Stand-Alone Photovoltaic Lighting Systems

A Decision-Maker's Guide

Volume 2: PV Lighting Components and System Design

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Volume 2: PV Lighting Components and System Design

Prepared for:

Florida Energy Office / Department of Community Affairs

By:

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First Edition September 1998

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Abstract

This document provides an overview of photovoltaic (PV) lighting components and system design principles. This information is intended for those individuals that specify PV lighting equipment and evaluate system designs, as well as those that design and integrate systems. Included in this report are fundamentals and selection criteria for the major PV lighting system components – the PV array, batteries, controls and luminaires. Sizing information is also provided using the requirements of a PV lighting system design example. A discussion on electrical and mechanical design requirements is also presented.

Preface

This document is one of four topical reports on stand-alone photovoltaic (PV) lighting systems. The information is based on current state-of-the-art understanding, and is intended for those individuals and organizations evaluating the potential of using PV systems for a number of lighting applications. These documents may also be useful to PV lighting system suppliers, by helping educate prospective customers in the process of identifying and implementing practical and cost-effective PV lighting solutions.

Principal target groups for this document include:

- Federal, state and local government agencies
- Transportation and navigational authorities
- Planners, developers and builders
- Electric utilities
- Consumers and homeowners
- Emergency management officials
- Development and conservation organizations
- PV lighting system manufacturers and suppliers

The information presented in this set of topical reports provides an overview of PV lighting systems from a technical perspective. The content covers considerations for evaluating the feasibility of PV lighting applications, PV lighting components and system design, developing technical project specifications, and fundamentals of lighting design and lighting equipment. At the end of each report, sources for PV lighting equipment and a reference list are provided.

The four documents in this set of topical reports are:

Volume 1: Photovoltaic Lighting Applications
Volume 2: PV Lighting Components and System Design
Volume 3: Technical Specifications and Case Studies
Volume 4: Lighting Fundamentals and Equipment

Disclaimer

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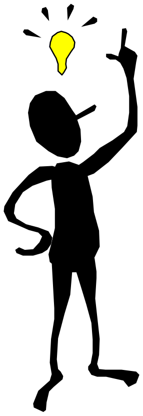
1. INTRODUCTION



"How do we cost-effectively provide power to our lighting needs in cases where utility power is not practical or available?"

This question is asked by many public and private concerns, including facilities managers, municipal planners and developers, navigation and transportation authorities, outdoor advertisers, utilities, contractors and property owners. For many, ***solar photovoltaic (PV)*** lighting systems have provided a practical and cost-effective solution for powering a diversity of lighting applications.

Thousands of PV lighting systems are being installed annually throughout the world, including applications for remote area lighting, sign lighting, flashing and signaling systems, consumer devices and for home lighting systems. PV lighting systems are simple, easy to install, and if properly designed and maintained, can provide years of exceptional service.

1.1 Advance Organizer for PV Lighting Systems

Figure 1-1 shows an ***"advanced organizer"*** for stand-alone PV lighting systems. This simplified diagram is intended to organize the reader's thinking about the major components and interactions in stand-alone PV lighting systems.

In typical PV lighting systems, the light source is powered by a battery, which is recharged during the day by direct-current (DC) electricity produced by the PV array. Electronic controls are used between the battery, light source and PV array to protect the battery from overcharge and overdischarge, and to control the timing and operation of the light.

In a basic way, these systems operate like a bank account. Withdrawals from the battery to power the light source must compensated for by commensurate deposits of energy from the PV array. As long as the system is designed so that deposits exceed withdrawals on an average daily basis during the critical design period, the battery remains charged and the light source is reliably powered.

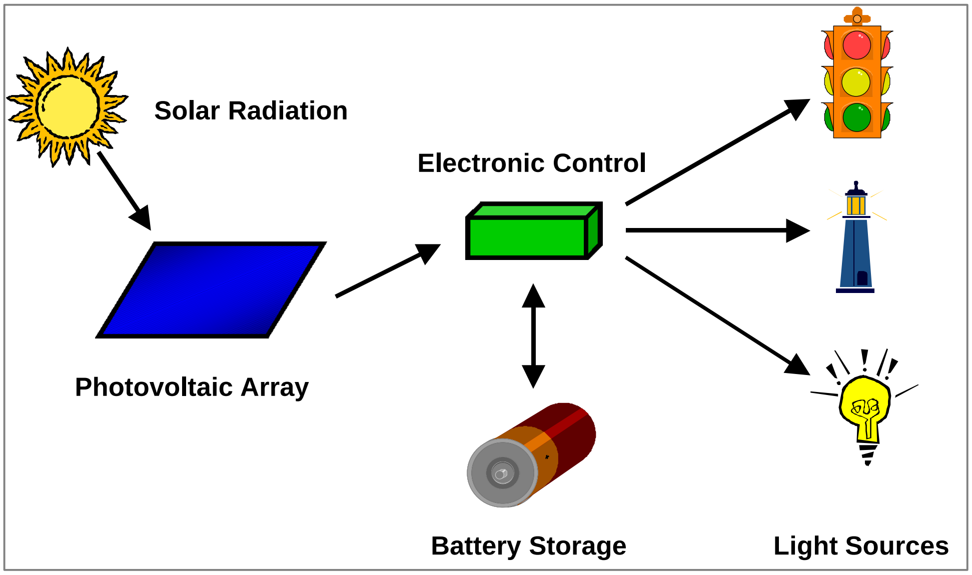


Figure 1-1. PV lighting system advance organizer.

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2. PV Lighting Components

The principal components in any PV lighting system are an array of photovoltaic modules, a battery, a battery charge and light controller, and the lighting load. The array charges the battery during the day, and the battery delivers energy to the lighting load at night. The control system manages the battery state-of-charge and in automatic systems, controls operation of the light.

In any system design, it is important that the individual components are compatible and interact properly with one another. The characteristics and functions of these major system components are described in the following sections.

2.1 Photovoltaic Modules and Array

Photovoltaic cells are semiconductor devices that convert sunlight to DC electricity. Groups of cells are connected electrically in series and/or parallel and sealed in environmentally protective laminates to construct *PV modules*. One or more modules comprising the complete PV generating unit for a system is called a *PV array*.

The primary function of the array in stand-alone PV lighting systems is to:

- Provide enough energy to satisfy the average daily electrical load during the month with the *lowest solar insolation to lighting load ratio.*
- Otherwise provide enough excess energy to maintain the storage battery at *high state-of-charge* and account for system losses.

Figure 2-1. PV modules - Solarex MSX-60 (L), Siemens SP-75 (R).

Figure 2-1 shows two typical PV modules produced by two principal U.S. manufacturers. The module on the left is constructed of polycrystalline cells and is rated to produce 60 watts at peak standard conditions. The module on the left is made from single-crystal silicon solar cells, and has a rated peak output of 75 watts. Both of these modules have 36 series-connected solar cells, resulting in a peak power operating voltage of about 16-17 volts, making them ideal for nominal 12-volt battery chargers. The surface area of the larger module is approximately 0.5 square meters and both modules have peak sunlight to electrical power conversion efficiencies of greater than ten percent.

The electrical performance of PV modules is given by its current-voltage (IV) characteristic, illustrated in Figure 2-2. This curve represents a PV device performance at certain conditions of sunlight and cell temperature. Key points on this curve are commonly used to rate PV module performance, and are defined as follows:

- ***Open-circuit voltage (Voc)*** - operating point under zero load, current and power output equal zero.
- ***Short-circuit current (Isc)*** - operating point with shorted output, voltage and power output equal zero.
- ***Maximum power voltage (Vmp)*** – operating voltage at peak power output.
- ***Maximum power current (Imp)*** – operating current at peak power output.
- ***Maximum power (Pmp)*** – peak output power point.

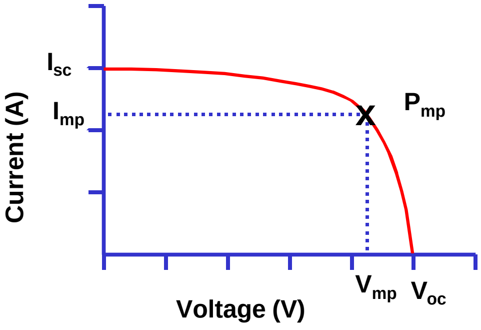


Figure 2-2. I-V curve.

Solar radiation and temperature are the two principal factors affecting PV device performance. Peak current and power output are directly proportional to the incident solar radiation, while the peak voltage remains relatively stable at irradiance levels above 200 watts per square meter (one-fifth peak sun). Higher temperatures reduce the peak voltage and power output of silicon-based PV devices by 0.4 to 0.5 percent per degree Centigrade.

