metering also uses two meters as illustrated in figure 11.6. One of the meters records all of the photovoltaic-generated energy (not just that which is sent to the utility, as in dual metering), and the other records all the energy supplied to the load (regardless of the energy's origin – photovoltaic or utility). A bill is rendered based upon the reading of these two meters, using a different value attached to the energy accumulated on each.



Source: M. Russell

Figure 11.6 Simultaneous buy/sell metering

Only in the situation where photovoltaic-generated energy is valued higher than the utility-supplied energy would simultaneous buy/sell metering be the homeowner's metering choice. Simultaneous buy/sell metering is used primarily for power producers much larger than a residential photovoltaic system, where the on-site load is negligible in comparison with the photovoltaic system's generation capacity.

11.3.2 Safety. Questions and concerns involving safety issues are:

- How can utilities be assured that distribution lines will not be accidentally energized by independent power producers?
- How reliable are isolation devices provided by the independent producer?
- What additional devices and equipment should be provided?

On safety issues, the utility must be conservative. It is the utility that is ultimately responsible for the electrical transmission and distribution system. Situations might arise in which a fuse or recloser isolates a section of line on which some independent generators are operating. The combination of line capacitance and load could possibly cause the generators to keep operating, resulting in a safety hazard to line crews working on the distribution system. Work rules may require manual disconnect and visual verification by the utility or live-line work procedures before line crews can work on deenergized lines. There must also be a means of disconnecting under utility control to isolate the independent power producer from the system.

11.3.3 Equipment Protection. The introduction of independently produced power raises questions about equipment and line protection.

- How can utilities be assured that power system equipment will be protected against damage from normal and abnormal operation by the independent producer?
- Will feeder line sectionalizing devices operate correctly with independent generators operating in parallel?

The power producer must be disconnected when faults or other abnormal conditions occur on the utility system. Protection equipment that interrupts short circuits on the customer side is required by code. However, the effects of short circuits on the customer side and the associated protection equipment may disrupt the coordination of fuses and other sectionalizing devices in the distribution system.

Power system protection is designed to minimize service interruptions to customers while isolating the problem. Fuses, reclosers, and relay-operated feeder circuit breakers that respond to current are all coordinated to ensure that the equipment nearest to the fault (between the fault and substation) will trip first, isolating a minimum number of customers.

Fuses or other devices under the control of utilities may be required at the independent power production facility to maintain system coordination. Line sectionalizing schemes must also be reevaluated if various independent power producers are interconnected. Small systems are not likely to contribute significantly to fault currents. However, if large systems or a large number of small producers are added in a specific locality, problems may arise.

11.3.4 Service Reliability. Providing continuous, reliable service is a major goal of all utilities. Consequently, it is important that malfunctions in photovoltaic systems be isolated from the distribution system so that unnecessary interruptions to nonphotovoltaic customers can be avoided.

11.3.5 Power Quality. Interconnection of uncontrolled power producers raises several questions regarding the quality of power.

- Will the power supplied by the independent producer degrade the utility system quality?
- Specifically, will power quality variations cause problems for other utility customers?
- If interference problems result from operation of an independent producer, who would be available to provide assistance and at whose expense?
- Should these independent producers be required to meet specific wave shape and noise objectives?

Small power production facilities should be designed to maintain power system quality. Power quality is evaluated in terms of voltage, frequency, harmonic distortion, power factor and flicker.

Utilities provide power within fixed ranges of voltage and frequency so electric appliances and other equipment will not be damaged. The typical 120/240-volt, single-phase power provided to residences is within 114-125/228-252 volts in accordance with the Standard System Voltages (recommended by the American National Standards Institute; ANSI C84.1). It is reasonable to expect dispersed generation facilities to provide power within these same limits.

Alternating current equipment and power systems need a relatively smooth, undistorted waveform. Distortions (or harmonics) are voltages or currents at frequencies that are multiples of the 60-Hz fundamental frequency. Inordinate levels of harmonic voltages and currents can cause excessive heating of motors, transformers and capacitors as well as communications interference.

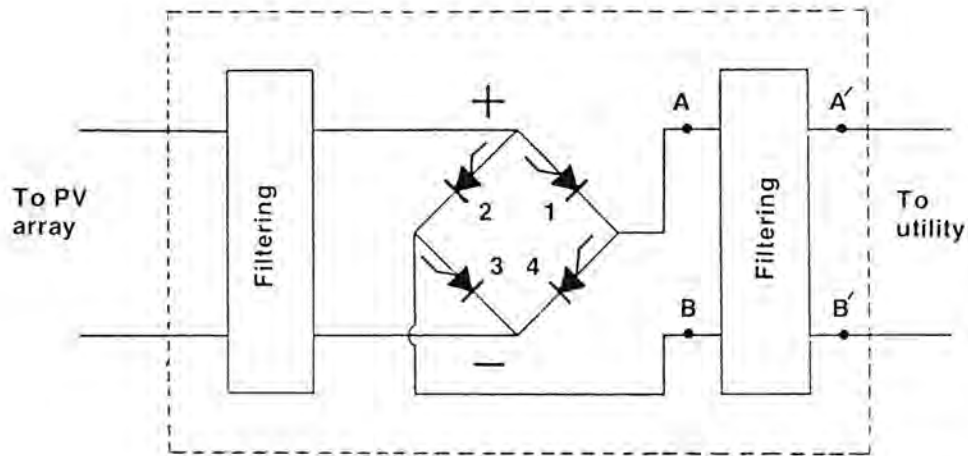
Harmonic content must be limited to avoid interference and damage to equipment and other customers. The inverter or power conditioning subsystem (PCS) used in photovoltaic power production facilities should be designed to minimize harmonic generation. If objectionable harmonics are produced by independent power producers, the utility may require that filters or other equipment be installed by the producer to eliminate problems.

An additional power quality problem is flicker due to voltage variations. Flicker causes visible flickering of incandescent lamps and shrinking and expanding pictures on television screens. It is caused by varying output of power producers. The exact level where flicker becomes objectionable is difficult to establish. The greatest effects would be on the premises of the production facility or others served by the same transformer. The utility may require suitable equipment to limit flicker or a dedicated transformer to limit the effects on other customers.

11.4 Utility-Interactive Inverters

11.4.1 Functions. In a utility-interactive photovoltaic system, an inverter not only converts dc electrical energy to ac electrical energy, it also functions as the control or brain of the system, allowing energy to flow to and from the grid.

A properly designed inverter should ensure the safety of the system, maximize ac energy generation consistent with the array operating at the maximum power point, ensure high conversion efficiency, and deliver high power quality. Figure 11.7 shows an electronic bridge consisting of four silicon-controlled rectifiers that act as high-speed switches to convert direct current into alternating current. In addition, filters are used to eliminate unwanted harmonics from the alternating current signal.



Source: M. Russell

Figure 11.7 Simplified utility-interactive inverter block diagram

11.4.2 Matching the Inverter and Array. The array's maximum power voltage at SOC should be compatible with the inverter dc input nominal voltage.

As an example, for Miami, the array maximum power voltage (V_{mp}) at SOC conditions (1 kW/m^2 insolation and NOCT) should be about 7% higher than the inverter dc input voltage plus the voltage drop across blocking diodes and dc wiring. For 200-volt dc nominal input inverter, the optimum array V_{mp} at SOC is about 216 volts ($200/0.93 + 2$ volts drop across diodes and wiring).

Array maximum power voltage under extreme meteorological conditions (high temperature with low insolation and low temperature with high insolation) should be within the inverter dc voltage range of operation. Energy loss due to inverter inoperation caused by voltage dc thresholds should be minimized, preferably less than 1% on an annual basis.

The maximum array open-circuit voltage (at high insolation and low temperature) should be well within the inverter survival voltage range.

11.4.3 Voltage Control. The two most common means of controlling the operating voltage of a photovoltaic array are: 1) maximum power point tracking and 2) fixed-voltage operation. Because maximum power point tracking can be accomplished simply and inexpensively with modern electronics, it is the most common and preferred means of voltage control for utility-interactive inverters.

11.4.4 Matching the Inverter and the Utility. It is important that the inverter output be compatible with the utility signal. The output voltage and frequency should be within prescribed limits of the corresponding utility values.

11.4.4.1 Inverter Output Requirements. The output frequency of the utility-interactive inverter must be synchronized with the utility signal. Also, to protect the utility distribution system, connected loads and appliances, the inverter should operate only in a narrow range of utility frequencies. The recommended range of utility frequencies for inverter operation is from 59.5 to 60.5 Hz. This narrow range of operational frequencies has been recommended by Sandia National Laboratories to alleviate some of the concerns of utilities.

11.4.4.2 Efficiency and Power Losses. The efficiency of an inverter is simply the output power divided by the input power. Typical peak efficiencies for utility-interactive inverters vary between 0.85 and 0.98. Average operating values are lower and depend on how well the inverter and array are matched in size. In addition to power losses associated with efficiency of the inverter during normal operation, the inverter also suffers standby power losses at night or when there is insufficient input power to produce an inverter output.

11.4.4.3 Power Quality. The power quality of the inverter output signal is determined by two parameters: harmonic distortion and power factor.

The utility service voltage is nominally sinusoidal at 60 Hz. The inverter output voltage and current waveforms may deviate, however, from a purely sinusoidal 60 Hz signal. Any distorted waveform can analytically be shown to consist of a 60 Hz (fundamental) frequency and higher harmonic frequencies (multiples of 60 Hz). Figure 11.8 shows a pure sine wave with no harmonic distortion, together with a square sine wave that has high distortion and a more typical inverter output signal that shows some distortion.

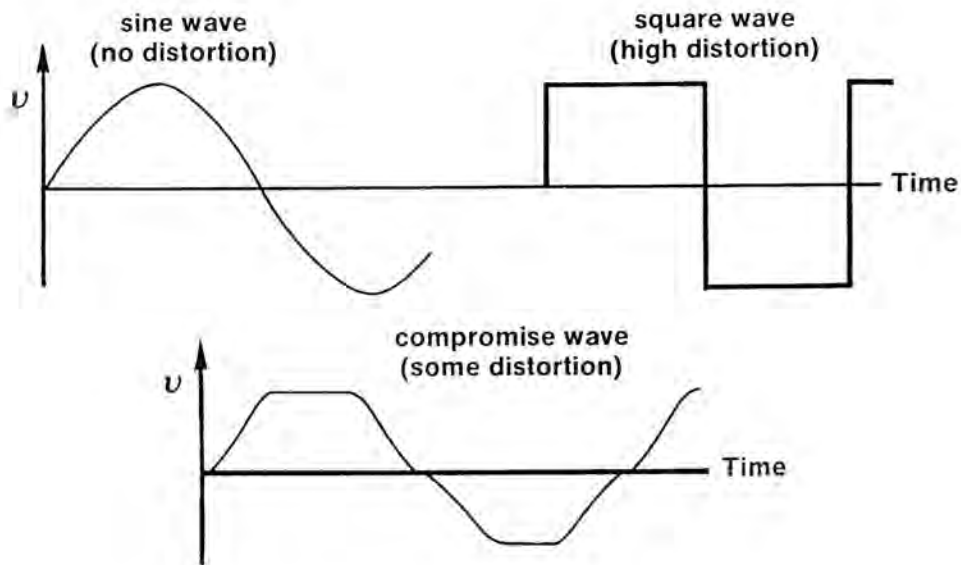
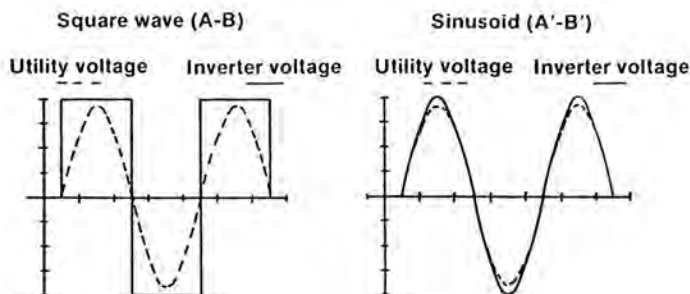


Figure 11.8 Harmonic distortion

The square root of the sum of the squares of the amplitudes of the individual harmonics, divided by the amplitude of the fundamental frequency, is called the total harmonic distortion (THD) of the waveform (current or voltage).

The current harmonics injected into the utility grid also produce voltage harmonics, whose magnitudes depend on the utility system impedance at the harmonic frequencies. Because the utility system impedance is usually low, the voltage THD is much lower than the current THD.

Harmonic distortion can be detrimental to connected loads and utility equipment because the higher-frequency components generate heat in the transformer, induction motors and other loads. This and the possibility of resonance from the combination of utility reactive components (capacitors and inductors) at harmonic frequencies have led to recommended limits on inverter output harmonic distortion. For a good quality utility-interactive inverter, the current THD should be less than or equal to 5%, and the voltage THD should be less than or equal to 2%. Single frequency harmonic components should be less than or equal to 3% for current distortion, and less than or equal to 1% for voltage distortion. Figure 11.9 illustrates the effect of filters in the power conditioning subsystem, which eliminate harmonic frequencies to produce a nearly sinusoidal signal.



Source: M. Russell

Figure 11.9 Wave shaping using filters

Power factor is defined as power supplied divided by the product of current and voltage output. If the voltage and current output are in phase, then the power factor is unity and all the volt-amperes are used to do work. If the power factor is less than unity, then volt-ampere output of the system is greater than the useful power measured in watts.

Figure 11.10 shows that when the voltage and current signals are out of phase, the product of voltage and current (i.e., power) can be negative as well as positive. This is in contrast to when the voltage and current are in phase, producing only positive power output. Consequently, power factor is a measure of the percentage of usable power output for the inverter.

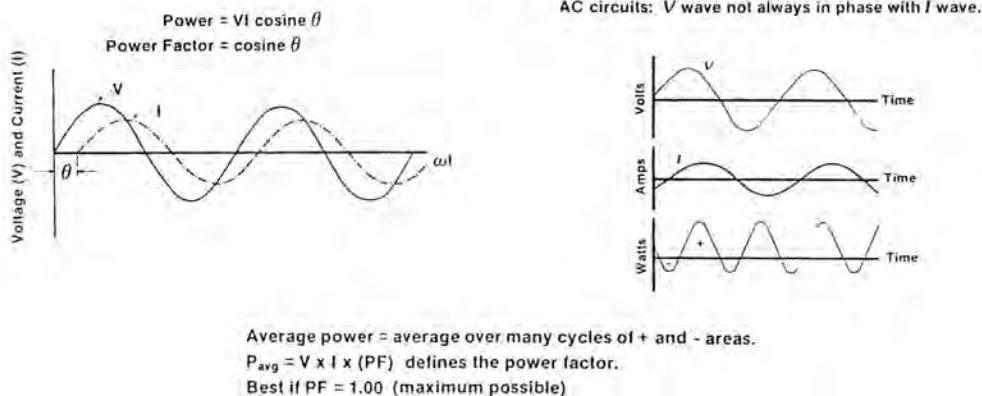


Figure 11.10 Power factor

With a lower power factor, not only do the transmission losses increase but also the utility system has to be designed to handle more volt-amperes, thus requiring oversized distribution system components. Also a lower power factor may affect voltage regulation. The recommended range of power factors for grid-interactive inverters is from 0.95 lagging (inductive) to 0.95 leading (capacitive).