For these reasons, module performance information only has meaning when the rating conditions are specified. The most common condition used by manufacturers to rate module performance is Standard Test Conditions (STC). The STC rating prescribes a module operating condition of 25 ^{o}C cell temperature under a peak solar irradiance level of 1000 watts per square meter (1 kW/m^2). In the field, modules typically operate at higher temperatures and another rating condition - Standard Operating Conditions (SOC) - is sometimes used. This performance ratings information must be displayed on the back of all PV modules. Figure 2-3 shows the performance label on a Siemens Solar SP-75 module with UL listing.

Figure 2-3. Module listing label.

2.1.1 *Selection Criteria for PV Modules and Arrays*

A number of factors should be considered when selecting PV modules for a given lighting application. These criteria include:

- Electrical performance (rated output)
- Physical properties (e.g., size, weight)
- Mechanical properties (construction materials, mounting attachment, etc.)
- Reliability (qualification tests, UL listing)
- Efficiency and surface area requirements for array
- Cost, lifetime and warranty.

2.2 Batteries

Batteries are electrochemical cells that store energy in chemical bonds. This chemical energy is converted to electrical energy when a battery is connected to an electrical load and discharged. By reversing the flow of current, the chemical nature of the battery is restored to its charged condition.

Because the electrical energy produced by the PV array does not always coincide with when energy is needed, rechargeable batteries are commonly used in stand-alone PV lighting systems. The principal functions of batteries in these systems are to:

- Store energy produced by the PV array during the day, and supply it to the lighting load at night and for days of below average sunlight.
- Operate the lighting loads at stable voltages, and supply surge currents if needed.
- Establish a suitable operating voltage to maximize PV array output.

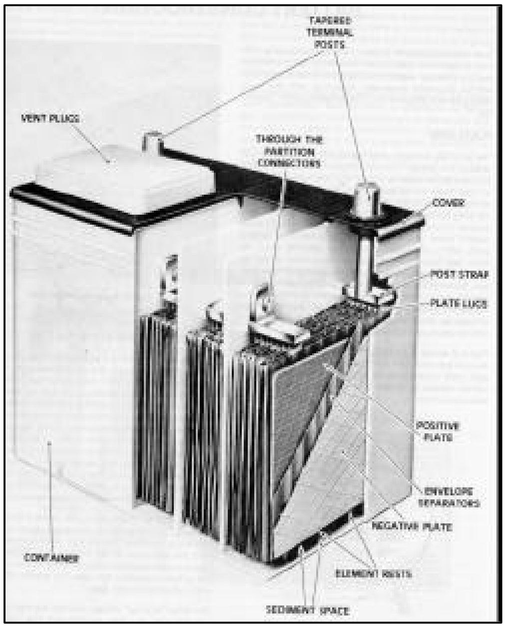


Figure 2-4. Battery cut-away view.

The batteries are the central part of any stand-alone PV system, and must be designed for the service requirements of the application. Because batteries in PV lighting systems sometimes experience deep discharge cycles, they should be tolerant of this treatment to maximize performance and cycle life.

One of the single most important cost drivers for PV lighting systems is battery replacement. For this reason, optimal battery cycle life is desired. For typical PV lighting applications, batteries may last anywhere from three to ten years. Factors that affect battery cycle life include:

- Battery design and construction
- Temperature
- Frequency and depth of discharges
- Average state-of-charge
- Charging methods
- Required maintenance.

Temperature is perhaps the most important operational variable affecting battery life. Higher temperatures accelerate grid corrosion and result in greater gassing and electrolyte loss. For all types of batteries, lifetime decreases by a factor of about two for every 10 ^{o}C increase in average operating temperature. On the other hand, low operating temperatures extend battery life, although available battery capacity is reduced. In any application, battery life can be optimized by proper charging (not overcharging or over discharging), maintaining high state-of-charge, limiting the frequency and depth of discharges, moderating the temperature and conducting regularly scheduled maintenance.

2.2.1 *Battery Selection Criteria*

Certain battery designs are more suitable for the operating conditions found in PV lighting systems. However, the ultimate selection of a battery involves many tradeoffs, including:

- Performance (capacity, voltage)
- Lifetime (cycles, years to certain average daily depth of discharge)
- Physical characteristics (size, weight, case)
- Electrical configuration (series, parallel arrangement)
- Maintenance requirements (testing, cleaning, water additions)
- Warranty and cost (initial and replacement)
- Availability.

Both flooded and sealed valve-regulated lead-acid (VRLA) batteries are commonly used in PV lighting systems, the latter having lower maintenance requirements. Nickel-cadmium and nickel-metal hydride cells are sometimes used in small consumer products and in extremely low temperature and critical power applications such as navigational aids. Table 1 lists some advantages and disadvantages of various battery types used in PV lighting applications.

Table 1. Battery Comparison

Battery Type	Advantages	Disadvantages
Flooded Lead-Acid		
Lead-Antimony	Low cost, wide availability, good deep cycle and high temperature performance. Can replenish electrolyte. Good cycle life.	High water loss and maintenance. Need for periodic equalization.
Lead-Calcium Open Vent	Low cost, wide availability, low water loss. Can replenish electrolyte.	Average to poor deep cycle performance, intolerant of high temperatures and overcharge. Need for periodic equalization.
Lead-Calcium Sealed Vent	Low cost, wide availability, low water loss.	Average to poor deep cycle performance, intolerant to high temperatures and overcharge. Can not replenish electrolyte.
Lead Antimony/Calcium Hybrid	Moderate cost, low water loss, good deep cycle performance. Good cycle life.	Limited availability, potential for stratification. Need for periodic equalization.
Captive Electrolyte Lead-Acid		
Gelled	Moderate cost and cycle life, little or no maintenance. No liquid electrolyte, install in any orientation.	Fair deep cycle performance, intolerant of overcharge and high temperatures. Limited availability.
Absorbed Glass Mat	Moderate cost and cycle life, little maintenance. No liquid electrolyte, install in any orientation.	Fair deep cycle performance, intolerant to overcharge and high temperatures. Limited availability.
Nickel-Cadmium		
Sealed Sintered-Plate	Wide availability, excellent low and high temperature performance. Maintenance-free and long life.	High cost, only available in low capacities. Suffer from 'memory' effect when partially discharged.
Flooded Pocket-Plate	Excellent deep cycle and high/low temperature performance. Tolerant of overcharge.	High cost, limited availability. Water additions required.

2.3 PV Lighting System Controllers

System controllers are required in PV lighting systems to regulate the battery charge and to control the operation of the lighting load. The functions of a PV lighting system controller are to:

- Prevent battery overcharge by the PV array (voltage regulation -temperature compensated)
- Prevent battery overdischarge by the lighting load (low voltage load disconnect)
- Maintain battery at highest possible state-of-charge
- Control the timing and operation of the lighting load
- Serve as a terminal connection point between the array, battery and lighting load.

Optional features of some PV lighting controllers include:

- System status indicators, lights and meters
- Advanced load control
- Battery charge equalization
- Data monitoring and recording for system diagnostics.

Figure 2-5 and Figure 2-6 show two typical system controllers used in PV lighting applications. These controllers use battery voltage sensing to regulate the battery state-of-charge and disconnect the load if the battery becomes over-discharged to a low voltage. These controllers use the PV array to sense dusk conditions to activate the light, and can be set to operate the light until dawn or for a fixed number of hours after dusk. In some cases, a separate lighting controller may be used independent of the battery charge controller. Two of these devices are shown in Figure 2-7 below. The controller on the left allows for time of day and weekly programming, and the unit on the right uses PV array sensing and timing circuits to control the light.

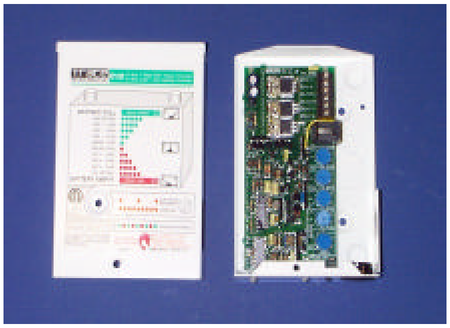


Figure 2-5. PV lighting system controller (Trace Engineering).

Figure 2-6. PV lighting system controller (Morningstar).

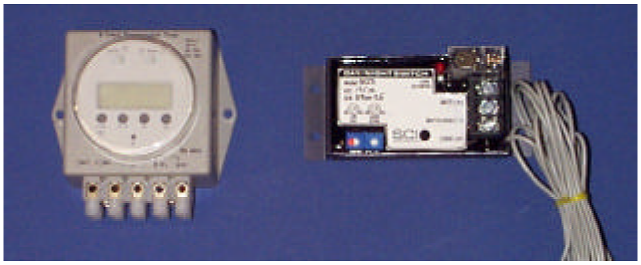


Figure 2-7. PV lighting controls (SEPCO, SCI).