11.4.5 Safety and Protection Features. Safety and protection features that inverters must possess in order for the photovoltaic system to be acceptable to the utility include:

- Loss of utility protection
- Fault protection (over-current protection)
- Input dc under/over voltage protection
- Output ac under/over voltage protection
- Under/over frequency protection
- Surge suppression
- Input and output power limitations.

Any time the utility line voltage or frequency, as measured at the residence, lies outside the normal operating range, the photovoltaic system's inverter should automatically cease operating and disconnect itself from the house service distribution panel. Normal operation may be defined differently by different utilities.

The utility wants to know that the photovoltaic system includes equipment that will preclude the possibility of array dc power being introduced onto the utility power lines under any circumstance. To meet this requirement, a so-called isolation transformer has become standard equipment on most of the power conditioners (inverters) that are intended for use in utility-interconnected photovoltaic systems.

11.4.6 Physical and Environmental Considerations. Physical and environmental considerations include inverter size, weight, acceptable range of ambient temperatures, acceptable range of ambient relative humidities, type of mounting configuration, wiring terminations, cabinet construction and materials, and the associated National Electrical Manufacturers Association (NEMA) rating.

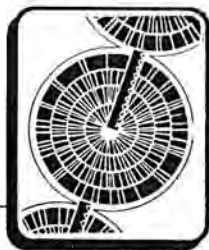
11.4.7 Instrumentation. Unless the inverter is to be used as a research tool, sophisticated instrumentation is not recommended, because usually this type of instrumentation is more problematic than other inverter components. Most inverters include several meters to provide voltage and current output information.

References:

- Russell, Miles C., *Residential Photovoltaic System Handbook*, Reading, MA: Sundance Publications, 1984. p. 204-213.
- Atmaram, Gobind H., "*Characteristics of Grid-Interactive Residential Inverters*," **Fundamentals and Applications of Photovoltaics**, Cape Canaveral, FL: Florida Solar Energy Center, 1983, pp. 7-1 through 7-20.
- Healey, Henry, "*Utility Interconnection Issues and Requirements*," **Fundamentals and Applications of Photovoltaics**, Cape Canaveral, FL: Florida Solar Energy Center, 1983, pp. 10-3 through 10-12.

Exercises

1. For utility-interactive systems, list three different metering options. In general, is the homeowner free to choose the metering option he/she wants?
2. Explain why some utility companies may require an outdoor disconnect switch.
3. List four reasons why photovoltaic system and utility interconnection is of much concern to utility companies.
4. What are harmonic distortion and power factor? Explain why you, your neighbors and the utility company should be concerned if the output of your power conditioning subsystem is poor quality electrical power.
5. In terms of dollars per watt, would you expect utility-interactive photovoltaic systems to be more or less costly than stand-alone photovoltaic system? Explain.



Glossary

The number in parentheses refers to the section in which the entry can be found.

AC (7) - See *alternating current*.

Adjustable tilt array (2) - An array with a support structure that enables the tilt angle to be altered (usually seasonally) to maximize the amount of insolation gathered.

Air mass (2) - A measure of distance that light travels through the earth's atmosphere.

Air mass zero (2) - The condition immediately outside the earth's atmosphere where sunlight is not attenuated by atmospheric effects.

Allowable depth of discharge (6) - The maximum fraction of battery capacity that can be withdrawn without permanently damaging the battery.

Alternating current (7) - Electric current that reverses its direction of flow, usually 120 reversals (60 cycles) per second; symbolized *AC* or *ac*.

Ambient temperature (5) - The temperature of the environment surrounding a device or apparatus.

Ampere-hour (5) - A measure of electrical charge.

Angle of incidence (2) - The angle between a ray striking a surface and a line perpendicular to that surface. Rays perpendicular to the surface have zero angle of incidence.

ANSI (II) - American National Standards Institute.

Array (4) - A collection of photovoltaic modules, electrically wired together and mechanically installed in their working environment.

Autonomous operation (5) - Self-contained operation. Capable of existing independently.

Azimuth (2) - The angular measure between due south and the point on the horizon directly below the sun.

Balance-of-system (BOS) components (5) - Components of a photovoltaic system other than the array, such as the support structure, storage components, power conditioning equipment and electrical hardware.

Battery bus voltage (6) - The nominal operating voltage of a battery subsystem and photovoltaic array.

Battery charger (6) - A device that converts alternating current produced by a generator into direct current charge batteries.

Battery round-trip efficiency (6) - The ratio of the energy output to the energy input during a full discharge-charge cycle.

Block V (4) - Module qualification tests designed and conducted by the Jet Propulsion Laboratory. Modules undergo electrical performance measurements and mechanical tests, such as thermal cycling, humidity-freezing, cyclic pressure loading, hail-impact and twisted mounting surface requirements.

Blocking diode (4) - A device for preventing a reverse flow of current through photovoltaic modules (also called a *series diode* or an *isolation diode*).

Bypass diode (4) - A device placed in parallel with a photovoltaic module or group of modules allowing a route for the current under conditions of shading and cell failure (also called a *shunt diode*).

Capacitor (11) - An electrical device that blocks the flow of direct current and allows the passage of alternating current. It usually consists of two or more parallel conducting plates separated by an insulation. Voltage applied across the plates leaves one plate positively charged and one negatively charged, creating an electric field, and enabling the capacitor to store energy. (Compare with *inductor*.) Capacitance is measured in farads (f) or microfarads (μ f).

Capacity (5) - The quantity of electrical charge that a battery can store under specified conditions.

Cell efficiency (3) - The ratio of the electrical energy produced by a photovoltaic cell (under full sun conditions) to the energy from sunlight falling upon the cell.

Charge controller (5) - A component that controls the flow of current to and from the battery subsystem to protect the batteries from overcharge and overdischarge. The charge controller may also monitor system performance and provide system protection.

Circuit breaker (7) - A switch that automatically interrupts an electrical circuit when excessive current is present.

Combiner box (or panel) (7) - An electrical box where wiring terminates and where switches, fuses, blocking diodes and surge arrestors are often located.

Concentrator array (2) - A photovoltaic array that uses optical lenses and mirrors to focus sunlight onto small, high efficiency cells. Concentrator arrays usually directly face or track the sun.

Conductor (7) - A wire, cable or other medium suitable for carrying (and offering low resistance to) electric current.

Current (3) - The rate of flow of electrical charge; the net transfer of electrical charge per unit time.

Current-Voltage (I-V) characteristic (3) - The output current of a photovoltaic generator at a particular temperature and irradiance, plotted as a function of output voltage.

Cycle (5) - The unit of time used to measure battery life span. One period of battery charge-discharge is one cycle.

Days of storage desired/required (6) - The number of days without sunshine for which the battery storage system must provide electrical energy.

DC (7) - See *direct current*.

Depth of discharge (5) - The fraction of battery capacity withdrawn during discharge.

Design temperature (6) - The temperature at which a device is designed to operate.

Design tilt (6) - The tilt of the array at which design and sizing calculations are made. Often the design tilt is optimized for energy output under prescribed conditions.

Diffuse radiation (2) - Sunlight received indirectly as a result of scattering due to clouds, fog, haze, dust or other substances in the atmosphere.

Diode (4) - A semiconductor that allows current to flow in only one direction.

Direct-coupled (6) - Direct connection of a photovoltaic array to a load without an intermediate battery or electronic device.

Direct current (7) - Electric current that flows in only one direction - from positive to negative; symbolized *DC* or *dc*.

Direct mount (8) - A method of mounting a photovoltaic array to a roof by affixing it directly to the roofing material of the building.

Direct radiation (2) - Light that has traveled in a straight path from the sun (also referred to as *beam radiation*). An object in the path of direct radiation casts a shadow on a clear day.

Direct strike interception (7) - The use of highly conductive equipment (e.g., lightning rods) to dissipate lightning's energy, thereby diverting it from and protecting sensitive electrical equipment.

Discharge head (6) - The vertical distance from the center of a pump to the point of free discharge.

Discount rate (10) - An annual percentage rate used to reduce the value of future dollars in relation to present dollars.

Distribution box (11) - The point at which the photovoltaic system output is wired to load circuits and to the incoming utility line.

Dual metering (11) - Using two meters to monitor electricity. One measures the electricity sent onto the utility grid, and the other measures the electricity drawn from the utility grid.

Dynamic head (6) - The measure of pressure required to move a liquid at a given velocity and to overcome effects due to friction.

Economic assumptions (10) - Those conditions stated and used to compare the economics of various systems.

Electrical load (5) - See *load*.

Electrolyte (5) - A non-metallic electric conductor in which current is carried by the movement of ions.

Energy (2) - The capacity to do work.

Equalizing charge (5) - Overcharging a battery bank to restore equality in the state of charge of individual battery cells.

Fill factor (3) - The ratio of maximum power to the product of open-circuit voltage and short-circuit current. Fill factor is the "squareness" of the I-V curve shape.

Finishing charge (5) - The charge near battery full state of charge.

Fixed orientation (2) - An orientation (of an array, for example) that does not change with time.

Flat-plate array (2) - A photovoltaic array in which the incident solar radiation strikes a flat surface and no concentration of sunlight is involved.

Flicker (II) - Irregular or unsteady flow of current.

Flow rate (6) - The rate at which water is delivered by a pump, usually measured in gallons per minute.

Frequency (II) - The rate at which a periodic event occurs. For example, alternating current (ac) in the U.S. has a frequency of 60 cycles per second, i.e., 60 Hertz (60 Hz).

Friction head (6) - The equivalent feet of head required to overcome energy lost as fluid flows through a pipe.

Fuel escalation rate (10) - An annual percentage rate used to compensate for future increases in the price of fuel.

Fuse (7) - An electrical safety device consisting of or including a wire or strip of fusible metal that melts and interrupts the circuit when the current exceeds a certain amperage.

Generator (6) - A device by which mechanical energy is changed into electrical energy.

Grid-connected (II) - An energy producing system connected to the utility grid. (Also called *utility-interactive*.)

Grounding (7) - Connection to a large conducting body (such as the earth), which is used as a common return for an electrical circuit and as an arbitrary zero potential.

Harmonic distortion (II) - A measure of undesirable electrical signals in a circuit.

Head (6) - A measure of height a pump must lift water. A unit of pressure usually given in inches or feet of water. Thirty-two feet of water equal one atmosphere of pressure.

Heat sink (7) - A device with large surface area used to dissipate heat.

Holes (3) - Vacancies where electrons would normally be in a perfect crystalline structure.

Hybrid system (I) - A power system consisting of two or more power generating subsystems (e.g., the combination of a wind turbine and a photovoltaic system).

Hydraulic energy (6) - The mechanical energy required for a pump to deliver a given quantity of liquid at a given pressure.

Hydraulic power (6) - The mechanical power required for a pump to deliver a given quantity of liquid at a given pressure.

Imp (3) - See *maximum power current*.

Inductor (11) - An electrical device, generally in the form of a coil, that blocks the flow of alternating current and allows the passage of direct current. (Compare with *capacitor*.) Inductance is measured in henrys (H), microhenrys (μ H) or millihenrys (mH).

Inflation rate (10) - The annual percentage rate of increase in the amount of money required to purchase the same goods over a period of time.

Infrared radiation (2) - Radiant energy of wavelengths exceeding 7600 angstroms and not visible to the human eye.

Insolation (2) - The amount of sunlight reaching an area. Usually expressed in watts per square meter per day.

Integral mount (8) - A method of mounting a photovoltaic array in which the array replaces the roofing material.

Interconnection (11) - The connecting of an electric generating system to the utility grid.

Inverter (5) - An electrical component which converts dc power to ac power (usually at 60 cycles per second).

Irradiance (2) - Radiant flux density. Solar power per unit area.

Irradiance enhancement (8) - Methods used to increase the solar power per unit area falling on the photovoltaic device, such as optimizing orientation, seasonally adjusting tilt, sun-tracking and concentrating.

Isc (3) - See *short-circuit current*.

Isolation device (11) - A device that electrically isolates a utility-interactive inverter from the utility grid so that failure in a photovoltaic system does not cause hazard to the utility grid operation.

Junction box (7) - A protective enclosure into which wires or cables are led and connected.

Life cycle costing (10) - A method of economic evaluation that recognizes the sum total of all costs associated with a system during the time it is in use.

Load (3) - Electrical power being consumed at any given moment. The load that an electric generating system supplies varies greatly with time of day and to some extent season of year. Also, in an electrical circuit, a load is any device or appliance that is using power.

Maintenance costs (10) - Any costs incurred in the upkeep of a system. These costs may include replacement and repair of components.

Maximum power current (Imp) (3) - The corresponding current for the maximum power point on an I-V curve.

Maximum power point (Pmax) (3) - The desired operating point on an I-V curve where the product of the current and voltage (power) is maximized.

Maximum power voltage (Vmp) (3) - The corresponding voltage for the maximum power point on an I-V curve.

Metering (11) - The method of measuring and recording electricity that is produced, consumed or sold.

Module (4) - A number of photovoltaic cells electrically wired together, usually in a sealed unit of convenient size for handling and assembling into panels and arrays.

Mounting configurations (8) - Methods for supporting photovoltaic arrays either on the ground or a roof.

NEMA (5) - National Electrical Manufacturer's Association.

NOC (4) - See *nominal operating conditions*.

NOCT (3) - See *nominal operating cell temperature*.

Nominal operating cell temperature (NOCT) (3) - The photovoltaic cell junction temperature corresponding to nominal operating conditions in a standard reference environment of 1 kW/m² irradiance, 20°C ambient air temperature, 1 m/s wind, and electrically open circuit.

Nominal operating conditions (NOC) (4) - Photovoltaic device operation under conditions in a standard reference environment of 0.8 kW/m² irradiance, 1.5 air mass, and cell temperature at NOCT conditions (0.8 kW/m², 20°C ambient air temperature, 1 m/s wind, and electrically open circuit).

Normal incidence (2) - Solar radiation that is perpendicular to the receiving surface.

Open-circuit voltage (Voc) (3) - The voltage output of a photovoltaic device when no current is flowing through a circuit.

Operating costs (10) - The costs of using a system. For stand-alone systems with generators these costs include all fuel costs over the system's lifetime.

Orientation (2) - The surface slope and surface azimuth angle of a photovoltaic device.

Output frequency (11) - The frequency of the ac voltage or current output from an inverter – usually 60 cycles per second.

Over-current protection (5) - The use of devices such as fuses and circuit breakers to protect conductors and other electrical components from excessive current.

Panel (4) - A number of modules wired together, which in turn can be wired to other panels to form an array.