2.3.1 *PV Lighting System Controller Selection Criteria*

The controller in PV lighting systems plays a critical role in the operational performance of the systems. The following criteria should be considered when specifying or selecting controllers for PV lighting applications:

- Nominal system operating voltage (12, 24 or 48 volts DC)
- Maximum PV array and lighting load currents
- Battery characteristics (charging requirements, allowable depth of discharge)
- Regulation and load disconnect set point requirements
- Charge algorithms and switching element
- Lighting load control strategies
- Battery charge voltage temperature compensation (on board or external probe)
- Expected environmental operating conditions and appropriate mechanical packaging
- Availability of system status indicators
- Availability of battery overcurrent and disconnect provisions
- Overall compatibility with system functional requirements and other components
- Cost and warranty.

One of the most important features of battery charge controllers are the voltage settings at which they control the PV array and load to protect the battery from overcharge and over discharge. Table 2 provides recommended set point values for PV array regulation and load disconnect for two classifications of controllers and for four battery technologies. Specific set point requirements may vary for particular designs and applications.

Table 2. Suggested charge controller set point values.

Charge Controller		**Suggested Regulation and Load Disconnect Voltages** *(per nominal 12-volt battery)*			
Controller Design Type	**Controller Set Points at 25 °C**	***Flooded Lead-Antimony***	***Flooded Lead-Calcium***	***Sealed, Valve Regulated Lead-Acid***	***Flooded Pocket Plate Nickel-Cadmium***
On-Off, Interrupting	**Charge Regulation Voltage**	14.6 - 14.8	14.4 - 15.0	14.2 - 14.4	14.5 - 15.0
	Array Reconnect Voltage	13.5 – 14.0	13.5 – 14.0	13.5 – 14.0	13.5 – 14.0
Constant-Voltage, PWM, Linear	**Charge Regulation Voltage at 25 °C**	14.4 - 14.6	14.4 - 14.7	14.0 - 14.2	14.5 - 15.0
All Controllers	**Load Disconnect Voltage**	11.3 – 12.0	11.3 – 12.0	11.3 – 12.0	11.3 – 12.0
	Load Reconnect Voltage	12.5 –13.5	12.5 –13.5	12.5 –13.5	12.5 –13.5

2.4 Luminaires

Luminaires are the complete lighting unit consisting of lamp, socket, ballast, reflector, diffuser and fixture housing. Considerations in luminaire selection include:

- Proper candlepower distribution for the intended application
- Efficiency of converting electrical power to light output
- Equipment listing and outdoor rating
- Mechanical design, construction and use of materials
- Ease of lamp and ballast replacement
- Aesthetic appearance
- Cost and reliability.

Figure 2-8 shows a fluorescent lighting fixture designed for PV applications. The 36-watt compact fluorescent lamp is housed in an anodized aluminum housing mounted above with a highly polished reflector. The lens is made from vandal-resistant Lexan and sealed with a neoprene gasket. The fixture assembly attaches directly to a common 2-inch diameter tenon mount. The light distribution from this fixture is directed downward, thus the designation "cut-off."

Figure 2-8. Fluorescent cut-off type fixture (C-Ran).

A luminaire designed expressly for PV lighting applications using a metal-halide lamp is shown in Figure 2-9. This luminaire uses a "cobra-head" fixture with a round diffusing type lens to provide a more uniform light distribution and to reduce glare from the small metal-halide light source. This type of fixture design is generally more acceptable to utilities and other commercial lighting users. The metal-halide source provides good light quality and is not affected by low temperatures as much as fluorescent lamps are.

Figure 2-10 shows a low-pressure sodium luminaire common in PV lighting systems. This luminaire uses a weather-resistant fiberglass housing and diffusing lens. A photocell to control the light operation can be seen at the top. Low-pressure sodium lamps offer high efficiency lighting; however the color rendition under this monochromatic yellow light source is poor.

Figure 2-10. Metal-halide luminaire (Advanced Energy Systems).

Figure 2-9. Low-pressure sodium luminaire (Thin-Lite).

Since most PV area and sign 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 include the effects of voltage, frequency, temperature, and transients on the lamp starting, output and lifetime. Figure 2-11 shows typical low-voltage dc ballasts for fluorescent lamps.

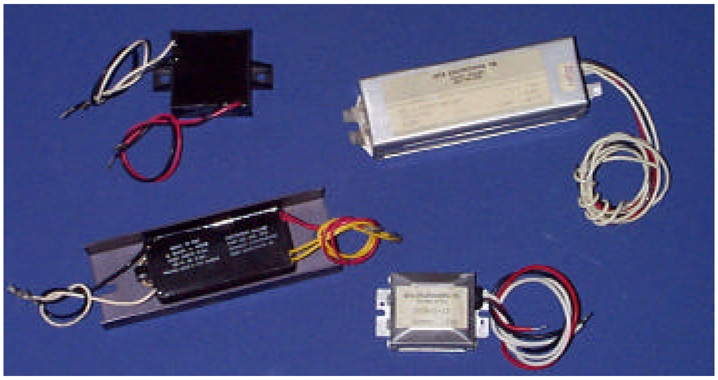
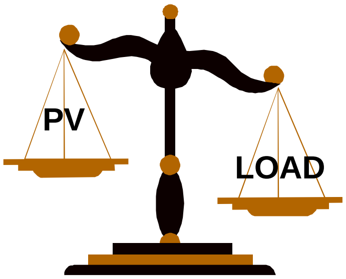


Figure 2-11. Low voltage DC ballasts (Sunalex, IOTA Engineering).

3. Sizing and Design of Stand-Alone PV Lighting Systems



Stand-alone PV lighting systems are independent, fully integrated power supplies with the primary function to operate lighting equipment. Depending on the given application, the PV power supply may be mechanically integrated with the lighting equipment in different ways, although the function, electrical design and component sizing considerations remain essentially the same.

The design of PV lighting systems involves a number of steps and possible iterations to select and size the individual components required for a functional system. This section covers the basics of sizing and design, and demonstrates the process by use of an example. A worksheet is presented later in this section summarizing the sizing example.

The following steps outline the process for designing PV lighting systems. Refer to the PV lighting system advance organizer below in Figure 3-1 to help in understanding this design process as it relates to the basic system configuration.

1. Establish the ***quantity and quality of lighting*** needs. Select lighting fixture(s) based on application requirements.
2. Determine the ***magnitude and duration of the lighting electrical load*** on average daily and seasonal bases.
3. Estimate ***battery storage size*** based on the desired autonomy period and maximum and average daily depth of discharge. Select a battery based on application requirements.
4. Estimate ***PV array size*** based on the time of year with the highest average daily lighting load and minimum solar radiation. Select PV modules and array based on application requirements.
5. Determine the ***control strategy*** to be used for battery protection and lighting control and specify the control set points and conditions. Select system controls based on application requirements.
6. Complete ***electrical design*** requirements.
7. Complete the ***mechanical design*** and system configuration.

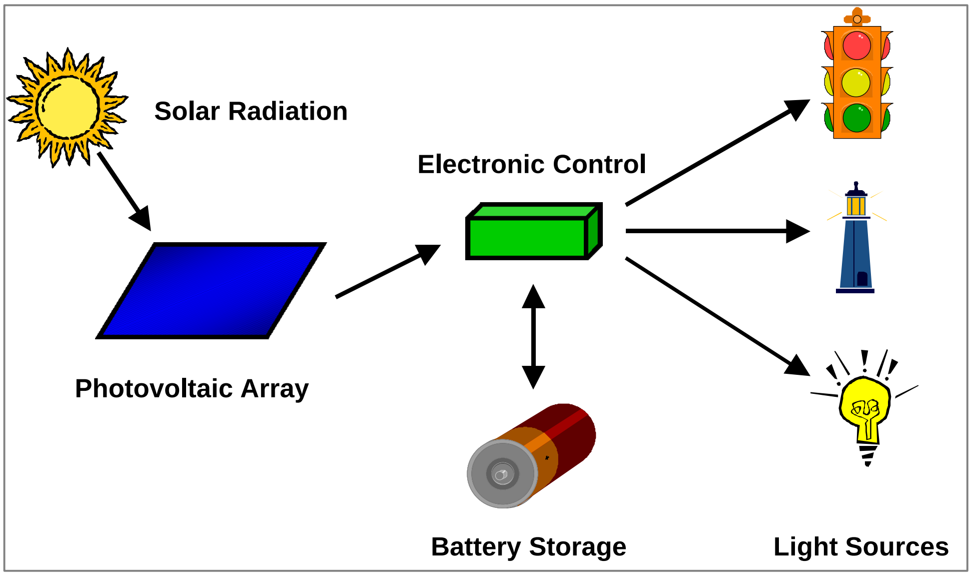


Figure 3-1. PV lighting system advance organizer.

3.1 Estimating the Lighting Electrical Load

The first step in any PV system sizing process is to quantify the magnitude and duration of the electrical load. It is the electrical load that determines the size and cost of a PV-powered system; therefore the energy efficiency of the load is a critical concern. For this reason, steps are often taken to improve the efficiency of lighting design as part of any PV lighting application. As discussed earlier, this may involve several factors, including selection of more efficient light sources and improved luminaire design, better aiming and distribution of the light, and special controls to limit the time of operation or to reduce the level of lighting when not needed. Adoption of any of these measures will result in a corresponding reduction in the size and cost of the PV system required.

The daily energy requirement for the lighting load is determined by the product of the load current and operation time, expressed in units of ***ampere-hours (Ah)***. For example, a three-amp light load operated for six hours per night would require 18 Ah. If the lighting is designed to operate from dusk to dawn annually, then seasonal variations in the lighting load should also be considered. For PV lighting systems operating in the Northern Hemisphere, the maximum load occurs on the winter solstice (December 21) and the minimum load occurs on the summer solstice (June 21). At higher latitudes, greater seasonal variation occurs in the length of days and nights. At the equator, all days and nights throughout the year are exactly 12 hours, where at all other north and south latitudes the days and nights are exactly 12 hours only at the spring and fall equinoxes. Figure 3-2 shows the annual variation in night hours in three U.S. cities and on the equator.

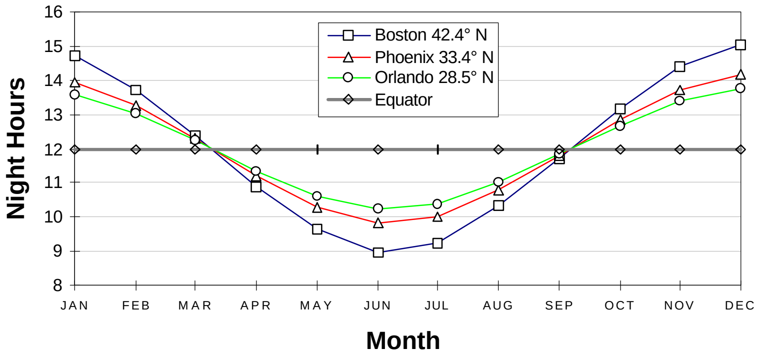


Figure 3-2. Night hours vs. month for different latitudes.

The following equations can be used to calculate the night hours for any location as a function of the latitude and time of year.

$$D = \sin^{-1}[0.3975\cos(0.98563(N-173))]$$

$$H = \cos^{-1}[-\tan(L)\tan(D)]$$

$$T = 2[12-(12H/180)]$$

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)

Example: A PV area lighting system design is needed for Orlando, Florida, latitude 28.5^o N. The light fixture selected for the application draws 3 amps at 24 volts DC (72 watts), and lighting is required between dusk and dawn throughout the year. Calculate the average daily load requirement for the critical design month.

Solution: Since Orlando is in the Northern Hemisphere, the maximum nightly operation period occurs at the winter solstice, therefore December is the critical design month. Referring to the chart in Figure 3-2 or by calculating from the equations for 28.5^o N latitude, we find that nighttime at the winter solstice in Orlando is 13.4 hours. The average daily load requirement is then calculated by the product of the load current and nightly operation time: *3 amps x 13.4 hours = 40.2 amp-hours per day*.

When factoring in the insolation available at a given location, the effect on the size of asystem required for a given load can be seen. Figure 3-3 shows the monthly average insolation on latitude tilt surfaces divided by the average night hours during the month for three U.S. cities. 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 and Phoenix to meet the load. However, to meet the load only in the summer, the system sizes for Boston and Orlando would be comparable.

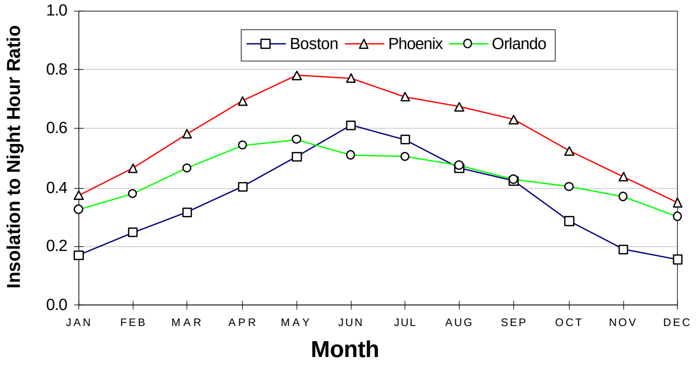


Figure 3-3. Insolation to night hour ratios, latitude tilt surfaces.

3.2 Estimating Battery Storage Requirements

Battery size is a design variable, and is generally based on the desired autonomy period, maximum allowable depth of discharge, and derating for low operating temperatures. Similar to the load energy calculation, the amount of battery storage capacity is expressed in units of ***ampere-hours***.

Also referred to as the days of energy storage, ***autonomy*** is the time a fully charged battery can supply energy to the lighting load when there is no energy input from the PV array, for example, conditions that could occur with several days of heavily overcast skies. Less critical PV lighting applications are typically designed for three to five days of autonomy, while more critical applications can be sized for ten or more days. Greater autonomy means that the battery will be cycled less deeply on an average daily basis. However, a much larger and more expensive battery is required. It also means that while it takes a long time for the battery to become fully discharged, it takes equally as long to recharge it. This could present a problem in systems with marginally sized PV arrays, increasing the potential for the battery to remain at damaging low levels of charge for extended periods.

The ***maximum allowable depth of discharge*** is the desired limit of battery discharge or usable capacity, and is established by the low voltage load disconnect set point on the system controller and the discharge rate of the lighting load. For deep-cycle battery designs, 80 percent maximum depth of discharge (DOD) is typically used. For the size range of most PV lighting system designs, this occurs at a battery voltage of between 11.3 and 11.7 volts for nominal 12-volt lead-acid batteries. For batteries designed for shallower cycle service, the maximum allowable DOD is typically limited to 40 to 60 percent to achieve rated lifetime. Note that the allowable depth of discharge is a design limit, and is seldom reached for well-designed PV lighting systems.

The maximum allowable depth of discharge must also be limited for batteries operating in cold climates to protect the battery from freezing. Although the freezing point of a typical fully charged lead-acid battery is between -50 and -70 ^{o}C, the freezing point of a battery at 50 percent state-of-charge is about -15 ^{o}C. As a lead-acid battery becomes more discharged, the concentration of the sulfuric acid electrolyte solution decreases to a point where the electrolyte is essentially water. At this fully discharged condition, the freezing point of the battery is 0 ^{o}C. In cases where low battery temperatures are expected, a higher low-voltage load disconnect set point must be used to limit the maximum DOD to prevent freezing.

Low temperatures also slow down a battery's electrochemical process, reducing the available capacity. Lead-acid batteries are particularly affected, and can only deliver approximately 80 percent of their 25 ^{o}C rated capacity when operated at 0 ^{o}C and at the typical low discharge rates found in PV lighting systems.

The following simple formula can be used to calculate battery storage capacity requirements in PV lighting systems.

Required Battery Capacity (rated at 25 ^{o}C at load discharge rate) =

[Days of Autonomy x Average Daily Load Amp-Hours] / [Allowable DOD x Low Temperature Capacity Factor]

Example: The area lighting application in Orlando requires 5 days autonomy. A deep-cycle lead-acid battery is selected, allowing a maximum DOD of 80%. Calculate the required battery capacity for the design load of 40.2 amp-hours per day.

Solution: The minimum design month temperature for Orlando is 0 ^{o}C (December), requiring a low temperature capacity derating factor of 0.8. The maximum allowable DOD of 80 percent does not need to be reduced because a lead-acid battery cannot freeze at 0 ^{o}C when discharged to this level. We calculate the required battery capacity by the product of the autonomy period and average daily load amp-hours, divided by the product of the allowable DOD and temperature/capacity derating factor: *[(5 days x 40.2 Ah/day) / (0.8 x 0.8)] = 314 amp-hours rated at 25* ^{o}*C and at the system discharge rate of 3 amps.*

Often discharge rates are expressed by *C/t*, where *t* is the discharge time in hours and *C* is the rated battery capacity. Discharge hours are calculated by dividing the rated battery capacity by the load current. For example, a 100 Ah battery loaded at 5 amps would have a discharge rate of 20 hours, or C/20. Low discharge rates are common in stand-alone PV system designs, and result from the high autonomy requirements and allowable DOD limits.