Parallel connected (4) - A method of connection in which positive terminals are connected together and negative terminals are connected together. Current output adds and the voltage remains the same.

Passive trackers (2) - Tracking devices that rely on the sun and/or the local environment for their source of tracking power.

Peak flow rate (6) - The flow rate of water (or other liquid) through a pumping system under peak or full sun conditions.

Peak sun hours (2) - The equivalent number of hours at peak sun conditions (i.e., 1 kW/m^2) that produces the same total insolation as actual sun conditions.

Peak velocity (6) - The velocity of water (or other liquid) through a pumping system under peak or full sun conditions.

Photon (3) - The actual (physical) particle unit of light. Light has both wave properties and particle properties.

Photovoltaic cell (3) - The basic device that converts light into dc electricity; the building block or photovoltaic modules.

Photovoltaic device (Lab) - A photovoltaic cell, module, panel or array.

Plug/receptacle connectors (7) - Wire connectors that allow for rapid interconnection of modules with no special tools and increased safety. A male plug fits into a female receptacle.

P_{max} (3) - See *maximum power point*.

p-n junction (3) - The junction formed at the interface between two differently doped layers of semiconductor material, one layer being doped with a positive-type dopant, the other with a negative-type dopant. An electric field is established at the p-n junction with gives direction to the flow of light-stimulated electrons.

Potential energy (3) - The capacity to do work that a body or system has due to its position or configuration.

Power (2) - Rate of doing work or expending energy.

Power converter (5) - A device that converts dc electricity at one voltage into dc electricity at another voltage.

Power density (5) - Power per unit area.

Power factor (11) - A measure of the phase difference between ac voltage and ac current. A power factor of unity is desirable for the output of inverters used in photovoltaic systems.

Power quality (11) - A measure of how well an ac signal compares with a pure sine wave.

Present value (10) - The value of electricity per kilowatt hour.

Present worth (10) - The worth of a system determined by adding the initial cost of the system to the present costs of all replacements that must be made during the system's lifetime and any operating costs (such as fuel).

Pressure head (6) - The equivalent feet of water needed to produce a given pressure.

Primary battery (5) - A battery that cannot be recharged once it has been discharged.

Protection diodes (7) - Solid state devices that protect modules from overheating and from reverse flow of current.

PURPA (11) - Public Utilities Regulatory Policies Act. Federal legislation which mandates that utilities must allow small power producers (such as residential photovoltaic systems) to connect to their grids, and that utilities must pay a fair price for photovoltaic-generated electricity that is delivered to the utility grids.

Rack mount (8) - A method of connecting an array to the ground or a roof such that the array makes a non-zero angle with the mounting surface.

Radiant-flux density (2) - Irradiance. Solar power per unit area, usually measured in kW/m².

Rated wattage (6) - The amount of electrical power required to operate a device.

Real discount rate (10) - The nominal discount rate minus the inflation rate.

Regulator (5) - A device that maintains a quantity (such as voltage) in a predetermined range or varies it according to plan.

Repair and replacement costs (10) - The costs of returning a system to its original working condition.

Required battery capacity (6) - The capacity of battery storage needed for a given system determined by dividing the days of storage required/desired by the daily allowable depth of discharge and then multiplying this number by the total amp-hour demand per day.

Resistance (3) - The opposition that a device or material offers to the flow of current.

Resonance (11) - A phenomenon wherein excitation causes a component to oscillate at its natural frequency, amplifying the signal several-fold.

Roof load (8) - Any weight the roof must support, including dead loads (roofing materials), live loads (wind, snow) and added loads (photovoltaic array).

Secondary battery (5) - A storage battery that can be recharged repeatedly by sending a current through it in a reverse direction.

Self-discharge rate (5) - The rate at which a battery discharges when it is idle. For many batteries the self-discharge rate increases as the battery gets older.

Semiconductor material (3) - A material with an atomic structure such that it has an electrical conductivity intermediate between an insulator and a metal. This material's conductivity can be greatly influenced by the addition of doping agents.

Series block (4) - A unit of the photovoltaic system composed of two parallel strings.

Series connected (4) - A method of connection in which the positive terminal of one device is connected to the negative terminal of another. The voltages add and the current is limited to the least of any device in the string.

Shielding (7) - Protecting metal conductors with armored cable so that the effects of lightning are significantly reduced.

Short circuit (3) - The condition that exists when positive and negative terminals of an electrical device are connected to each other without intermediate loads or circuit elements.

Short-circuit current (I_{sc}) (3) - The current flowing freely from a photovoltaic cell through an external circuit that has no load or resistance; the maximum current possible under normal operating conditions.

Simultaneous buy/sell metering (11) - A metering method that uses two meters – one to record all of the photovoltaic-generated electricity and one to record all of the energy supplied to the load (from both the photovoltaic system and the utility). The utility bill is based on the reading of these two meters, attaching a different value to the energy on each.

Single net metering (11) - A metering method in which a bidirectional meter is connected at the point where utility service enters a building. Photovoltaic-generated electricity flowing from the building back through the meter causes the reading to decrease while utility-supplied energy causes the reading to increase.

Sinusoidal wave (11) - A type of alternating current generated by utility companies, rotary inverters, sophisticated solid-state inverters, and alternating-current (ac) generators.

SOC (4) - See *standard operating conditions*.

Solar constant (2) - The rate at which energy is received from the sun just outside the earth's atmosphere on a surface perpendicular to the sun's rays. Approximately equal to 1.36 W/m^2 .

Solar power density (2) - Solar power per unit area.

Solar spectrum (2) - The total distribution of electromagnetic radiant solar power over the band of wavelengths present in solar radiation.

Solar window (2) - The area in the sky above a given location through which all of the solar direct radiation passes throughout the year.

Specific gravity (5) - The ratio of the mass of a substance to the mass of an equal volume of distilled water at 39.2°F (4°C).

Splice connection (7) - A type of electrical wiring connection.

Stand-alone photovoltaic system (1) - An isolated photovoltaic system not connected to an electric utility grid. The system may or may not have storage, but most stand-alone applications require battery or other form of storage.

Standard operating conditions (SOC) (4) - Photovoltaic cell operation under conditions in a standard reference environment of 1 kW/m^2 irradiance, 1.5 air mass, and cell temperature at NOCT conditions (0.8 kW/m^2 , 20°C ambient air temperature, 1 m/s wind, and electrically open circuit).

Standard test conditions (STC) (4) - Test conditions in a standard reference environment of 1 kW/m^2 , 25°C cell temperature and 1.5 air mass spectrum.

Standoff mount (8) - A method of supporting a photovoltaic array above and parallel to a roof.

Static head (6) - The total head required to lift the water to a desired level and to store it in a tank at a prescribed pressure – the sum of the suction lift (or head), discharge head and pressure head.

STC (4) - See *standard test conditions*.

Subsystem (5) - A major, separable, functional assembly of a system, such as an array or battery subsystem.

Suction lift (of head) (6) - The vertical distance from the surface of the water source to the center of a pump. When the pump is located below the water level, suction lift is a negative value.

Sun-tracking (2) - Solar collectors that closely follow the sun's path.

Surge arrestors (5) - Devices used to protect conductors and circuit elements from the harmful effects of high-energy electrical surges, such as may be caused by nearby lightning strikes.

Switch (7) - A device for making, breaking or changing the connections in an electrical circuit.

System head (6) - The sum of suction head, discharge head, pressure head, friction head and velocity head of fluids. System head and flow rate determine the power requirements for pumping.

System life (10) - The expected life, in years, of a system.

Temperature correction factor (3) - A correction factor (usually $-0.005/^{\circ}\text{C}$ for crystalline silicon cells) used to determine power output for other than a given temperature.

Terminals (7) - The termination points for wiring.

THD (total harmonic distortion) (11) - See *harmonic distortion*.

Thick cells (3) - Conventional cells, such as crystalline silicon cells, which are typically from 4 to 17 mils thick. In contrast, thin-film cells are several microns thick.

Thin-film cells (3) - Photovoltaic cells made from a number of layers of photo-sensitive materials. These layers are typically applied using a chemical vapor deposition process in the presence of an electric field.

Total harmonic distortion (THD) (11) - See *harmonic distortion*.

Total system head (6) - See *system head*.

Two-axis tracking (2) - A tracking mode in which the receiving surface always faces directly at the sun.

Typical meteorological year (TMY) (2) - A representative year made up of 12 months. Each month is selected so that it best represents the average of that particular month over past years.

Ultraviolet radiation (2) - Electromagnetic radiation with wavelengths shorter than those of visible light but longer than that for x-rays; radiant energy of wavelengths from 0.1 to 0.4 microns.

Unmatched devices (4) - Photovoltaic devices whose current and voltage outputs are dissimilar.

Utility-interactive photovoltaic system (1) - An electric generating system connected directly to the utility grid. (Also called *grid-connected*.)

Utility-interactive inverter (11) - A device that converts dc electricity into ac electricity and forms the interface between the photovoltaic array and the utility.

Velocity head (6) - The equivalent feet of water that a pump must supply to move the water or liquid at a given velocity.

Visible radiation (2) - Radiant energy of wavelengths from 0.4 to 0.76 microns, the visible spectrum.

V_{mp} (3) - See *maximum power voltage*.

V_{oc} (3) - See *open-circuit voltage*.

Voltage (3) - A measure of the force or “push” given the electrons in an electrical circuit; a measure of electric potential. One volt produces one amp of current when acting against a resistance of one ohm.

Voltage control (11) - The process of controlling the operating voltage of a photovoltaic array.

Voltage regulator (5) - A device that controls the operating voltage of a photovoltaic array.

Watt (2) - A measure of electrical power or amount of work done in a unit of time. One amp of current flowing at a potential of one volt produces one watt of power.

Waveform (11) - The pictorial representation of the form or shape of a wave, obtained by plotting the displacement of the wave as a function of time, at a fixed point in space.

Wiring terminations (7) - Termination methods, including splice connections (crimp, solder), terminals (stud and nut, binding screw) and plug/receptacle connectors.

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Appendix A

Photovoltaic Stand-Alone Systems with Battery Storage: Sizing Worksheet and Instructions

The following sizing worksheet provides a systematic approach for designing a stand-alone photovoltaic system with battery storage. Step-by-step instructions follow the worksheet.

Sizing of Stand-Alone Photovoltaic Systems WORKSHEET

Application _____

Location _____ Latitude _____

A. Loads

A1 Inverter efficiency (decimal) _____

A2 Battery bus voltage _____ volts

A3 Inverter ac voltage _____ volts

	A4	A5	A6	A7	A8
	Rated	Adjustment	Adjusted	Hours Per	Energy
Appliance	Wattage	Factor 1.0 for dc (A1) for ac	Wattage (A4 / A5)	Day Used	Per Day (A6 x A7)
_____	_____	_____	_____	_____	_____
_____	_____	_____	_____	_____	_____
_____	_____	_____	_____	_____	_____
_____	_____	_____	_____	_____	_____
_____	_____	_____	_____	_____	_____
_____	_____	_____	_____	_____	_____

A9 Total energy demand per day (summation of A8) _____ watt-hours

A10 Total amp-hour demand per day (A9 / A2) _____ amp-hours

A11 Maximum ac power requirement (summation of A4) _____ watts

A12 Maximum dc power requirement (summation of A6) _____ watts

B. Battery Sizing

Design Temperature _____

B1 Days of storage desired/required _____ days

B2 Allowable depth-of-discharge limit (decimal) _____

B3 Required battery capacity (A10 x B1 / B2) _____ amp-hours

B4 Amp-hour capacity of selected battery * _____ amp-hours

B5 Number of batteries in parallel (B3 / B4) _____

B6 Number of batteries in series (A2 / battery voltage) _____

B7 Total number of batteries (B5 x B6) _____

B8 Total battery amp-hour capacity (B5 x B4) _____ amp-hours

B9 Total battery kilowatt-hour capacity (B8 x A2 / 1000) _____ kilowatt-hours

B10 Average daily depth of discharge (.75 x A10 / B8) _____

* Use amp-hour capacity at a rate of discharge corresponding to the total storage period, B1.

C. Photovoltaic Array Sizing **Design Tilt** _____ **Design Month** _____

- C1 Total energy demand per day (A9) _____ watt-hours
- C2 Battery round-trip efficiency (0.70 - 0.85) _____
- C3 Required array output per day (C1 / C2) _____ watt-hours
- C4 Selected PV module max power voltage at STC x 0.85 _____ volts
- C5 Selected PV module guaranteed power output at STC _____ watts
- C6 Peak sun hours at design tilt for design month _____ hours
- C7 Energy output per module per day (C5 x C6) _____ watt-hours
- C8 Module energy output at operating temperature. Use derating factor, DF = 0.80 for hot climates and critical applications; DF = 0.90 for moderate climates and non-critical applications (DF x C7) _____ watt-hours
- C9 Number of modules required to meet energy requirements (C3 / C8) _____ modules
- C10 Number of modules required per string (A2 / C4) rounded to next higher integer _____ modules
- C11 Number of strings in parallel (C9 / C10) rounded to next higher integer _____ strings
- C12 Number of modules to be purchased (C10 x C11) _____ modules
- C13 Nominal rated PV module output _____ watts
- C14 Nominal rated array output (C13 x C12) _____ watts

D. Balance-of-System (BOS) Requirements

1. A voltage regulator is recommended unless array output current (at 1000 W/m² condition), less any continuous load current, is less than 5% of the selected battery bank capacity (at the 8-hour discharge rate).
2. Wiring should be adequate to ensure that losses are less than 1% of the energy produced.
3. In low voltage (i.e., less than 50 volts) systems, germanium or Schottky blocking diodes are preferred over silicon diodes.
4. Fuses, fuse holders, switches, and other components should be selected to satisfy both voltage and current requirements.
5. All battery series branches should contain fuses.
6. Fused disconnects are strongly recommended to isolate the battery bank from the rest of the system.
7. Refer to electrical and mechanical design sections for other considerations.

APPLICATION : Define type of application.

LOCATION : Determine where the system will be located. Is there insolation data available for this location? If the answer is no, determine the nearest location for which there is available insolation data.

LATITUDE : Latitude of location with available insolation data.

A. LOADS

Evaluating the load (i.e., the energy and power requirements of the equipment to be served by the photovoltaic system) is the next step in the design process.

Note that the size of the array and battery subsystem are proportional to the average daily energy requirements of the residence. Consequently, it is *extremely important to use energy efficient appliances with photovoltaic systems*. Sometimes, this involves replacing existing appliances with more efficient ones that have a higher first cost, but result in a longer life cycle for the system. Using dc equipment, thereby eliminating the inverter, also results in more efficient utilization of energy.

Determine the appliances your system will power. Are they ac or dc? If the appliances are ac, select an inverter and determine its efficiency at typical load.