In stand-alone PV systems with large autonomy, the average daily DOD is considerably less than the allowable DOD. The average daily DOD is calculated by dividing the average daily load by the total rated battery capacity. For example, a ten amp-hour average daily load results in ten percent average daily DOD for a 100 Ah battery.

Example: Determine the maximum discharge rate and average daily depth of discharge for the PV area lighting system design for Orlando.

Solution: We calculate the discharge rate by dividing the rated battery capacity by the maximum load current: *[314 amp-hours / 3 amps] = 104 hours or approximately a C/100 discharge rate*. The average daily DOD is calculated by: *[(40.2 amp-hours/day) / 314 amp-hours] = 0.128 or 12.8 percent daily.*

Given a particular battery type, the designer must next determine the series/parallel configuration required for the battery bank. The number of selected batteries required in series is determined by dividing the nominal load (system) voltage by the voltage of an individual battery. To determine the number of batteries to be connected in parallel, simply divide the required capacity by the rated capacity of the selected battery and round up to the next integer.

Example: Continuing with the previous area lighting application in Orlando, we have selected a nominal 6-volt deep-cycle battery with a C/20 rating of 190 amp-hours. Determine the series/parallel configuration required for the battery bank.

Solution: For the number of batteries required in series, we divide the nominal load (system) voltage by individual battery voltage: *[24 volts / 6 volts per battery] = 4 series connected batteries required.* To determine the number of batteries in parallel, we divide the required battery capacity by the capacity of an individual battery and round to the next highest integer: [314 amp-hours / 190 amp-hours per battery] = 1.65 round up to 2 batteries in parallel. The selected battery requires a configuration of 4 series by 2 parallel in this design, for a total of 8 batteries.

3.3 Estimating the PV Array Size

Estimating the size of PV array required for PV lighting systems is based on providing adequate energy to meet the load during the period with the highest average daily load and lowest solar insolation on the array surface. Steps for determining the size of PV array required are:

1. Obtain solar radiation data and determine the optimal array tilt angle required to maximize the minimum monthly ratio of solar insolation to electrical load.
2. Estimate the average daily load ampere-hour (Ah) requirement for each month of the year.
3. Increase the system load requirement due to system losses and inefficiencies in charging and discharging batteries (typically 110 to 120 percent).
4. Select a PV module and derate the module output for temperature and degradation (typically 85 to 90 percent).
5. Determine the number of parallel-connected modules required to satisfy the average daily system amp-hour demand under design month solar insolation.
6. Determine the number of series-connected PV modules based on the nominal system voltage and module peak power voltage.

Before the PV array can be sized, the designer must obtain solar radiation data for the application site. The optimal array tilt angle must also be determined to maximize the solar insolation to load ratio during the critical design month – thus minimizing the size of the PV array. Solar insolation data is usually given in units of kWh/m^2/day on an average daily basis for each month. This information can also be though of as the equivalent number of hours per day that the irradiance on a surface is at a peak level of 1 kW/m^2 - the same standard used for module peak output ratings. For this reason, solar insolation data in units of kWh/m^2/day is often referred to as ***peak sun hours.*** The National Renewable Energy Laboratory (NREL) publishes this data in tabular and graphical form for the purposes of solar energy system design [ref]. Figure 3-4 and Figure 3-5 show U.S. solar radiation data maps for latitude tilt surfaces for the months of December and June, respectively.

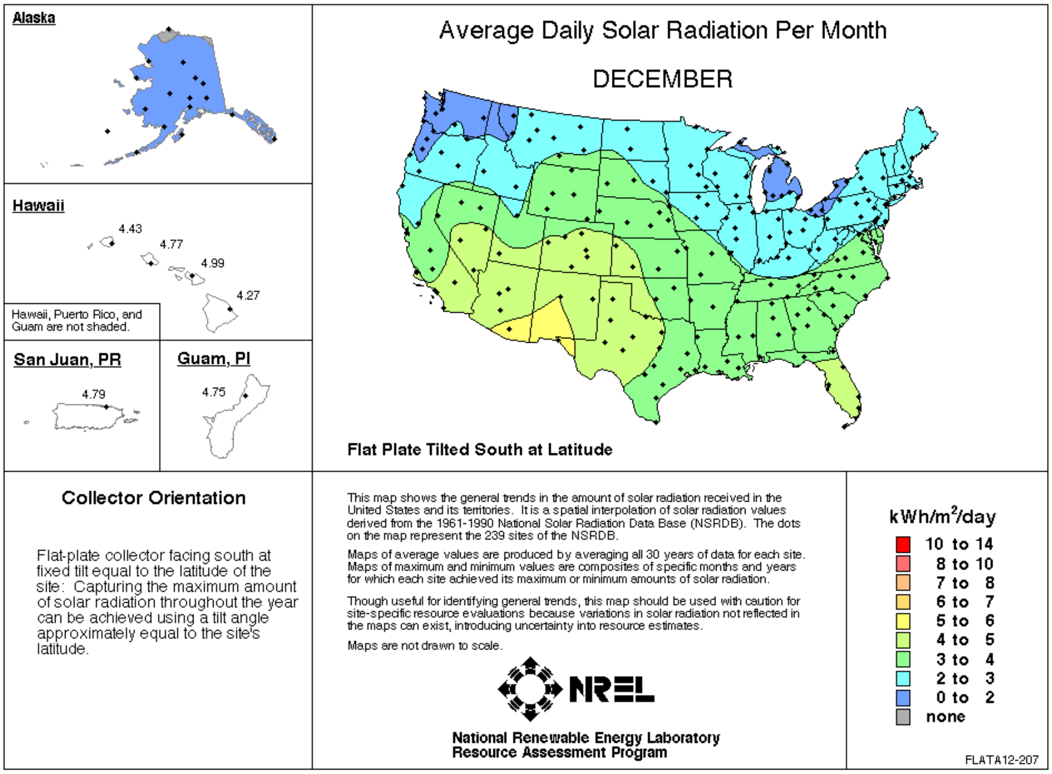
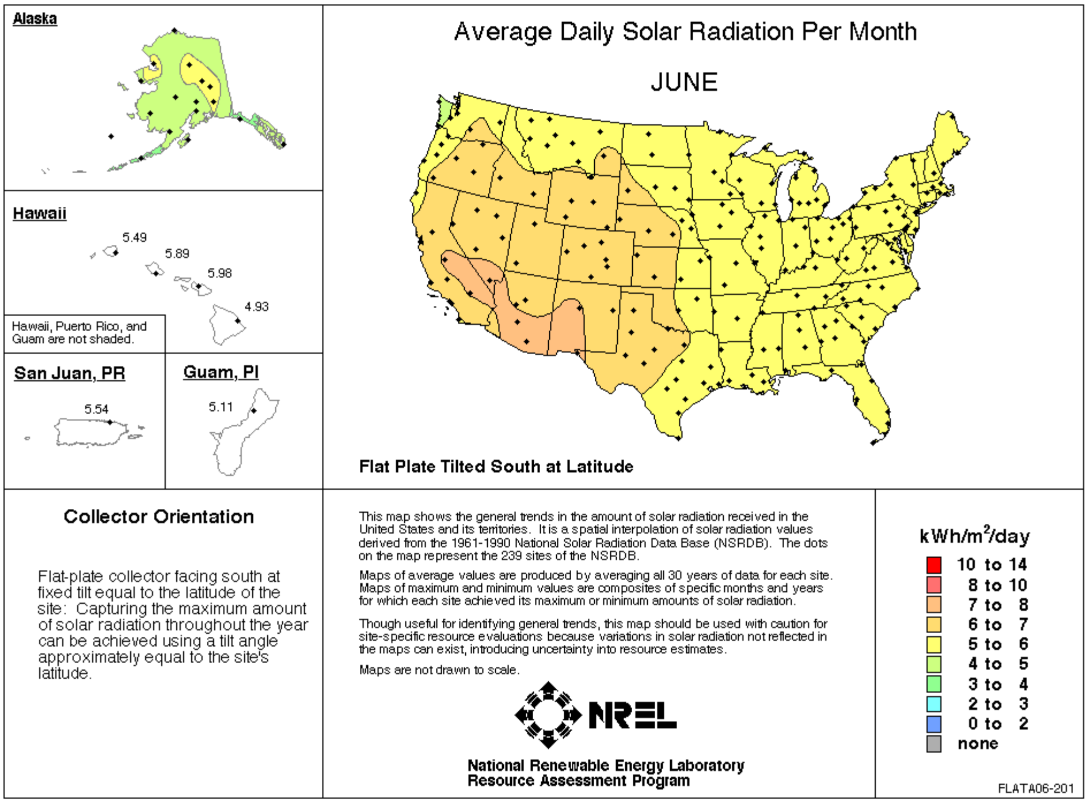


Figure 3-4. U.S. solar radiation data map for latitude tilt surfaces in December (NREL).



Flat-plate collector facing south at fixed tilt equal to the latitude of the site: Capturing the maximum amount of solar radiation throughout the year can be achieved using a tilt angle approximately equal to the site's latitude.

This map shows the general trends in the amount of solar radiation received in the United States and its territories. It is a spatial interpolation of solar radiation values derived from the 1961-1990 National Solar Radiation Data Base (NSRDB). The dots on the map represent the 239 sites of the NSRDB.

Maps of average values are produced by averaging all 30 years of data for each site. Maps of maximum and minimum values are composites of specific months and years for which each site achieved its maximum or minimum amounts of solar radiation.

Though useful for identifying general trends, this map should be used with caution for site-specific resource evaluations because variations in solar radiation not reflected in the maps can exist, introducing uncertainty into resource estimates.

Maps are not drawn to scale.

Figure 3-5. U.S. solar radiation data map for latitude tilt surfaces in June (NREL).

Example: Using our previous design example of a PV area lighting system for Orlando, determine the critical design month for solar insolation and for the insolation to load ratio. Also identify the optimal array tilt angle.

Solution: In referencing tabular insolation data for Orlando, Florida, we find that the critical design month is December, with an optimal solar insolation value of 4.03 kWh/m^2/day on a south-facing 45-degree tilted surface. Since this insolation level is exceeded all other months of the year on this surface, and December is also the maximum load month for the all night lighting system, the 45-degree tilt angle is the appropriate choice for this application.

Example: Determine the adjusted daily load amp-hour requirements based on system losses and battery charge/discharge inefficiency.

Solution: We assume that our system losses are about 15% of the average daily load energy requirement. Using the design month average daily load of 40.2 amp-hours, we determine the adjusted system load requirement: *[40.2 amp-hours / 0.85 factor] = 47.3 amp-hours per day.*

The next step is to select a PV module for use in the design and derate its peak current output. Module current output derating factors used are typically 85 to 95 percent, depending on conditions such as array soiling, and manufacturers' guaranteed output (not rated output). Based on the derated individual module output, the solar insolation and the daily system load, we can then determine the number of parallel modules required. Based on the module temperature derated maximum power voltage and the nominal system voltage, we can then determine the number of series connected modules. Module peak voltage temperature deratings depend on the application environment, and can range from 75 to 80 percent for warm climates and 85 to 90 percent for temperate and cool climates. The product of the series and parallel modules gives the total number of modules required for the application.

Number of Parallel Connected PV Modules Required (round up to next integer) =

[Avg. Daily Adjusted Ah Requirement] / [Module Peak Current Output at STC x Derating Factor x Peak Sun Hours]

Number of Series Connected PV Modules Required (round up to next integer) =

[Nominal System Voltage] / [Module Peak Voltage Output x Derating Factor]

Example: For our PV lighting system design for Orlando, we select a PV module with a STC rated maximum power current of 4 amps and maximum power voltage of 17.4 volts. Calculate the number of parallel and series modules required.

Solution: Based on the application environment, we assume a module current derating factor of 0.9 and a module voltage temperature derating factor of 0.85. To determine the number of parallel-connected modules needed, we divide the adjusted daily load amp-hour requirement by the product of the individual module current output, the derating factor and the average daily design month insolation (peak sun hours): *[47.3 amp-hours / (4 amps x 0.9 factor x 4.03 peak sun hours)] = 3.26 rounded up to 4 parallel modules required.* To determine the number of series-connected modules required, we divide the nominal system voltage by the product of the rated maximum power module voltage and the temperature derating factor: *[24 volts / (17.4 volts x 0.85 factor)] = 1.62 rounded up to 2 series-connected modules required. The total number of modules required is eight.*

A parameter that is often used to evaluate the critical design month sizing for stand-alone PV systems is the average daily PV ampere-hour output to load Ah demand ratio, often called ***PV to load ratio.*** Values of PV to load ratio below 1.0 mean that the PV array can not provide enough energy to meet the load during the critical design month. Well-sized systems typically have conservative PV to load Ah ratios for the critical design month in excess of 1.2 to account for system inefficiencies, module derating and other losses. The PV to load ratio is typically based on module manufacturer rated current output and the actual system load (not derated).

Example: Calculate the PV to load ratio for the previous design example.

Solution: We calculate the PV to load ratio by dividing the product of the array rated peak current output and peak sun hours by the average daily load amp-hours: *[(4 amps x 4 parallel strings x 4.03 peak sun hours) / 40.2 amp-hours] = 1.6.* Note that by not rounding up to the next whole number of PV modules in parallel (3.26) would have given a minimum design month PV to load Ah ratio of 1.31 using this particular sizing approach.

As one can see, the sizing process for PV lighting systems is simple yet requires consideration of a number of variables related to component selection and desired performance objectives. Sizing a stand-alone PV system is not an exact science, and at best, is an estimate of system requirements based on the quality of available data and assumptions. Typically, system integrators make a number of iterations and use different methods to refine the sizing and to estimate the size and ratings for components needed in the design. In practice, costs, reliability needs, availability and ratings of products, and field experience often influence the specification and sizing for stand-alone PV lighting systems. The sizing discussion and examples presented above only give a cursory overview of the sizing process using a particular method. References for other sizing guidelines are given at the end of this document [refs].

3.4 Sizing Summary

Table 3 shows the combined results of the sizing example presented in the preceding section.

Table 3. PV Lighting System Sizing Example

PV Lighting System Sizing Worksheet	
Application: Remote Area Lighting System	
Location: Orlando, Florida **Latitude:** 28.5^{o} N	
Electrical Load Estimation	
A1: Total Load DC Current Requirement (amps)	3
A2: Average Daily Load Usage, Design Month (hours)	13.4
A3: Average Daily Load Energy Requirement, Design Month = A1x A2 (amp-hours)	40.2
A4: Nominal Load (System) DC Voltage (volts)	24
A5: Maximum Load DC Current (amps)	3
Battery Sizing	
B1: Autonomy Period, Days of Storage (days)	5
B2: Allowable Maximum Depth of Discharge (decimal)	0.8
B3: Minimum Battery Operating Temperature (^{o}C)	0
B4: Battery Capacity Temperature Derating Factor (decimal)	0.8
B5: Required Battery Capacity = (A3 x B1) / (B2 x B4) (amp-hours)	314
B6: Nominal Capacity of Selected Battery (amp-hours)	190
B7: Nominal Voltage of Selected Battery (volts)	6
B8: Number of Batteries Required in Series = A4 / B7 (#)	4
B9: Number of Batteries Required in Parallel = B5 / B6 rounded up to next integer (#)	(1.65) 2
B10: Total Number of Batteries Required = B8 x B9 (#)	8
B11: Total Battery Capacity = B9 x B6 (amp-hours)	380
B12: Battery Average Daily Depth of Discharge = (A3 *100) / B11 (%)	10.6
B13: Battery Maximum Discharge Rate = B11 / A5 (hours)	126
PV Array Sizing	
C1: Design Month	December
C2: Design Month Insolation (kWh/m^{2}/day)	4.03
C3: Optimal Array Tilt Angle to Maximize Insolation to Load Ratio during Design Month (degrees)	45
C4: Design Month Average Daily Load Requirement (amp-hours)	40.2
C5: Load Adjustment Factor for System Inefficiencies (decimal)	0.85
C6: Adjusted Design Month Average Daily Load = C4 / C5 (amp-hours)	47.3
C7: Selected Module Maximum Power Current Output at STC, Imp (amps)	4
C8: Module Output Derating Factor (decimal)	0.9
C9: Adjusted Module Maximum Power Current Output = C7 x C8 (amps)	3.6
C10: Selected Module Maximum Power Voltage at STC, Vmp (volts)	17.4
C11: Module Voltage Temperature Derating Factor (decimal)	0.85
C12: Temperature Derated Module Maximum Power Voltage = C10 x C11 (volts)	14.8
C10: Module Daily Output = C2 x C9 (amp-hours)	14.5
C11: Number of Parallel Modules Required = C6 / C10 rounded up to next integer (#)	(3.26) 4
C12: Number of Series Modules Required = A4 / C12 rounded up to next integer (#)	(1.62) 2
C13: Total Number of PV Modules Required = C11 x C12 (#)	8
C14: Nominal Rated PV Module Output (watts)	70
C15: Nominal Array Rated Output = C14 x C13 (watts)	560
Sizing Summary	
Lighting Load (Ah/day)	40.2
Design Autonomy Period (days)	5
Selected Battery Series/Parallel Configuration (S x P)	4 x 2
Total Number of Selected Batteries (#)	8
Battery Storage Capacity (Ah)	380
Allowable Depth of Discharge Limit (%)	80
Average Daily Depth of Discharge (%)	10.6
Selected Module Series/Parallel Configuration (S x P)	2 x 4
Total Number of Selected Modules (#)	8
Estimated PV to Load Ah Ratio for Design Month = (C7 x C11 x C2) / C4	1.6

3.5 Electrical Design Requirements

Once the size requirements for the various system components have been established, the next step in the design process is to configure the components electrically in a reliable and safely functioning PV system. The electrical design process not only involves the configuration of the system but also the selection of proper size and rating for electrical hardware.