- (A1): Inverter efficiency (decimal). This quantity is used as a power adjustment factor when current is changed from dc to ac. Inverter efficiency varies with the amount of power being drawn from the inverter. If the inverter is not used to capacity then some power loss will occur and efficiency will decrease. A 0.85 rating is a good efficiency rating to use if you plan to use all of the power from the inverter. If the inverter is sized larger than your present power needs, decrease efficiency to 0.75 or lower. The size of the inverter you choose will determine whether or not you can add appliances (increase your load) in the future.
- (A2): Battery bus voltage. This is the actual dc operating voltage of the system and battery bank.
- (A3): Inverter ac voltage. This is the nominal operating voltage of the battery corresponding to the required input voltage for the dc side of the inverter. Obtain this figure from manufacturer's information on the selected inverter.

List the appliances that the system will power (such as refrigerator, lights, etc.) under the heading **Appliances**. For each of these appliances, provide:

- (A4): Rated wattage. This is the power required in watts to operate an appliance. Note that the rated wattage may differ from the actual power consumed by an appliance.
- (A5): Adjustment factor. The adjustment factor is related to the efficiency of the inverter and reflects the actual power consumed from the battery bank to operate ac loads from the inverter. For ac loads, the value (A1) is inserted in column (A5). For dc loads operating from the battery bank, an adjustment factor of 1.0 is used.
- (A6): Adjusted wattage. Divide the rated wattage (A4) by the adjustment factor (A5) to determine the adjusted wattage for each appliance. $(A4) / (A5)$.
- (A7): Hours per day used. Estimate the number of hours each appliance will be used per day. The duty cycle, or actual time of load operation, must be considered here. For example, a refrigerator may be functional 24 hours a day but the compressor may only operate 5 hours per day.
- (A8): Energy per day. Multiply the adjusted wattage (A6) by the hours used per day (A7) to determine the total amount of energy required by each appliance per day. $(A6) \times (A7)$.
- (A9): Total energy demand per day. Add all of the quantities in column (A8) to determine the total energy demand per day in watt-hours.
- (A10): Total amp-hour demand per day. The battery storage system is sized independent of the photovoltaic array. In order to size the battery bank the equipment load is converted from watt-hours to ampere-hours. Divide the total energy demand per day (A9) by the battery bus voltage to determine the total amp-hour demand per day. $(A9) / (A2)$.
- (A11): Maximum ac power requirement. Add all of the quantities in column (A4). Note that this is the maximum continuous power required and does not include surge requirements. This value (A11) is the maximum continuous ac power output required of the inverter if all loads were to operate simultaneously. The peak, or surge requirement (due to motor starting, etc.) must also be considered when selecting an inverter.
- (A12): Maximum dc power requirement. Add all of the quantities in column (A6). This value (A12) is the maximum dc input power required by the inverter and is necessary to determine wire sizes, fusing and disconnect requirements. If load management techniques are employed to eliminate the possibility of loads operating simultaneously, the inverter maximum output requirements may be reduced accordingly.

B. BATTERY SIZING

DESIGN TEMPERATURE: Determine the battery design temperature. The location where batteries are stored should be designed to minimize fluctuations in battery temperature. If battery temperature cannot be kept at $25^{\circ}\text{C} \pm 10^{\circ}\text{C}$, use the average daily temperature over 24 hours for the worst month of the year as the battery substation design temperature.

- (B1): Days of storage desired/required (autonomy). The battery subsystem is sized for the worst case and should be assumed to carry the entire load for a fixed number of days. The number of days of storage to use is a subjective judgement arrived at by considering "actual conditions" and how much they may vary from "average conditions" at the design location. Generally typical storage periods range from 3 to 10 days (although some storage periods are as high as 30 days). Less critical applications may use 3 to 4 days of storage, although this would increase the depth of battery cycling and reduce battery life. For critical applications such as those that would impact public safety, more days of storage may be desirable.

Indicate the number of days of storage desired/required.

- (B2): Allowable depth-of-discharge limit (decimal). Specify the maximum percentage of capacity that can be withdrawn from the battery. Note that the battery selected must be capable of this or greater depth of discharge.
- (B3): Required battery capacity. Battery capacity, in units of amp-hours, is temperature dependent, and manufacturers' ratings should be corrected for temperature in order to serve the load as intended. First multiply the total amp-hours per day (A10) by daily allowable depth of discharge (B1). Then, divide this number by the allowable depth-of-discharge limit (B2) to determine the required battery capacity (capacity needed). $[(A10) \times (B1)] / (B2)$.
- (B4): Amp-hour capacity of selected battery. After the required number of amp-hours has been determined (B3), select a battery or battery cell that provides the amount of amp-hours needed for the days of storage desired/required. Transfer amp-hour capacity from manufacturer's specifications to the worksheet.
- (B5): Number of batteries in parallel. To determine the number of batteries needed to provide the desired battery capacity, divide the required battery capacity (B3) by the amp-hour capacity of selected battery (B4). $(B3) / (B4)$.
- (B6): Number of batteries in series. Divide the battery bus voltage (A2) by the battery voltage to determine the number of batteries in series needed to provide necessary voltage. $(A2) / \text{battery voltage}$.

- (B7): Total number of batteries. Determine the total number of batteries needed by multiplying the number of batteries in parallel (B5) by the number of batteries in series (B6). $(B5) \times (B6)$.
- (B8): Total battery amp-hour capacity. Determine the total rated capacity of the selected batteries by multiplying the number of batteries in parallel (B5) by the amp-hour capacity of the selected battery (B4). $(B5) \times (B4)$.
- (B9): Total battery kilowatt-hour capacity. Determine the energy capacity based on selected batteries by multiplying the total battery amp-hour capacity (B8) by the battery bus voltage (A2). Then, divide this number by 1000.
 $[(B8) \times (A2)] / 1000$.
- (B10): Average daily depth-of-discharge. Multiply the total battery amp-hour demand per day (A10) by 0.75. Then, divide this number by the total battery amp-hour capacity (B8) to determine the actual amount of discharge on a daily basis.
 $[(A10) \times 0.75] / (B8)$.

C. PHOTOVOLTAIC ARRAY SIZING

The size of the photovoltaic array is determined by analyzing the load, the available solar insolation, the tilt of the array and the characteristics of the photovoltaic modules being considered. The available insolation striking a photovoltaic array varies throughout the year and is a function of the tilt of the array.

DESIGN MONTH: Define the design month. If the load is constant, use the time of year with the minimum amount of sunlight (in the Northern hemisphere typically December or January). If the load varies, use the month in which the maximum load occurs.

DESIGN TILT: Determine the optimum tilt angle for the design month by examining insolation data and selecting the angle which provides the maximum amount of insolation for the design month.

Once you know the insolation available (at tilt) and the power output required by the load, you can size the array using module specifications supplied by manufacturers.

- (C1): Total energy demand per day. Insert total energy demand (A9).
- (C2): Battery round-trip efficiency. Choose a factor between 0.70 and 0.85 as an estimate for battery round-trip efficiency.

- (C3): Required array output per day. Because batteries are less than 100% efficient, the amp-hours required by the load are adjusted (upwards). Usually 80% battery efficiency is assumed. Divide the total energy demand per day (C1) by the battery round-trip efficiency (C2). $(C1) / (C2)$.

Select a photovoltaic module using selection criteria given in Section 5.

- (C4): Selected PV module max power voltage at STC x 0.85. Obtain the maximum power voltage for the selected module from the manufacturer's specifications. Multiply this number by 0.85 to establish a design operating voltage for each module.
- (C5): Selected PV module guaranteed power output at STC. Obtain the nominal power output from the manufacturer's specifications for the selected module.
- (C6): Peak sun hours at design tilt for design month. Obtain this figure from solar radiation data for the design location, array tilt and the design month.
- (C7): Energy output per module per day. Multiply selected photovoltaic module power output at STC (C5) by the peak sun hours at design tilt for the design month (C6). $(C5) \times (C6)$.
- (C8): Operating temperature derating factor. Use a derating factor of 0.80 for hot climates and critical applications; use 0.90 for moderate climates and non-critical applications. Multiply the derating factor (DF) by the energy output per module (C7) to get an average energy output from one module. $[DF \times (C7)]$.
- (C9): Number of modules required to meet energy requirements. Divide the required array output per day (C3) by the operating temperature derating factor (C8) to determine the number of modules required to meet energy requirements. $(C3) / (C8)$.
- (C10): Number of modules required per string. Divide the battery bus voltage (A2) by the selected photovoltaic module maximum power at STC x 0.85 (C4). Round this number to the next higher integer to determine the number of modules required per string. $(A2) / (C4)$ rounded to the next higher integer.
- (C11): Number of strings in parallel. Divide the number of modules required to meet energy requirements (C9) by the number of modules required per string (C10). Round this number to the next higher integer to determine the number of strings in parallel. $(C9) / (C10)$ rounded to the next higher integer.

- (C12): Number of modules to be purchased. Multiply the number of modules required per string (C10) by the number of strings in parallel (C11) to determine the number of modules to be purchased. $(C10) \times (C11)$.
- (C13): Nominal rated PV module output. Obtain the photovoltaic module's nominal rated output from manufacturer's specifications. Photovoltaic modules are usually priced in terms of the rated module output (\$/watt).
- (C14): Nominal rated array output. Multiply the number of modules to be purchased (C12) by the nominal rated module output (C13) to determine the nominal rated array output. Use this figure to determine the cost of the photovoltaic array. $(C12) \times (C13)$.

D. BOS REQUIREMENTS

Balance-of-system design involves the design and selection of additional components such as wiring, voltage regulators, power conditioners, disconnects, blocking and bypass diodes, mounting structure, etc.

1. Note that the voltage regulator, or charge controller, is an important device when using batteries. The regulator controls the current and voltage input to the batteries and protects them from damage. A voltage regulator is recommended unless array output current (at 1000 W/m² conditions), less any continuous load current, is less than 5% of the selected battery bank capacity (at the 8-hour discharge rate).
2. Use wiring that ensures that energy losses are less than 1% of the energy produced.
3. Germanium or Schottky blocking diodes are recommended over silicon diodes in low voltage (i.e., less than 50-volts) systems.
4. Select fuses, fuse holders, switches, and other components to satisfy both voltage and current requirements.
5. Design wiring, fuses and disconnects per National Electrical Code.

The following worksheet is used for performing the cost analysis for stand-alone photovoltaic systems.

Cost Analysis for Stand-Alone Photovoltaic Systems WORKSHEET

Application _____

E. Economic Conditions for Analysis

- E1 Desired system life _____ years
- E2 Inflation rate (decimal) _____
- E3 Discount rate (decimal) _____
- E4 Real discount rate (E3 - E2) _____

F. Present Worth Analysis for PV and BOS

- F1 Peak watts of array (C14) _____ watts
- F2 Cost per peak watt for PV array and BOS, installed _____ \$/watt
- F3 Initial cost for PV and BOS (F1 x F2) _____ \$
- F4 Expected PV array life _____ years

F5 Replacement Year *	F6 Present Worth
Initial Installation	(F3) _____
(F4) _____	$(F3 / (1 + E4)^{F4})$ _____
(2 x F4) _____	$(F3 / (1 + E4)^{(2 \times F4)})$ _____
(3 x F4) _____	$(F3 / (1 + E4)^{(3 \times F4)})$ _____

- F7 Present worth of PV and BOS (summation of F6) _____ \$
- F8 Energy production over desired system life, E1 ($A9 \times E1 \times 365 / 1000$) _____ kW-hours
- F9 Present value of PV electricity (F7 / F8) _____ \$/kW-hour

G. Present Worth Analysis for Batteries

- G1 Total battery kW-hour capacity (B9) _____ kW-hours
- G2 Cost per kW-hour for battery _____ \$/kW-hour
- G3 Initial cost for battery (G1 x G2) _____ \$
- G4 Expected battery life in cycles _____ cycles
- G5 Expected battery life in years (G4 / 365) _____ years

* Do not calculate for replacement years greater than or equal to the system life, E1.
 ** Estimate from battery literature at average daily depth of discharge, B10.

G6 Replacement Year *	G7 Present Worth
Initial Installation	(G3) _____
(G5) _____	$(G3 / (1 + E4)^{G5})$ _____
(2 x G5) _____	$(G3 / (1 + E4)^{(2 \times G5)})$ _____
(3 x G5) _____	$(G3 / (1 + E4)^{(3 \times G5)})$ _____
(4 x G5) _____	$(G3 / (1 + E4)^{(4 \times G5)})$ _____
(5 x G5) _____	$(G3 / (1 + E4)^{(5 \times G5)})$ _____
G8 Present worth of battery (summation of G7)	_____ \$
G9 Total present worth of PV and batteries (F7 + G8)	_____ \$
G10 Present value of PV and battery (G9 / F8)	_____ \$/kW-hour

H. Present Worth Analysis of Inverter

H1 Rated power for inverter	_____ watts
H2 Cost per rated watt for inverter	_____ \$/watt
H3 Initial cost for inverter (H1 x H2)	_____ \$
H4 Expected inverter life	_____ years

H5 Replacement Year *	H6 Present Worth
Initial Installation	(H3) _____
(H4) _____	$(H3 / (1 + E4)^{H4})$ _____
(2 x H4) _____	$(H3 / (1 + E4)^{(2 \times H4)})$ _____
(3 x H4) _____	$(H3 / (1 + E4)^{(3 \times H4)})$ _____
(4 x H4) _____	$(H3 / (1 + E4)^{(4 \times H4)})$ _____
H7 Present worth of inverter (summation of H6)	_____ \$
H8 Total present worth of PV system (G9 + H7)	_____ \$
H9 Present value of PV system (H8 / F8)	_____ kW-hour
H10 Total initial cost for PV system (F3 + G3 + H3)	_____ \$

* Do not calculate for replacement years greater than or equal to the system life, E1.



Appendix B

Stand-Alone Generator Systems: Sizing Worksheet and Instructions

The following sizing worksheet provides a systematic approach for designing a stand-alone generator system with battery storage. Step-by-step instructions follow the worksheet.

Sizing of Stand-Alone Generator Systems WORKSHEET

Application _____

Location _____ Latitude _____

A. Loads

A1 Inverter efficiency (decimal) _____

A2 Battery bus voltage _____ volts

A3 Inverter ac voltage _____ volts

	A4	A5	A6	A7	A8
	Rated	Adjustment	Adjusted	Hours Per	Energy
Appliance	Wattage	Factor 1.0 for dc (A1) for ac	Wattage (A4 / A5)	Day Used	Per Day (A6 x A7)
_____	_____	_____	_____	_____	_____
_____	_____	_____	_____	_____	_____
_____	_____	_____	_____	_____	_____
_____	_____	_____	_____	_____	_____
_____	_____	_____	_____	_____	_____
_____	_____	_____	_____	_____	_____

A9 Total energy demand per day (summation of A8) _____ watt-hours

A10 Total amp-hour demand per day (A9 / A2) _____ amp-hours

A11 Maximum ac power requirement (summation of A4) _____ watts

A12 Maximum dc power requirement (summation of A6) _____ watts

B. Battery Sizing

Design Temperature _____

- B1 Daily depth of discharge desired (decimal) _____
- B2 Allowable depth-of-discharge limit (decimal) _____
- B3 Required battery capacity (A10 / B1) _____ amp-hours
- B4 Amp-hour capacity of selected battery * _____ amp-hours
- B5 Number of batteries in parallel (B3 / B4) _____
- B6 Number of batteries in series (A2 / battery voltage) _____
- B7 Total number of batteries (B5 x B6) _____
- B8 Total battery amp-hour capacity (B5 x B4) _____ amp-hours
- B9 Total battery kilowatt-hour capacity (B8 x A2 / 1000) _____ kilowatt-hours
- B10 Average daily depth of discharge (A10 / B8) _____
- B11 Maximum allowable battery charge rate (B8 / 3 hours) _____ amps
- B12 Days of storage (B2 x B8 / A10) _____ days

* Use amp-hour capacity at 24-hour rate of discharge.