PV lighting systems are independent electrical power systems, and should comply with accepted engineering practices and associated electrical design requirements. PV lighting system integrators should be aware of the differences between DC and conventional AC electrical systems, and in the guidelines established by the National Electrical Code (NEC) [ref]. An excellent document on PV system electrical design and suggested NEC practices is available through the Sandia National Laboratories PV Design Assistance Center [ref].

The electrical design of stand-alone PV lighting systems involves a number of factors, including:

- Configuring the series and parallel wiring scheme for PV modules and arrays
- Selecting a battery charge and lighting controller based on the voltage and current requirements of the application
- Selecting types, sizes and ratings for conductors based on location, temperature, ampacity, and voltage drop requirements
- Identifying the appropriate ratings and locations for overcurrent protection and disconnect devices
- Identifying the appropriate ratings and locations for surge protection and grounding equipment
- Identifying the appropriate ratings and locations for protection diodes
- Identifying appropriate test points for system instrumentation and monitoring
- Completing as-installed electrical schematics.

3.6 Mechanical Design Requirements

The mechanical design requirements for PV lighting systems varies considerably, depending on the application. Mechanical design involves the integration of the system components in a functional, structurally sound, easy to install and maintain lighting system. Many vendors offer pre-packaged PV lighting systems that use standard configurations, although some PV lighting applications require special design.

Mechanical design considerations for stand-alone PV lighting systems should include:

- Calculating structural loads for weight of the equipment and wind forces
- Complying with applicable standards and building/structural codes
- Using appropriate and compatible materials to avoid corrosion and degradation
- Using appropriate enclosures for batteries, controls and lighting equipment to protect from the elements, from unauthorized access and to minimize temperature swings
- Facilitating installation processes and access for maintenance
- Optimizing array mounting design and orientation to improve thermal performance, gain maximum solar exposure and to avoid shading of the array
- Ensuring aesthetic and architectural compatibility of the complete installation
- Eliminating any potential risks and safety hazards
- Considering possible tradeoffs to reduce first and life-cycle costs.

3.7 PV Lighting System Performance Characteristics

The information and data presented in this section are intended to provide the reader with some understanding of how a PV lighting system might operate on a typical daily basis. To provide this illustration, a clear-day operational profile from a PV lighting system tested at the Florida Solar Energy Center is used as an example. The operational profile is shown in Figure 3-6.

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

The top graph shows the battery and PV array voltage versus time of day. For clarity, the battery voltage is plotted on the left y-axis, while the PV array voltage is plotted with respect to the right y-axis on a different scale. The bottom graph shows the battery and PV array currents over the day, as well as the solar irradiance. In this chart, the currents are plotted on the left y-axis, and the irradiance is plotted on the right y-axis. The following discussion briefly explains what is happening at key points throughout the day in this lighting system example.

Beginning at the left of the top and bottom charts (midnight), the load is operating and battery voltage decreases steadily from about 12.2 volts to 11.9 volts while being discharged at about 3 amps. At about 0430 hours, a timing circuit disconnects the lighting load. At this point the battery current goes to zero (excluding the small parasitic consumption of the system controller), and there is a sharp rise in the battery voltage as it approaches an open-circuit (no load) voltage of about 12.3 volts. At sunrise (about 0700 hours), the battery voltage begins to increase as the PV array current charges the battery. Until about noontime (1200 hours), the PV array current and the battery voltage increase steadily with increasing insolation as the battery is being recharged. Note that during this period, the battery charge controller is not regulating and the PV array current is approximately the same as the battery current.

At about noon (1200 hours), the battery voltage reaches the regulation voltage set point for the battery charge controller (about 14.5 volts), and the controller begins to regulate the PV array current. When this occurs, the battery current decreases steadily and remains in a current-limited mode through the remainder of the day. Once regulation begins, the average PV array current also decreases while the average PV array voltage approaches the open-circuit array voltage. This is characteristic of the series-type switching design of the controller used in this system. After regulation begins, the battery average, minimum and maximum voltages stay about the same through the remainder of the day, characteristic of the pulse-width-modulated (PWM) charge algorithm.

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

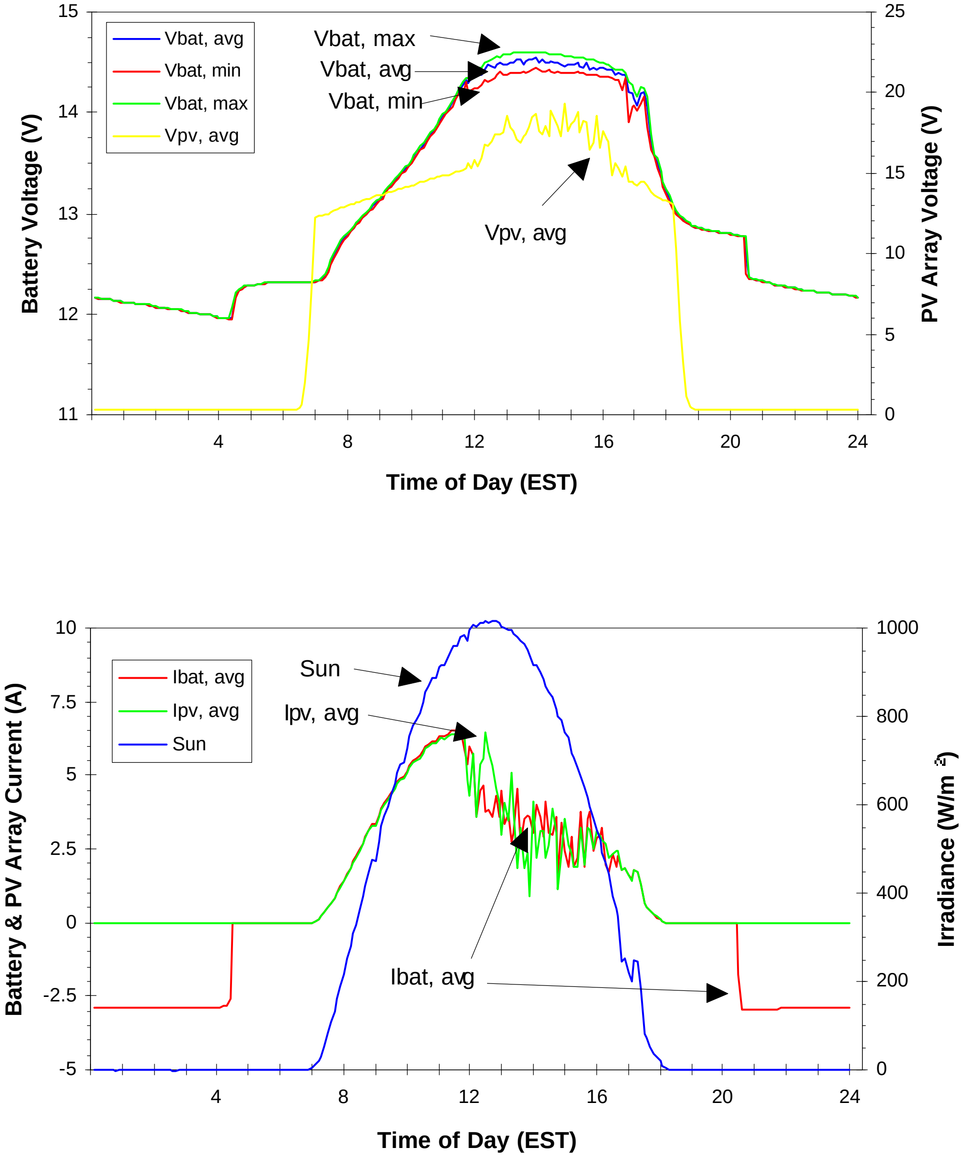


Figure 3-6. Daily operational profile for PV lighting system.

4. Sources for PV Lighting Systems and Equipment

The following lists suppliers of PV lighting systems and equipment. This list is not comprehensive, and appearance of any company on this list does not imply endorsement or approval by the author nor by the Florida Solar Energy Center.

Effective September 1998

Advanced Energy Systems, Inc.
9 Cardinal Dr.
Longwood, FL 32779 USA
Phone: (407) 333-3325
Fax: (407) 333-4341
magicpwr@magicnet.net
http://www.advancednrg.com/

ALTEN srl
Via della Tecnica 57/B4
40068 S. Lazzaro di Savena
Bologna, Italy
Tel: 39 51 6258396
Fax: 39 51 6258398
alten@mbox.vol.it
http://www.bo.cna.it/cermac/alti.htm

Alternative Energy Engineering
1155 Redway Drive - Box 339
Redway, CA 95560, USA
Tel: (707) 923-2277
Fax: (707) 923-3009
energy@alt-energy.com
http://www.alt-energy.com/

Applied Power Corporation
1210 Homann Drive SE
Lacey, WA 98503, USA
Tel: (360) 438-2110
Fax: (360) 438-2115
info@appliedpower.com
http://www.appliedpower.com/

Ascension Technology
235 Bear Hill Road
Waltham, MA 02451 USA
Tel: (781) 890-8844
Fax: (781) 890-2050
info@ascensiontech.com
http://www.ascensiontech.com/

Atlantic Solar Products, Inc.
P.O. Box 70060
Baltimore, MD 21237 USA
Tel: (410) 686-2500
Fax: (410) 686-6221
mail@atlanticsolar.com
http://www.atlanticsolar.com/

BP Solar, Inc.
2300 N. Watney Way
Fairfield, CA 94533 USA
Tel: (707) 428-7800
Fax: (707) 428-7878
solarusa@bp.com
http://www.bp.com/bpsolar/

C-RAN Corp.
699 4th Street, N.W.
Largo, FL 34640-2439 USA
Tel: (813) 585-3850
Fax: (813) 586-1777
http://www.scild.com/web/cran/

Cornette and Co.
P.O. Box 3443
Tampa, FL 33601-3443 USA
Tel: (813) 251-5915

Eco-Wise
110 W. Elizabeth
Austin, TX 78704
Tel: (512) 326-4474
eco@ecowise.com
http://www.ecowise.com/

Energy Conservation Services of North Florida
6120 SW 13th Street
Gainesville, FL 32608 USA
Tel: (352) 377-8866
Fax: (352) 338-0056

Electro Solar Products, Inc.
502 Ives Place
Pensacola, FL 32514 USA
Tel: (850) 479-2191
Fax: (850) 857-0070
espsolar@cheney.net
http://scooby.cheney.net/~espsolar/

Golden Genesis (Photocomm)
7812 Acoma Drive
Scottsdale, AZ 85260 USA
Tel: (602) 948-8003
Fax: (602) 951-4381
info@goldengenesis.com
http://www.photocomm.com/

GeoSolar Energy Systems, Inc.
P.O. Box 812467
Boca Raton, FL 33481 USA
Tel: (561) 218-3007
Fax: (561) 487-0821
abtahi@geosolar.com
http://www.geosolar.com/

Hutton Communications, Inc.
1775 McLeod Drive
Lawrenceville, GA 30043 USA
Tel: (800) 741-3811
Tel: (770) 963-1380
Fax: (770) 963-7796
locker@huttoncom.com
http://www.huttoncom.com/

IOTA Engineering
1301 E. Wieding Road
Tucson, AZ 85706 USA
Tel: (520) 294-3292
Fax: (520) 741-2837
iotaeng@iotaengineering.com
http://www.iotaengineering.com/

Jade Mountain Inc.
P.O. Box 4616
Boulder, CO 80306 USA
Tel: (800) 442-1972
Fax: (303) 449-8266
jade-mtn@indra.com
http://www.jademountain.com/

Morningstar Corporation
1098 Washington Crossing Road
Washington Crossing, PA 18977 USA
Tel: (215) 321-4457
Fax: (215) 321-4458
http://www.morningstarcorp.com/

Neste Advanced Power Systems
PL 3, 02151
Espoo, Finland
Tel: 358 204 501
Fax: 358 204 50 4447
jaana.sirkia@neste.com
http://www.neste.com

Precision Solar Controls
2915 National Court
Garland, TX 75041 USA
Tel: (972) 278-0553
Fax: (972) 271-9853

Real Goods Trading Co.
555 Leslie St.
Ukiah, CA 95482-5576 USA
Tel: (800) 762-7325
http://www.realgoods.com/

Quasar Solar Electric Co.
001 Tullamore
Offaly, Ireland
Tel: 353 882 706 775
Fax: 353 506 41650
quasar@tinet.ie
http://homepage.tinet.ie/~quasar

Trace Engineering
5916 195th St. NE
Arlington, WA 98223
Tel: (360) 435-8826
Fax: (360) 435-2229
inverters@traceengineering.com
http://www.traceengineering.com/

Siemens Solar Industries
P.O. Box 6032, Dept. FL
Camarillo, CA 93011 USA
Tel: (800) 947-6527
Fax: (805) 388-6395
http://www.solarpv.com/

Simpler Solar Systems
3118 W. Tharpe St.
Tallahassee, FL 32303 USA
Tel: (850) 576-5271
Fax: (850) 576-5274
simpler@simplersolar.com
http://www.simplersolar.com/

Solar Depot
8605 Folsom Blvd.
Sacramento, CA 95826 USA
Tel: (916) 381-0235
Fax: (916) 381-2603
solrdpo@calweb.com
http://www.solardepot.com

Solar Electric Light Co.
35 Wisconsin Circle Suite 510
Chevy Chase, MD 20815 USA
Tel: (301) 657-1161
Fax: (301) 657-1165
bcook@selco-intl.com
http://www.selco-intl.com

Solar Electric Light Fund
1734 20th Street, NW
Washington, DC 20009 USA
Tel: (202) 234-7265
Fax: (202) 328-9512
solarlite@self.org
http://www.self.org/

Solar Electric Power Co.
7984 Jack James Drive
Stuart, FL 34997 USA
Tel: (561) 220-6615
Fax: (561) 220-8616
sepco@tcol.net
http://www.sepco-solarlighting.com/new/

Solar Electric Specialties Co.
101 North Main St.
Mail: PO Box 537
Willits, CA 95490 USA
Tel: (707) 459-9496
Fax: (707) 459-5132
ses@solarelectric.com
http://www.solarelectric.com/

Solar Electric Systems of Kansas City
13700 W. 108th Street
Lenexa, KS 66215 USA
Tel: (913) 338-1939
Fax: (913) 469-5522
solarelectric@compuserve.com
solarbeacon@msn.com

Solar Outdoor Lighting, Inc.
3131 S.E. Waaler Street
Stuart, FL 34997, USA
Tel: (800) 959-1329
Tel: (561) 286-9461
Fax: (561) 286-9616
info@solarlighting.com
http://www.solarlighting.com/

Solarex Corp.
630 Solarex Court
Frederick, Maryland 21703 USA
Tel: (301) 698-4200
Fax: (301) 698-4201
info@solarex.com
http://www.solarex.com/

Sollatek
Unit 4/5, Trident Industrial Estate
Blackthorne Road
Poyle Slough, SL3 0AX
United Kingdom
Tel: 44 1753 688-3000
Fax: 44 1753 685306
sales@sollatek.com
http://www.sollatek.com/

Sunelco
PO Box 1499
Hamilton, MT 59840, USA
Tel: (406) 363-6924
Fax: (406) 363-6046
info@sunelco.com
http://www.sunelco.com

Sunalex Corp.
5955-T N.W. 31st Avenue
Ft. Lauderdale, FL 33309 USA
Tel: (954) 973-3230
Fax: (954) 971-3647

SunWize Technologies, Inc.
90 Boices Lane
Kingston, NY 12401 USA
Tel: (914) 336-0146
Tel: (800) 817-6527
Fax: (914) 336-0457
sunwize@besicorp.com
http://www.sunwize.com/

The Bodine Company
236 Mount Pleasant Road
Collierville, TN 38017 USA
Tel: (800) 223-5728
Tel: (901) 853-7211
Fax: (901) 853-5009
ldailey@bodine.com
http://www.bodine.com/
http://www.tran-bal.com/

Tideland Signal Corp.
P.O. Box 52430-2430
Houston, TX 77052 USA
Tel: (713) 681-6101
Fax: (713) 681-6233
hq@tidelandsignal.com
http://www.tidelandsignal.com

Traffic Control Devices, Inc.
P.O. Box 418
Altamonte Springs, FL 32715-0418
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