C. Generator/Battery Charger Sizing

- C1 Choose battery charger to meet the maximum allowable battery charge rate, B11, at the nominal battery bus voltage, A2 _____ model #
- C2 Battery charger maximum dc output power _____ watts
- C3 Battery charger maximum ac input power _____ watts
- C4 Battery charger average ac input power _____ watts
- C5 Battery charger average dc output power _____ watts
- C6 Battery charger average efficiency (C5 / C4) _____
- C7 Choose generator which will meet the peak battery charger ac input power, C3, and the peak load, A11. Choose the larger of the two. _____ model #
- C8 Peak generator output _____ watts
- C9 Generator/battery charger turn-on point [BSOC] (1 - B10) _____
- C10 Generator/battery charger turn-off point [BSOC] _____
- C11 Required generator/battery charger amp-hour production during daily charging cycle ($A10 / 0.85$) _____ amp-hours
- C12 Battery charger average charge rate (estimate from battery charger literature between turn-on and turn-off [BSOC], C9 and C10) ** _____ amps
- C13 Average daily generator/battery charger on-time ($C11 / C12$) _____ hours
- C14 Average yearly generator/battery charger on-time ($C13 \times 365$) _____ hours
- C15 Average generator ac output power ($C12 \times A2 / C6$) _____ watts
- C16 Average yearly generator energy production ($C15 \times C14 / 1000$) _____ kilowatt-hour
- C17 Average generator load (fraction of generator peak ac output), ($C15 / C8$) _____

** If unavailable, use $B11 / 3$.

APPLICATION : Define type of application.

LOCATION : Determine where the system will be located. Is there insolation data available for this location? If the answer is no, determine the nearest location for which there is available insolation data.

LATITUDE : Latitude of location with available insolation data.

A. LOADS

Evaluating the load (i.e., the energy and power requirements of the equipment to be served by the generator system) is the next step in the design process. Equipment to be powered by the generator should be as energy efficient as possible. Using dc equipment, thereby eliminating the inverter, results in more efficient utilization of energy. The end result of the load evaluation should be a load profile over 24 hours for a typical day of each month. This information will be required in order to size both the generator and the battery bank. Determine if the appliances your system will power are ac or dc. If the appliances are ac, select an inverter and determine its efficiency.

(A1): Inverter efficiency (decimal). This quantity is used as a power adjustment factor when current is changed from dc to ac. Inverter efficiency varies with the amount of power being drawn from the inverter. If the inverter is not used to capacity then some power loss will occur and efficiency will decrease. A 0.85 rating is a good efficiency rating to use if you plan to use all of the power from the inverter. If the inverter is sized larger than your present power needs, decrease efficiency to 0.75 or lower. The size of the inverter you choose will determine whether or not you can add appliances (increase your load) in the future.

(A2): Battery bus voltage. The battery bus voltage is determined by the nominal operating voltage of the dc side of a battery.

(A3): Inverter ac voltage. Obtain the output voltage of the inverter from manufacturer's information.

List the appliances that the system will power (such as refrigerator, lights, etc.) under the heading **Appliances**. For each of these appliances, provide:

(A4): Rated wattage. This is the power required in watts to operate an appliance. Note that the rated wattage may differ from the actual power consumed by a load.

(A5): Adjustment factor. Use 1.0 if an appliance is dc; use inverter efficiency (A1) if the appliance is ac. The adjustment factor increases wattage to compensate for wattage loss due to inverter inefficiency.

- (A6): Adjusted wattage. Divide the rated wattage (A4) by the adjustment factor (A5) to determine the adjusted wattage for each appliance. $(A4) / (A5)$.
- (A7): Hours per day used. Estimate the number of hours each appliance will be used per day.
- (A8): Energy per day. Multiply the adjusted wattage (A6) by the hours used per day (A7) to determine the total amount of energy required by each appliance per day. $(A6) \times (A7)$.
- (A9): Total energy demand per day. Add all of the quantities in column (A8) to determine total energy demand per day in watt-hours.
- (A10): Total amp-hour demand per day. Convert the total energy demand per day from watt-hours to ampere-hours by dividing the total energy demand per day (A9) by the battery bus voltage (A2). $(A9) / (A2)$.
- (A11): Maximum ac power requirement. Add all of the quantities in column (A4). Note that this is the maximum continuous power required and does not include surge requirements. This value (A11) is the maximum continuous ac power output required of the inverter if all loads were to operate simultaneously. The peak, or surge requirement (due to motor starting, etc.) must also be considered when selecting an inverter.
- (A12): Maximum dc power requirement. Add all of the quantities in column (A6). This value (A12) is the maximum dc input power required by the inverter and is necessary to determine wire sizes, fusing and disconnect requirements. If load management techniques are employed to eliminate the possibility of loads operating simultaneously, the inverter maximum output requirements may be reduced accordingly.

B. BATTERY SIZING

DESIGN TEMPERATURE: Determine the battery design temperature. The location where batteries are stored should be designed to minimize fluctuations in battery temperature. If battery temperature cannot be kept at $25^{\circ}\text{C} \pm 10^{\circ}\text{C}$, use the average daily temperature over 24 hours for the worst month of the year as the battery substation design temperature.

- (B1): Daily depth of discharge desired (decimal). Specify the planned amount of battery capacity to be extracted on a daily basis. Do not design to battery's limit because it will shorten cycle life.

- (B2): Allowable depth-of-discharge limit (decimal). Specify the percentage of capacity that can be withdrawn from battery. Note that the battery selected must be capable of this or greater depth of discharge.
- (B3): Required battery capacity. Battery capacity, in units of amp-hours, is temperature dependent. Manufacturer's ratings should be corrected for temperature in order to serve the load as intended. Determine the required battery capacity (capacity needed) by dividing the total amp-hours per day (A10) by daily allowable depth of discharge (B1). $(A10) / (B1)$.
- (B4): Amp-hour capacity of selected battery. After the required number of amp-hours have been determined (B3), select a battery or battery cell that provides the amount of amp-hours needed for the days of storage desired/required.
- * Note: Use amp-hour capacity at 24-hour rate of discharge.
- (B5): Number of batteries in parallel. Divide the required battery capacity (B3) by the amp-hour capacity of selected battery (B4) to determine the number of batteries needed to provide desired capacity. $(B3) / (B4)$.
- (B6): Number of batteries in series. Divide the allowable depth of discharge limit (A2) by the battery voltage to determine the number of batteries needed to provide necessary voltage. $(A2) / \text{battery voltage}$.
- (B7): Total number of batteries. Multiply the number of batteries in parallel (B5) times the number of batteries in series (B6) to determine the total number of batteries needed. $(B5) \times (B6)$.
- (B8): Total battery amp-hour capacity. Determine the total rated capacity of selected batteries by multiplying the number of batteries in parallel (B5) times the amp-hour capacity of the selected battery (B4). $(B5) \times (B4)$.
- (B9): Total battery kilowatt-hour capacity. Determine the total energy capacity by multiplying the total battery amp-hour capacity (B8) times the battery bus voltage (A2). Divide this number by 1000. $[(B8) \times (A2)] / 1000$.
- (B10): Average daily depth of discharge. Divide the total amp-hour demand per day (A10) by the total battery amp-hour capacity (B8) to determine the actual depth of discharge to be expected on average for the selected battery subsystem. $(A10) / (B8)$.

- (B11): Maximum allowable battery charge rate. Divide the total battery amp-hour capacity (B8) by 3 hours to determine the maximum current that can be imposed through the battery bank during charging. $(B8) / 3$.
- (B12): Days of storage. Multiply the allowable depth of discharge limit (B2) by the total battery amp-hour capacity (B8). Then, divide this number by the total amp-hour demand per day (A10) to determine the amount of energy stored in batteries that will supply power to the load for an equivalent number of days without charging.

C. GENERATOR/BATTERY CHARGER SIZING

After the load (energy requirement) has been determined and the battery storage subsystem has been sized, the next step in sizing a stand-alone generator system is sizing the electric generator. Because the output of an engine generator is ac it cannot directly charge the batteries (which store dc electricity). Therefore, a battery charger is needed to convert ac electricity to dc.

- (C1): Battery charger. Select a battery charger that meets the maximum allowable battery charge rate (B11) at the nominal bus voltage (A2).
- (C2): Battery charger maximum dc output power. Obtain the battery charger's maximum dc output power from manufacturer's data for the battery charger selected in (C1).
- (C3): Battery charger maximum ac input power. Obtain the battery charger's maximum ac input from manufacturer's data.
- (C4): Battery charger average ac input power. Obtain the battery charger's average ac input power from manufacturer's data.
- (C5): Battery charger average dc output power. Obtain the battery charger's average dc output power from manufacturer's data.
- (C6): Battery charger average efficiency. Divide the battery charger's average dc output power (C5) by its average ac input power (C4) to determine the battery charger's average efficiency. $(C5) / (C4)$.
- (C7): Generator. The generator converts mechanical power into electrical power. Select a generator that meets the peak battery charger ac input power (C3) and the peak load (A11). Selected generator must meet the larger demand of the two.

- (C8): Peak generator output power. This is the maximum electrical output from the generator. Obtain peak generator output power from manufacturer's data for the selected generator (C7).
- (C9): Generator/battery charger turn-on point [BSOC]. Determine the level of battery discharge at which point the generator turns on to recharge the battery subsystem by subtracting the average daily depth of discharge (B10) from full state of charge [1.0]. $1.0 - (B10)$.
- (C10): Generator/battery turn-off point [BSOC]. The level of battery charge at which point the generator turns off is equal to 1.0 or full state of charge.
- (C11): Required generator/battery charger amp-hour production during the daily charging cycle. Divide the total amp-hour demand per day (A10) by 0.85 (a representative number for battery round-trip efficiency) to determine the total amount of charge developed by the combination of the generator and battery charger. $(A10) / 0.85$.
- (C12): Battery charger average charge rate. Determine the average current output from the battery charger. This number is an estimate between turn-on point (C9) and turn-off point (C10) determined from battery charger literature. If (C10) is unavailable, use $(B11) / 3$.
- (C13): Average daily generator/battery charger on-time. Divide the required generator/battery charger amp-hour production during daily charging cycle (C11) by battery charger average charge rate (C12) to determine the average amount of time that the generator/battery charger is on per day. $(C11) / (C12)$.
- (C14): Average yearly generator/battery charger on-time. Multiply the average daily generator/battery charger on-time (C13) by 365 to determine the average amount of time that the generator/battery charger is on per year. $(C13) \times 365$.
- (C15): Average generator ac output power. Generator operates over a range of output power. Determine the average of this operating range by multiplying the battery charger average charge rate (C12) by the battery bus voltage (A2). Divide this number by the battery charger average efficiency (C6) to determine the average generator ac output power. $[(C12) \times (A2)] / (C6)$.
- (C16): Average yearly generator energy production. Multiply the average generator ac output power (C15) by the average yearly generator/battery charger on-time (C14). Then, divide this number by 1000 to determine the number of kWh the generator will produce in a year. $[(C15) \times (C14)] / 1000$.

(C17): Average generator load. The generator system does not operate at peak output. Determine the average generator load by dividing the average generator ac output power (C15) by the peak generator output (C8). $(C15) / (C8)$.

The following worksheet is used for performing the cost analysis for stand-alone generator systems.

Cost Analysis for Stand-Alone Generator Systems WORKSHEET

Application _____

E. Economic Conditions for Analysis

- E1 Desired system life _____ years
- E2 Inflation rate (decimal) _____
- E3 Fuel escalation rate (decimal) _____
- E4 Discount rate (decimal) _____
- E5 Real discount rate (E4 - E2) _____
- E6 Current fuel cost including transportation _____ \$/gal

F. Present Worth Analysis for Generator

- F1 Peak generator output (C8) _____ watts
- F2 Cost per peak watt for generator, installed _____ \$/watt
- F3 Initial cost for generator (F1 x F2) _____ \$
- F4 Expected generator life in hours _____ hours
- F5 Average yearly generator run time (C14) _____ hours/year
- F6 Expected generator life in years (F4 / F5) _____ years

F7 Replacement Year *	F8 Present Worth
Initial Installation	(F3) _____
(F6) _____	$(F3 / (1 + E5)^{F6})$ _____
(2 x F6) _____	$(F3 / (1 + E5)^{(2 \times F6)})$ _____
(3 x F6) _____	$(F3 / (1 + E5)^{(3 \times F6)})$ _____
(4 x F6) _____	$(F3 / (1 + E5)^{(4 \times F6)})$ _____

- F9 Present worth of generator alone (summation of F8) _____ \$
- F10 Expected yearly maintenance cost for generator _____ \$/year
- F11 Present worth of annual maintenance over system life, E1

$$F10 \times \left(\frac{((1 + E5)^{E1} - 1)}{(E5 \times (1 + E5)^{E1})} \right) \quad \text{_____ \$}$$

- F12 Average generator load (fraction of peak ac output), (C17) _____
- F13 Estimated generator fuel consumption at average load, F12 _____ gal/hour
- F14 Annual generator fuel consumption (F5 x F13) _____ gal/year

* Do not calculate for replacement years greater than or equal to the system life, E1.

F15 Present worth of fuel over sytem life

$$F14 \times E6 \times \left(\frac{1 + E3}{E4 - E3} \right) \times \left(1 - \left(\frac{1 + E3}{1 + E4} \right)^{E1} \right) \quad \text{_____ \$}$$

F16 Present worth of generator (F9 + F11 + F15) _____ \$

F17 Generator energy production over desired system life
(A9 x 365 x E1 / 1000) _____ kW-hours

F18 Present value of generaor (F16 / F17) _____ \$/kW-hour

G. Present Worth Analysis for Batteries

G1 Total battery kW-hour capacity (B9) _____ kW-hours

G2 Cost per kW-hour for battery, installed _____ \$/kW-hour

G3 Initial cost for battery (G1 x G2) _____ \$

G4 Expected battery life in cycles ** _____ cycles

G5 Expected battery life in years (G4 / 365) _____ years

G6 Replacement Year *	G7 Present Worth
Initial Installation	(G3) _____
(G5) _____	(G3 / (1 + E5) ^{G5}) _____
(2 x G5) _____	(G3 / (1 + E5) ^(2 x G5)) _____
(3 x G5) _____	(G3 / (1 + E5) ^(3 x G5)) _____
(4 x G5) _____	(G3 / (1 + E5) ^(4 x G5)) _____
(5 x G5) _____	(G3 / (1 + E5) ^(5 x G5)) _____

G8 Present worth of battery (summation of G7) _____ \$

G9 Total present worth of generator and battery (F16 + G8) _____ \$

G10 Present value of generator and battery (G9 / F17) _____ \$/kW-hour

H. Present Worth Analysis for Battery Charger

H1 Rated power for battery charger (C2) _____ watts

H2 Cost per rated watt for battery charger _____ \$/watt

H3 Initial cost for battery charger (H1 x H2) _____ \$

H4 Expected battery charger life _____ years

H5 Replacement Year *	H6 Present Worth
Initial Installation	(H3) _____
(H4) _____	(H3 / (1 + E5) ^{H4}) _____
(2 x H4) _____	(H3 / (1 + E5) ^(2 x H4)) _____
(3 x H4) _____	(H3 / (1 + E5) ^(3 x H4)) _____
(4 x H4) _____	(H3 / (1 + E5) ^(4 x H4)) _____

* Do not calculate for replacement years greater than or equal to the system life, F1.

** Estimate from battery literature at average daily depth of discharge, B10.

- H7** Present worth of battery charger (summation of H6) _____ \$
- H8** Total present worth of generator, batteries and battery charger
(H7 + G9) _____ \$
- H9** Total present value for generator, batteries and battery charger
(H8 / F17) _____ \$/kW-hour

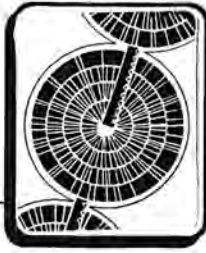
I. Present Worth Analysis of Inverter

- I1** Rated inverter power output _____ watts
- I2** Cost per rated watt for inverter _____ \$/watt
- I3** Initial cost for inverter (I1 x I2) _____ \$
- I4** Expected inverter life _____ years

I5 Replacement Year * Initial Installation	I6 Present Worth
(I4) _____	(I3) _____
(2 x I4) _____	$(I3 / (1 + E5)^{I4})$ _____
(3 x I4) _____	$(I3 / (1 + E5)^{(2 \times I4)})$ _____
(4 x I4) _____	$(I3 / (1 + E5)^{(3 \times I4)})$ _____
(4 x I4) _____	$(I3 / (1 + E5)^{(4 \times I4)})$ _____

- I7** Present worth of inverter (summation of I6) _____ \$
- I8** Present worth of generator system (I7 + H8) _____ \$
- I9** Present value of generator system (I8 / F17) _____ \$/kW-hour
- I10** Total initial cost for generator system (F3 + G3 + H3 + I3) _____ \$

* Do not calculate for replacement years greater than or equal to the system life, E1.



Appendix C

Hybrid Photovoltaic-Generator Systems: Sizing Worksheet and Instructions

The following sizing worksheet provides a systematic approach for designing a hybrid photovoltaic-generator system. Step-by-step instructions follow the worksheet.

Sizing of Hybrid Photovoltaic-Generator Systems WORKSHEET

Application _____

Location _____ Latitude _____

A. Loads

A1 Inverter efficiency (decimal) _____

A2 Battery bus voltage _____ volts

A3 Inverter ac voltage _____ volts

	A4	A5	A6	A7	A8
	Rated	Adjustment	Adjusted	Hours Per	Energy
Appliance	Wattage	Factor 1.0 for dc (A1) for ac	Wattage (A4 / A5)	Day Used	Per Day (A6 x A7)
_____	_____	_____	_____	_____	_____
_____	_____	_____	_____	_____	_____
_____	_____	_____	_____	_____	_____
_____	_____	_____	_____	_____	_____
_____	_____	_____	_____	_____	_____
_____	_____	_____	_____	_____	_____

A9 Total energy demand per day (summation of A8) _____ watt-hours

A10 Total amp-hour demand per day (A9 / A2) _____ amp-hours

A11 Maximum ac power requirement (summation of A4) _____ watts

A12 Maximum dc power requirement (summation of A6) _____ watts

B. Battery Sizing

Design Temperature _____

B1 Daily depth of discharge desired (decimal) _____

B2 Allowable depth-of-discharge limit (decimal) _____

B3 Required battery capacity (A10 x .75 / B1) _____ amp-hours

B4 Amp-hour capacity of selected battery * _____ amp-hours

B5 Number of batteries in parallel (B3 / B4) _____

B6 Number of batteries in series (A2 / battery voltage) _____

B7 Total number of batteries (B5 x B6) _____

B8 Total battery amp-hour capacity (B5 x B4) _____ amp-hours

B9 Total battery kilowatt-hour capacity (B8 x A2 / 1000) _____ kilowatt-hours

B10 Average daily depth of discharge (.75 x A10 / B8) _____

B11 Maximum allowable battery charge rate (B8 / 3 hours) _____ amps

B12 Days of storage (B2 x B8 / A10) _____ days

* Use amp-hour capacity at 24-hour rate of discharge.

C. Photovoltaic Array Sizing Design Tilt _____ Design Month _____

- C1 Total energy demand per day (A9) _____ watt-hours
- C2 Battery round-trip efficiency (0.70 - 0.85) _____
- C3 Required array output per day (C1 / C2) _____ watt-hours
- C4 Selected PV module max power voltage at STC x 0.85 _____ volts
- C5 Selected PV module guaranteed power output at STC _____ watts
- C6 Peak sun hours at design tilt for design month _____ hours
- C7 Energy output per module per day (C5 x C6) _____ watt-hours
- C8 Module energy output at operating temperature. Use derating factor, DF = 0.80 for hot climates and critical applications; DF = 0.90 for moderate climates and non-critical applications (DF x C7) _____ watt-hours
- C9 Number of modules required to meet energy requirements (C3 / C8) _____ modules
- C10 Number of modules required per string (A2 / C4) rounded to next higher integer _____ modules
- C11 Number of strings in parallel (C9 / C10) rounded to next higher integer _____ strings
- C12 Number of modules to be purchased (C10 x C11) _____ modules
- C13 Peak watts of array (C12 x C5) _____ watts
- C14 Peak sun hours at design tilt for worst month _____ hours
- C15 Usable average daily PV energy during worst month (C14 x DF x C13 x C2) _____ watt-hours
- C16 Average daily PV amp-hours production during worst month (C15/A2) _____ amp-hours
- C17 Nominal rated PV module output _____ watts
- C18 Nominal rated array output (C17 x C12) _____ watts

D. Generator/Battery Charger Sizing

- D1 Choose generator to meet or exceed peak ac power demand, A11 _____ model #
- D2 Peak generator output power _____ watts
- D3 Choose battery charger so that the maximum battery charger input ac watts is nearly equal to but less than D2, and the charger dc voltage is the same as the nominal battery bus voltage, A2 _____ model #
- D4 Battery charger maximum charge rate * _____ amps
- D5 Battery charger maximum ac input power _____ watts
- D6 Battery charger average ac input power _____ watts
- D7 Battery charger average dc output power _____ watts
- D8 Battery charger average efficiency (D7 / D6) _____
- D9 Generator turn-on point [BSOC], (1 - B10 - .05) ** _____
- D10 Average daily PV energy deficit during worst month (A9 - C15) _____ watt-hours

* Make sure this charge rate does not exceed the maximum safe battery charge rate, B11.

** Not less than (1 - B2).

- D11** Average daily PV amp-hour deficit during worst month ($D10 / A2$) _____ amp-hours
- D12** Fraction of battery capacity supplied to battery from generator/battery charger during worst month ($D11 / B8$) _____
- D13** Generator/battery charger turn-off point [BSOC] ($1 - B10 + D12$) _____
- D14** Number of months for which peak sun hours per day at design tilt are less than design month peak hours, C6 _____
- D15** Required number of months for which generator/battery charger backup is required daily (D14) _____
- D16** Required generator/battery charger amp-hour production during charging cycle ($D13 - D9 \times B8 / .85$) _____ amp-hours
- D17** Average yearly generator/battery charger amp-hour production ($(D15 / 12) \times 365 \times D16$) _____ amp-hours
- D18** Battery charger average charge rate (estimate from battery charger literature between turn-on and turn-off [BSOC], D9 and D13) *** _____ amps
- D19** Average generator/battery charger on-time during charging cycle ($D16 / D18$) **** _____ hours
- D20** Average yearly generator/battery charger on-time ($D17 / D18$) _____ hours
- D21** Average generator ac output power ($D18 \times A2 / D8$) _____ watts
- D22** Average yearly generator energy production ($D21 \times D20 / 1000$) _____ kilowatt-hours
- D23** Average generator load (fraction of generator peak ac output), ($D21 / D2$) _____

*** If unavailable, use $B11 / 2$.

**** Do not design generator to run less than 15 minutes (0.25 hours).

APPLICATION: Define type of application.

LOCATION: Determine where the system will be located. Is there insolation data available for this location? If the answer is no, determine the nearest location for which there is available insolation data.

LATITUDE: Latitude of location with available insolation data.

A. LOADS

Evaluating the load (i.e., the energy and power requirements of the equipment to be served by the hybrid system) is the next step in the design process.

Equipment to be powered by the hybrid system should be as energy efficient as possible. Using dc equipment, thereby eliminating the inverter, results in more efficient utilization of energy.

The end result of the load evaluation should be a load profile over 24 hours for a typical day of each month. This information will be required in order to size both the generator and the battery bank.

Determine the appliances your system will power. Are they ac or dc? If the appliances are ac select an inverter and determine its efficiency.

- (A1): Inverter efficiency (decimal). This quantity is used as a power adjustment factor when current is changed from dc to ac. Inverter efficiency varies with the amount of power being drawn from the inverter. If the inverter is not used to capacity then some power loss will occur and efficiency will decrease. A 0.85 rating is a good efficiency rating to use if you plan to use all of the power from the inverter. If the inverter is sized larger than your present power needs, decrease efficiency to 0.75 or lower. The size of the inverter you choose will determine whether or not you can add appliances (increase your load) in the future.
- (A2): Battery bus voltage. This is the nominal operating voltage of the dc side of a battery. Voltage is determined by the load.
- (A3): Inverter ac voltage. This is the nominal operating voltage of the battery corresponding to the required input voltage for the dc side of the inverter. Obtain this figure from manufacturer's information for the selected inverter.

List the appliances that the system will power (such as refrigerator, lights, etc.) under the heading **Appliances**. For each of these appliances, provide:

- (A4): Rated wattage. This is power required in watts to operate an appliance.
- (A5): Adjustment factor. Use 1.0 if appliance is dc, or inverter efficiency (A1) if the appliance is ac. The adjustment factor increases wattage to compensate for wattage loss due to inverter inefficiency.
- (A6): Adjusted wattage. Divide the rated wattage (A4) by the adjustment factor (A5) to determine the adjusted wattage for each appliance. $(A4) / (A5)$.
- (A7): Hours per day used. Estimate the number of hours each appliance will be used per day.
- (A8): Energy per day. Multiply the adjusted wattage (A6) by the hours used per day (A7) to determine the total amount of energy required by each appliance per day. $(A6) \times (A7)$.
- (A9): Total energy demand per day. Add all of the quantities in column (A8) to determine total energy demand per day in watt-hours.
- (A10): Total amp-hour demand per day. Convert the total energy demand per day from watt-hours to ampere-hours by dividing the total energy demand per day (A9) by the battery bus voltage (A2). $(A9) / (A2)$.
- (A11): Peak ac power requirement. Add all of the quantities in column (A4).
- (A12): Peak dc power requirement. Add all of the quantities in column (A6).

B. BATTERY SIZING

DESIGN TEMPERATURE: Determine the battery design temperature. The location where batteries are stored should be designed to minimize fluctuations in battery temperature. If battery temperature cannot be kept at $25^{\circ}\text{C} \pm 10^{\circ}\text{C}$, use the average daily temperature over 24 hours for the worst month of the year as the battery substation design temperature.

- (B1): Daily depth of discharge desired (decimal). Specify the planned amount of battery capacity to be extracted on a daily basis. Do not design to the battery's limit because it will shorten cycle life.

- (B2): Allowable depth-of-discharge limit (decimal). Specify the percentage of capacity that can be withdrawn from the battery. Note that the battery selected must be capable of this or greater depth of discharge.
- (B3): Required battery capacity. Battery capacity, in units of amp-hours, is temperature dependent. Manufacturer's ratings should be corrected for temperature in order to serve the load as intended. Determine the required battery capacity (capacity needed) by multiplying the total amp-hours per day (A10) by 0.75. Then, divide this number by the daily allowable depth of discharge (B1). $[(A10) \times 0.75] / (B1)$.
- (B4): Amp-hour capacity of selected battery. After the required number of amp-hours has been determined (B3), select a battery or battery cell that provides the amount of amp-hours needed for the days of storage desired/required. Use amp-hour capacity at 24-hour rate of discharge.
- (B5): Number of batteries in parallel. Divide the required battery capacity (B3) by the amp-hour capacity of selected battery (B4) to determine the number of batteries needed to provide desired capacity. $(B3) / (B4)$.
- (B6): Number of batteries in series. Divide the allowable depth of discharge limit (A2) by the battery voltage to determine the number of batteries needed to provide necessary voltage. $(A2) / \text{battery voltage}$.
- (B7): Total number of batteries. Multiply the number of batteries in parallel (B5) times the number of batteries in series (B6) to determine total number of batteries needed. $(B5) \times (B6)$.
- (B8): Total battery amp-hour capacity. Determine the total rated capacity of selected batteries by multiplying the number of batteries in parallel (B5) times the amp-hour capacity of the selected battery (B4). $(B5) \times (B4)$.
- (B9): Total battery kilowatt-hour capacity. Determine the total energy capacity by multiplying the total battery amp-hour capacity (B8) times the battery bus voltage (A2). Divide this number by 1000. $[(B8) \times (A2)] / 1000$.
- (B10): Average daily depth-of-discharge. Multiply the total amp-hour demand per day (A10) by 0.75. Then, divide this number by the total battery amp-hour capacity (B8) to determine the actual depth of discharge to be expected on average for the selected battery subsystem. $[0.75 \times (A10)] / (B8)$.

- (B11): Maximum allowable battery charge rate. Divide the total battery amp-hour capacity (B8) by 3 hours to determine the maximum current that can be imposed through the battery bank during charging. $(B8) / 3$.
- (B12): Days of storage. Multiply the allowable depth of discharge limit (B2) by the total battery amp-hour capacity (B8). Then, divide this number by the total amp-hour demand per day (A10) to determine the amount of energy stored in batteries that will supply power to the load for an equivalent number of days without charging. $[(B2) \times (B8)] / (A10)$.

C. PV ARRAY SIZING

The size of the photovoltaic array is determined by analyzing the available solar insolation, the tilt of the array and the characteristics of the photovoltaic modules being considered.

The available insolation striking a photovoltaic array varies throughout the year and is a function of the tilt of the array.

DESIGN MONTH: Define the design month. If the load is constant, use the time of year with the minimum amount of sunlight (in the Northern hemisphere, typically December or January). If the load varies, use the month in which the maximum load occurs.

DESIGN TILT: Determine the optimum tilt angle for the design month by examining insolation data and selecting the angle that provides the maximum amount of insolation for the design month.

Once you know the insolation available (at tilt) and the power output required by load, you can size the array using module specifications supplied by manufacturers.

- (C1): Total energy demand per day. Insert total energy demand (A9).
- (C2): Battery round-trip efficiency. Choose a factor between 0.70 and 0.85 as an estimate for battery round-trip efficiency.
- (C3): Required array output per day. Because batteries are less than 100% efficient, the amp-hours required by the load are adjusted (upwards). Usually 80% battery efficiency is assumed. Divide the total energy demand per day (C1) by the battery round-trip efficiency (C2). $(C1) / (C2)$.

Select a photovoltaic module using selection criteria given in Section 5.

- (C4): Selected PV module max power voltage at STC $\times 0.85$. Obtain the maximum power voltage for the selected module from the manufacturer's specifications. Multiply this number by 0.85 to establish a design voltage for each module.
- (C5): Selected PV module guaranteed power output at STC. Obtain the nominal power output from manufacturer's specifications for the selected module.
- (C6): Peak sun hours at design tilt for design month. Obtain this figure from solar radiation data for the design location, array tilt and design month.
- (C7): Energy output per module per day. Multiply selected photovoltaic module power output at STC (C5) by the peak sun hours at design tilt for the design month (C6). $(C5) \times (C6)$.
- (C8): Module energy output at operating temperature. Use a derating factor of 0.80 for hot climates and critical applications; 0.90 for moderate climates and non-critical applications. Multiply the derating factor by the energy output per module (C7) to get an average energy output from one module. $DF \times (C7)$.
- (C9): Number of modules required to meet energy requirements. Divide the required array output per day (C3) by the module energy output at operating temperature (C8) to determine the number of modules required to meet energy requirements. $(C3) / (C8)$.
- (C10): Number of modules required per string. Divide the battery bus voltage (A2) by the selected module maximum power at STC $\times 0.85$ (C4). Round this number to the next higher integer to determine the number of modules required per string. $(A2) / (C4)$ rounded to the next higher integer.
- (C11): Number of strings in parallel. Divide the number of modules required to meet energy requirements (C9) by the number of modules required per string (C10). Round this number to the next higher integer to determine the number of strings in parallel. $(C9) / (C10)$ rounded to the next higher integer.
- (C12): Number of modules to be purchased. Multiply the number of modules required per string (C10) by the number of strings in parallel (C11) to determine the number of modules to be purchased. $(C10) \times (C11)$.
- (C13): Peak watts of array. Multiply the number of modules to be purchased (C12) by the selected module power output at STC to determine the peak watts of the array. $(C12) \times (C5)$.

- (C14): Peak sun hours at design tilt for worst month. Obtain peak sun hours at design tilt from insolation data.
- (C15): Usable average daily PV energy during worst month. Multiply peak sun hours at design tilt for the worst month (C14) by the derating factor (0.80 for hot climates and critical applications; 0.90 for moderate climates and non-critical applications). Then, multiply this number by peak array watts (C13) and then by battery round-trip efficiency (C2). $(C14) \times DF \times (C13) \times (C2)$.
- (C16): Average daily PV amp-hour production during worst month. Divide usable average daily photovoltaic energy during the worst month (C15) by battery bus voltage (A2). $(C15) / (A2)$.

D. GENERATOR/BATTERY CHARGER SIZING

After the energy requirements have been determined, and the battery storage subsystem and the photovoltaic array have been sized, the next step in sizing a stand-alone photovoltaic-generator system is sizing the electric generator.

Because the output of an engine generator is ac it cannot directly charge the batteries (which store dc electricity). A battery charger is needed to convert ac electricity to dc.

- (D1): Generator. The generator converts mechanical power into electrical power. Select a generator which meets the peak ac power demand (A11).
- (D2): Peak generator output power. This is the maximum electrical output from the generator. Obtain peak generator output power from manufacturer's data for the selected generator (C7).
- (D3): Battery charger. Select a battery charger so that the maximum battery charger input ac watts are nearly equal to but less than the peak generator output power (D2), and the dc voltage is the same as the nominal battery bus voltage (A2).
- (D4): Battery charger maximum charge rate. Obtain the battery charger's maximum charge rate from manufacturer's data for the battery charger selected in (C1).
- (D5): Battery charger maximum ac input power. Obtain the battery charger's maximum ac input from manufacturer's data.
- (D6): Battery charger average ac input power. Obtain the battery charger's average ac input power from manufacturer's data.

- (D7): Battery charger average dc output power. Obtain the battery charger's average dc output power from manufacturer's data.
- (D8): Battery charger average efficiency. Divide the battery charger's average dc output power (D7) by its average ac input power (D6) to determine the battery charger's average efficiency. $(D7) / (D6)$.
- (D9): Generator/battery charger turn-on point [BSOC]. Subtract the average daily depth of discharge (B10) from full state of charge [1.0]. Then, from this number subtract 0.05 to determine the level of battery discharge at which point the generator turns on to recharge the battery subsystem. $[1.0 - (B10)] - 0.05$.
- (D10): Average daily PV energy deficit during worst month. Subtract the usable daily photovoltaic amp-hour production during the worst month (C15) from the total energy demand per day (A9) to determine the average daily photovoltaic energy deficit during the worst month. $(A9) - (C15)$.
- (D11): Average daily PV amp-hour deficit during worst month. Divide the average daily photovoltaic energy deficit during the worst month (D10) by the battery bus voltage (A2) to determine the average daily photovoltaic amp-hour deficit during the worst month. $(D10) / (A2)$.
- (D12): Fraction of battery capacity supplied to the battery from generator/battery charger during worst month. Divide the average daily photovoltaic amp-hour deficit during the worst month (D11) by the total battery amp-hour capacity (B8). $(D11) / (B8)$.
- (D13): Generator/battery charger turn-off point [BSOC]. Determine the state of charge at which the generator turns off by subtracting the average daily depth of discharge (B10) from 1.0. Then, add this number to the fraction of battery capacity supplied to the battery from the generator/battery charger during the worst month (D12). $[1.0 - (B10)] + (D12)$.
- (D14): Number of months in which peak sun hours per day at design tilt is less than design peak sun hours. Obtain this information from insolation data.
- (D15): Required number of months in which generator/battery charger backup is required daily. This number is equal to the number of months in which peak hours per day at design tilt are less than design peak sun hours (D14).

- (D16): Required generator/battery charger amp-hour production during charging cycle. Subtract the generator turn-on point (D9) from the generator turn-off point (D13). Then, multiply this number by the total battery amp-hour capacity (B8). Divide this total by 0.85.

$$\frac{[(D13) - (D9)] \times (B8)}{0.85}$$

- (D17): Average yearly generator/battery charger amp-hour production. Divide the required number of months in which generator/battery charger backup is required daily (D15) by 12. Then, multiply this number by 365. Multiply this total by the required generator/battery charger amp-hour production during charging cycle (D16) to determine the average yearly generator/battery charger amp-hour production. $[(D15) / 12] \times 365 \times (D16)$.
- (D18): Battery charger average charge rate. Using battery charger literature estimate the battery charger average charge rate between the turn-on and turn-off points [BSOC].
- (D19): Average generator battery charger on-time during charging cycle. Divide the required generator/battery charger amp-hour production during charging cycle (D16) by the battery charger average charge rate (D18). $(D16) / (D18)$.
- (D20): Average yearly generator/battery charger on-time. Divide the average yearly generator/battery charger amp-hour production (D17) by the battery charger average charge rate (D18). $(D17) / (D18)$.
- (D21): Average generator ac output power. Multiply the battery charger average charge rate (D18) by the battery bus voltage (A2). Then, divide this number by the battery charger average efficiency. $[(D18) \times (A2)] / (D8)$.
- (D22): Average yearly generator energy production. Multiply the average generator/battery charger on-time (D20) by the average generator ac output power (D21). Then, divide this number by 1000. $[(D20) \times (D21)] / 1000$.
- (D23): Average generator load. Divide the average generator ac output power (D21) by the peak generator output power (D2). $(D21) / (D2)$.

The following worksheet is used for performing the cost analysis for hybrid photovoltaic generator systems.

Cost Analysis for Stand-Alone Hybrid Photovoltaic-Generator Systems WORKSHEET

Application _____

F. Economic Conditions for Analysis

- F1 Desired system life _____ years
- F2 Inflation rate (decimal) _____
- F3 Fuel escalation rate (decimal) _____
- F4 Discount rate (decimal) _____
- F5 Real discount rate (F4 - F2) _____
- F6 Current fuel cost including transportation _____ \$/gal

G. Present Worth Analysis for PV and BOS

- G1 Peak watts of array (from PV array sizing, C13) _____ watts
- G2 Cost per peak watt for PV array and BOS, installed _____ \$/watt
- G3 Initial cost for PV and BOS (G1 x G2) _____ \$
- G4 Expected PV array life _____ years

G5 Replacement Year *	G6 Present Worth
Initial Installation	(G3) _____
(G4) _____	$(G3 / (1 + F5)^{G4})$ _____
(2 x G4) _____	$(G3 / (1 + F5)^{(2 \times G4)})$ _____
(3 x G4) _____	$(G3 / (1 + F5)^{(3 \times G4)})$ _____

- G7 Present worth of PV and BOS (summation of G6) _____ \$

H. Present Worth Analysis for Generator

- H1 Peak generator output (D2) _____ watts
- H2 Cost per peak watt for generator, installed _____ \$/watt
- H3 Initial cost for generator (H1 x H2) _____ \$
- H4 Expected generator life in hours _____ hours
- H5 Average yearly generator run-time (D20) _____ hours
- H6 Expected generator life in years (H4 / H5) _____ years

* Do not calculate for replacement years greater than or equal to the system life, F1.

H7	H8
Replacement Year *	Present Worth
Initial Installation	(H3) _____
(H6) _____	(H3 / (1 + F5)H6) _____
(2 x H6) _____	(H3 / (1 + F5)(2 x H6)) _____
(3 x H6) _____	(H3 / (1 + F5)(3 x H6)) _____
H9 Present worth of generator alone (summation of H8)	_____ \$
H10 Expected yearly maintenance cost for generator	_____ \$/year
H11 Present worth of annual maintenance over system life, F1	
$H10 \times \frac{((1 + F5)^{F1} - 1)}{(F5 \times (1 + F5)^{F1})}$	_____ \$
H12 Average generator load (fraction of peak ac output), (D23)	_____
H13 Estimated generator fuel consumption at average load, H12	_____ gal/hour
H14 Average yearly fuel consumption (H5 x H13)	_____ gal/year
H15 Present worth of fuel over system life	

$$H14 \times F6 \times \left(\frac{1 + F3}{F4 - F3} \right) \times \left(1 - \left(\frac{1 + F3}{1 + F4} \right)^{F1} \right)$$

_____ \$

H16 Present worth of generator (H9 + H11 + H15) _____ \$

I. Present Worth Analysis for Batteries

I1 Total battery kW-hour capacity (B9)	_____ kW-hours
I2 Cost per kW-hour for battery, installed	_____ \$/kW-hour
I3 Initial cost for battery (I1 x I2)	_____ \$
I4 Expected battery life in cycles **	_____ cycles
I5 Expected battery life in years (I4 / 365)	_____ years

I6	I7
Replacement Year *	Present Worth
Initial Installation	(I3) _____
(I5) _____	(I3 / (1 + F5) ^{I5}) _____
(2 x I5) _____	(I3 / (1 + F5) ^(2 x I5)) _____
(3 x I5) _____	(I3 / (1 + F5) ^(3 x I5)) _____
(4 x I5) _____	(I3 / (1 + F5) ^(4 x I5)) _____
(5 x I5) _____	(I3 / (1 + F5) ^(5 x I5)) _____

I8 Present worth of battery (summation of I7) _____ \$

* Do not calculate for replacement years greater than or equal to the system life, F1.

** Estimate from battery literature at average daily depth of discharge, B10.

J. Present Worth Analysis for Battery Charger

- J1 Rated power for battery charger ($D4 \times A2$) _____ watts
J2 Cost per rated watt for battery charger _____ \$/watt
J3 Initial cost for battery charger ($J1 \times J2$) _____ \$
J4 Expected battery charger life _____ years

J5 Replacement Year *	J6 Present Worth
Initial Installation	(J3) _____
(J4) _____	$(J3 / (1 + F5)^{J4})$ _____
(2 x J4) _____	$(J3 / (1 + F5)^{(2 \times J4)})$ _____
(3 x J4) _____	$(J3 / (1 + F5)^{(3 \times J4)})$ _____
(4 x J4) _____	$(J3 / (1 + F5)^{(4 \times J4)})$ _____

- J7 Present worth of battery charger (summation of J6) _____ \$

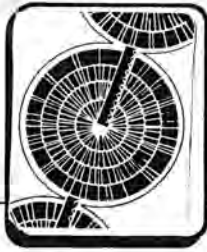
K. Present Worth Analysis of Inverter

- K1 Rated power for inverter _____ watts
K2 Cost per rated watt for inverter _____ \$/watt
K3 Initial cost for inverter ($K1 \times K2$) _____ \$
K4 Expected inverter life _____ years

K5 Replacement Year *	K6 Present Worth
Initial Installation	(K3) _____
(K4) _____	$(K3 / (1 + F5)^{K4})$ _____
(2 x K4) _____	$(K3 / (1 + F5)^{(2 \times K4)})$ _____
(3 x K4) _____	$(K3 / (1 + F5)^{(3 \times K4)})$ _____
(4 x K4) _____	$(K3 / (1 + F5)^{(4 \times K4)})$ _____

- K7 Present worth of inverter (summation of K6) _____ \$
K8 Present worth of hybrid system ($G7 + H16 + I8 + J7 + K7$) _____ \$
K9 Energy production over desired system life, E1 ($A9 \times F1 \times 365 / 1000$) _____ kW-hour
K10 Present value of hybrid system ($K8 / K9$) _____ \$/kW-hour
K11 Total initial cost for hybrid system ($G3 + H3 + I3 + J3 + K3$) _____ \$

* Do not calculate for replacement years greater than or equal to the system life, F1.



Appendix D

Photovoltaic Water Pumping Systems: Sizing Worksheet and Instructions

The following sizing worksheet provides a systematic approach for designing a stand-alone direct-coupled photovoltaic water pumping system. Typically, direct-coupled systems are only practical when centrifugal pumps are used. Positive displacement pumps usually require a maximum power point tracker or operation from batteries to perform effectively. For pumping systems operating from batteries, the procedure is the same as for stand-alone photovoltaic systems with battery storage once the wattage and time of operation for the pump-motor load is determined. Step-by-step instructions follow the worksheet.

Photovoltaic Water Pumping System Design WORKSHEET

Design period _____ Design tilt _____
Design location _____ Latitude _____

Insolation Availability

P1 Daily insolation = _____ [kWh/(m²-day)]
P2 Usable insolation = P1 _____ x derating factor _____ = _____ [kWh/(m²-day)]
P3 Peak sun hours available = P2 = _____ (hrs/day)

Pumping Flow Requirements

P4 Daily quantity of water required = _____ (gal/day)
P5 Peak flow rate = P4 _____ / (P3 _____ x 60) = _____ (gal/min)
P6 Pipe inside diameter = _____ (in) Type _____
P7 Peak velocity = P5 _____ / (P6 _____)² x .408 = _____ (ft/s)

Pumping Head Requirements

Static Head

P8 Suction lift (or Head) * = _____ (ft)
P9 Discharge head = _____ (ft)
P10 Pressure head = _____ (PSIG) x 2.31 = _____ (ft)
P11 Total static head = P8 _____ + P9 _____ + P10 _____ = _____ (ft)

Dynamic Head

P12 Velocity head = (P7 _____)² x 0.0155 = _____ (ft)

Friction Head	Equivalent	Equivalent			
Pipe Fitting	Quantity	Length Factor	Length		
_____	_____	x _____	=	_____	(ft)
_____	_____	x _____	=	_____	(ft)
_____	_____	x _____	=	_____	(ft)
_____	_____	x _____	=	_____	(ft)
_____	_____	x _____	=	_____	(ft)
				Actual pipe length	= _____ (ft)
				Total equivalent length	= _____ (ft)
P13					
P14 Friction head = P13 _____ / 100 x loss per 100 ft _____				=	_____ (ft)
P15 Total dynamic head = P12 _____ + P14 _____				=	_____ (ft)
P16 Total system head = P11 _____ + P15 _____				=	_____ (ft)

* Enter a negative number for suction head.

Pumping Energy Requirements

P17 Hydraulic energy =

$$P16 \text{ _____ (ft)} \times P4 \text{ _____ (gal/day)} \times 0.0031 = \text{_____ (Wh/day)}$$

P18 Hydraulic power =

$$P5 \text{ _____ (gal/min)} \times P16 \text{ _____ (ft)} \times 0.188 = \text{_____ (watts)}$$

Pump Selection

$$\text{Flow rate} = P5 \text{ _____ (gal/min)}$$

$$\text{Total system head} = P16 \text{ _____ (ft)}$$

Select a pump/motor combination capable of meeting flow and head requirements with high efficiency.

$$\text{Pump/motor model} \text{ _____}$$

$$\text{Efficiency} \text{ _____ (\%)}$$

P19 Motor voltage = _____ (volts)

P20 Electric power = _____ (watts)

P21 Daily electrical energy = P20 _____ x P3 _____ = _____ (Wh/day)

Photovoltaic Array Sizing

Selected PV Module _____

Standard tests conditions (STC): 1 kW/m², 25°C

M1 Module voltage at max power (STC) _____ (volts)

M2 Module current at max power (STC) _____ (amps)

M3 Module guaranteed power output at 1 kW/m² (STC) or (M1 x M2) _____ (watts)

M4 Total energy demand = P21 _____ (Wh/day)

M5 Impedance mismatch and non-linear effects for direct coupled systems = (0.7 - 0.9) _____

M6 Required array output = M4 / M5 _____ (Wh/day)

M7 PV module operating voltage = M1 x (1.1 - 1.2) _____ (volts)

M8 Daily energy output per module = M3 x P3 _____ (Wh/day)

M9 Temperature derating factor = (0.80 - 0.90) _____

M10 Derated module energy output = M8 x M9 _____ (Wh/day)

M11 Number of modules to meet daily energy requirements = M6 / M10 _____ (modules)

M12 Number of modules per string rounded to the closest integer
= P19 / M7 _____ (modules)

M13 Number of strings in parallel rounded to the closest integer
= M11 / M12 _____ (strings)

M14 Total number of modules required = M12 x M13 _____ (modules)

INSOLATION AVAILABILITY

Determine: Design Location: Nearest location to design site with available insolation data.

Design Latitude: Latitude of location with available insolation data.

Design Period: Month with least available insolation.

Design Tilt: Angle of array providing maximum insolation during design period.

P1: Daily insolation [kWh/m²-day]. From insolation data obtain the amount of daily insolation available at the design location during the design period at the design tilt.

P2: Usable insolation [kWh/m²-day]. Pump motors require a minimum current threshold before starting. Because insolation must reach a certain level before the pump starts, some of the daily insolation is not usable.

Determine the actual amount of insolation that is usable per day by multiplying the daily insolation (P1) by a derating factor. Use a derating factor between 0.7 and 0.95. (P1) x DF.

This derating factor is an estimated value determined by viewing pump turn-on and turn-off points in relation to the current available from the photovoltaic array in the early morning and late afternoon.

P3: Peak sun hours available (hrs/day). Insert the estimated amount of insolation that is usable per day (P2).

PUMPING FLOW REQUIREMENTS

P4: Daily quantity of water required (gal). Quantify the amount of water required per day for the application.

P5: Peak flow rate (gal/min). Divide the daily quantity of water required (P4) by the amount of usable peak sun hours in terms of minutes (P3 x 60) to determine a theoretical peak rate at which water is delivered by the pump.

$$\frac{(P4)}{(P3) \times 60}$$

- P6: Pipe inside diameter (in). Determine the inside diameter of the pipe you will use in the system. This figure is needed to determine the cross sectional area of the flow and pipe friction losses. Note that the worksheet assumes pipe size used in the system is consistent throughout. Define the material the pipe is made from.
- P7: Peak velocity (ft/sec). Divide the peak flow rate (P5) by the pipe diameter squared (P6)². Multiply this number by the conversion factor 0.408 to determine the maximum velocity water moves through the pipe in ft/sec.

$$\frac{(P5)}{(P6)^2 \times 0.408}$$

PUMPING HEAD REQUIREMENTS

STATIC HEAD

- P8: Suction lift or head (ft). Measure the vertical distance (in feet) from the surface of the water source to the center of the pump. Note that when the pump is located below water level, suction head is a negative value.
- P9: Discharge head (ft). Measure the total vertical distance (in feet) from the center of the pump to the point of free discharge.
- P10: Pressure head (ft). If a final discharge pressure higher than atmospheric pressure is desired (for example, with a pressurized storage tank), the pump must be able to supply the flow with the needed energy. Multiply the desired pressure in psig by 2.31 to determine the equivalent feet of head required to pressurize a tank to the design pressure.
- P11: Static head (ft). Determine the total head required to lift the water to a desired level and to store it in a tank at a prescribed pressure by adding suction lift (P8), discharge head (P9) and pressure head (P10) together. (P8) + (P9) + (P10).

DYNAMIC HEAD

- P12: Velocity head (ft). Multiply the peak velocity squared (P7)² by a conversion factor of 0.0155 to determine the equivalent feet of head that a pump must supply to move the fluid at a given velocity. Velocity head is generally insignificant for most PV water pumping systems. (P7)² x 0.0155.

- P13: List the different pipe fitting types. Fittings occur where two pipes are connected. Different fitting types provide different amounts of flow resistance.

List the number of pipe fittings by type to be used in the system.

Convert the resistance of different fitting types into the equivalent length of straight pipe. Obtain this information from a conversion chart.

Multiply the equivalent length factor for each fitting type by the number of fittings of that type to determine the equivalent length.

Insert the actual amount of straight pipe used in the application.

Add the quantities in the column titled **Equivalent Length** and the actual pipe length to determine the total equivalent length of pipe (the adjusted pipe length used in sizing to compensate for friction head). Friction head is the equivalent feet of head required to overcome energy losses that occur as fluid flows through the pipe. The pump must supply energy to overcome these losses.

- P14: Friction head (ft). Divide the total equivalent pipe length by 100. Then, multiply this number by friction loss per 100 ft of pipe (for a given material and diameter of pipe) to determine the equivalent feet of head required to overcome the loss of energy that occurs as fluid flows through the pipe.
- P15: Dynamic head (ft). Determine the head required to move liquid at a given velocity and overcome effects due to friction by adding the velocity head (P12) to the friction head (P14). $(P12) + (P14)$.
- P16: Total system head (ft). Determine the total system head by adding the total static head (P11) to the total dynamic head (P15). Both the system head and the flow rate determine the power requirements for pumping. $(P11) + (P15)$.

PUMPING ENERGY REQUIREMENTS

- P17: Hydraulic energy (Wh/day). Multiply the total system head (P16) by the daily quantity of water required per day (P4). Then, multiply this figure by a conversion factor of 0.0031 to determine the mechanical energy required to deliver a prescribed volume of water at a given head in units of watt-hours per day. $[(P16) \times (P4)] \times 0.0031$.
- P18: Hydraulic power (W). Multiply the peak flow rate (P5) by the total system head (P16). Multiply this quantity by a conversion factor of 0.188 to give units of watts. $[(P5) \times (P16)] \times 0.188$.

PUMP SELECTION

Select a pump/motor combination capable of meeting flow and head requirements efficiently. Analyze peak flow rate and total system head and determine if they fall within the high efficiency range of the pump/motor according to manufacturer's specifications.

- P19: Motor voltage (V). Determine the motor voltage from manufacturer's data by locating the point where peak flow rate and total system head intersect on the head vs. flow graph for the pump/motor. Given voltage curves may need to be interpolated to estimate the motor voltage for a given flow and head.
- P20: Electric power (W). The electric power required to operate the pump/motor at the design conditions is also obtained from manufacturer's efficiency curves. Draw in an interpolated curve for the motor voltage estimated in (P19) on the power vs. flow curves. Locate the intersection of flow rate and the interpolated curve voltage to determine the power required to operate the pump/motor at this point.
- P21: Daily electrical energy (Wh/day). Determine the electrical energy required to obtain the daily quantity of water at a given total system head with the selected pump/motor by multiplying the pump electric power (P20) by the peak sun hours available (P3). This is an approximation assuming all water is pumped during the number of peak sun hours (P3). $(P20) \times (P3)$.

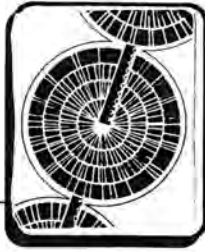
PHOTOVOLTAIC ARRAY SIZING

Select a photovoltaic module.

- M1: Module voltage at max power (STC) (V). Obtain selected module voltage at maximum power from the manufacturer's specifications.
- M2: Module current at max power (STC) (A). Obtain selected module current at maximum power from the manufacturer's specifications.
- M3: Module guaranteed power output at 1 kW/m^2 (STC) (W). Obtain module guaranteed power output at STC from the manufacturer's specifications.
- M4: Total energy demand (Wh/day). The total energy demand for the pump/motor is equal to the daily electrical energy required by the photovoltaic array (P21).

- M5: Impedance mismatch and non-linear effects for direct-coupled systems. Because modules do not operate consistently at the maximum power point when directly coupled to a pump/motor, choose a derating factor between 0.7 and 0.9 to adjust the required array energy. Note that the pump motor efficiency may decrease from the design point. For systems with a maximum power point tracker, a value of 0.9 is appropriate.
- M6: Required array output (Wh/day). Divide the total energy demand (M4) by the derating factor (M5) to determine the required array output. $(M4) / (M5)$.
- M7: PV module operating voltage (V). Multiply the module voltage at maximum power (M1) by an adjustment factor (AF) between 1.1 and 1.2 to establish a module operating voltage that is on the I-V curve to the right of the maximum power point at peak sun conditions. This is necessary to ensure that the pump/motor load line intersects the maximum power locus on the PV array family of I-V curves somewhere between 700 and 800 W/m². $(M1) \times (AF)$.
- M8: Daily energy output per module (Wh/day). Multiply the module power at STC (M3) by the peak sun hours available (P3) to determine the daily energy output per module. $(M3) \times (P3)$.
- M9: Temperature derating factor. Select a temperature derating factor between 0.80 and 0.90 to compensate for the difference between actual operating conditions and standard test conditions under which the modules are rated.
- M10: Derated module energy output (Wh/day). Multiply the daily energy output per module (M8) by the temperature derating factor (M9) to determine the derated module energy output. $(M8) \times (M9)$.
- M11: Number of modules to meet daily energy requirements. Divide the required array output (M6) by the derated module energy output (M10) to determine the number of modules needed to meet the daily energy requirements. $(M6) / (M10)$.
- M12: Number of modules per series string. Divide the motor voltage (P19) by the photovoltaic module operating voltage (M7). Round this number to the closest integer to determine the number of modules needed for each series string. $(P19) / (M7)$ rounded to closest integer.
- M13: Number of series strings in parallel. Divide the number of modules needed to meet the daily energy requirements (M11) by the number of modules per series string (M12) to determine the number of series strings in parallel required to meet the daily energy requirements. $(M11) / (M12)$.

- M14: Total number of modules required. Multiply the number of modules per string (M12) by the number of strings in parallel (M13) to determine the total number of modules required for the application. $(M12) \times (M13)$.



Appendix E

Cost Analysis for Utility Connected Systems: Completed Worksheet

The following is a completed example of a cost analysis for utility connected systems.

Cost Analysis for Utility Connected Systems WORKSHEET

Application Stand-Alone Home in Tallahassee, FL

A. Economic Conditions for Analysis

A1	Desired system life	<u>20</u>	years
A2	Inflation rate (decimal)	<u>.06</u>	
A3	Utility electricity escalation rate (decimal)	<u>.07</u>	
A4	Discount rate (decimal)	<u>.08</u>	
A5	Real discount rate (A4 - A2)	<u>.02</u>	
A6	Current cost for utility power	<u>.08</u>	\$/kW-hour
A7	Cost per foot for power line installation and connection	<u>10.00</u>	\$/foot

F. Present Worth Analysis for Utility Power

B1	Distance from utility power	<u>5 mi = 26,400</u>	feet
B2	Initial cost for power line installation and connection (B1 x A7)	<u>264,000</u>	\$
B3	Annual energy use	<u>2896</u>	kW-hours
B4	Present worth of utility energy over system life		
	$B2 + \left(B3 \times A6 \times \left(\frac{1 + A3}{A4 - A3} \right) \times \left(1 - \left(\frac{1 + A3}{1 + A4} \right)^{A1} \right) \right)$	<u>268,208</u>	\$
B5	Energy use over desired system life (B3 x A1)	<u>57,926</u>	kW-hours
B6	Present value of utility power (B4 / B5)	<u>4.63</u>	\$/kW-hour
B7	Total initial cost for utility power (B2)	<u>264,000</u>	\$