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# Photovoltaic Lighting Systems - A Decision Maker's Guide

**James Dunlop**
Florida Solar Energy Center (FSEC)

FSEC-RR-54-98

Introduction

This document provides general considerations for evaluating the feasibility of photovoltaic (PV) lighting applications. These considerations include assessing lighting requirements, understanding site conditions and investigating alternative lighting and power source options. These guidelines are intended to help prospective buyers of PV lighting equipment evaluate applications, as well as helping those supplying systems and equipment identify potential markets for their products. Also covered in this document is an overview of popular PV lighting system applications, including area and sign lighting, signal and warning systems, consumer lighting devices and solar home lighting systems.

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 (which are available in PDF) 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

FLORIDA SOLAR ENERGY CENTER®

# Stand-Alone Photovoltaic Lighting Systems

## A Decision-Maker's Guide

# Volume 1: Photovoltaic Lighting Applications

**Author**

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**Publication Number**

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# STAND-ALONE PHOTOVOLTAIC LIGHTING SYSTEMS

***A Decision-Maker's Guide***

## Volume 1: Photovoltaic Lighting Applications

*Prepared for:*

**Florida Energy Office / Department of Community Affairs**

*By:*

**Florida Solar Energy Center**

***First Edition September 1998***

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# STAND-ALONE PHOTOVOLTAIC LIGHTING SYSTEMS

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## *Abstract*

This document provides general considerations for evaluating the feasibility of photovoltaic (PV) lighting applications. These considerations include assessing lighting requirements, understanding site conditions and investigating alternative lighting and power source options. These guidelines are intended to help prospective buyers of PV lighting equipment evaluate applications, as well as helping those supplying systems and equipment identify potential markets for their products. Also covered in this document is an overview of popular PV lighting system applications, including area and sign lighting, signal and warning systems, consumer lighting devices and solar home lighting systems.

# *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.

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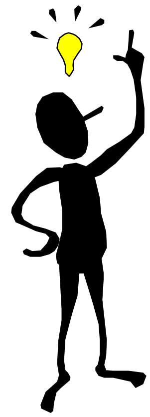
# 1. INTRODUCTION



***"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.

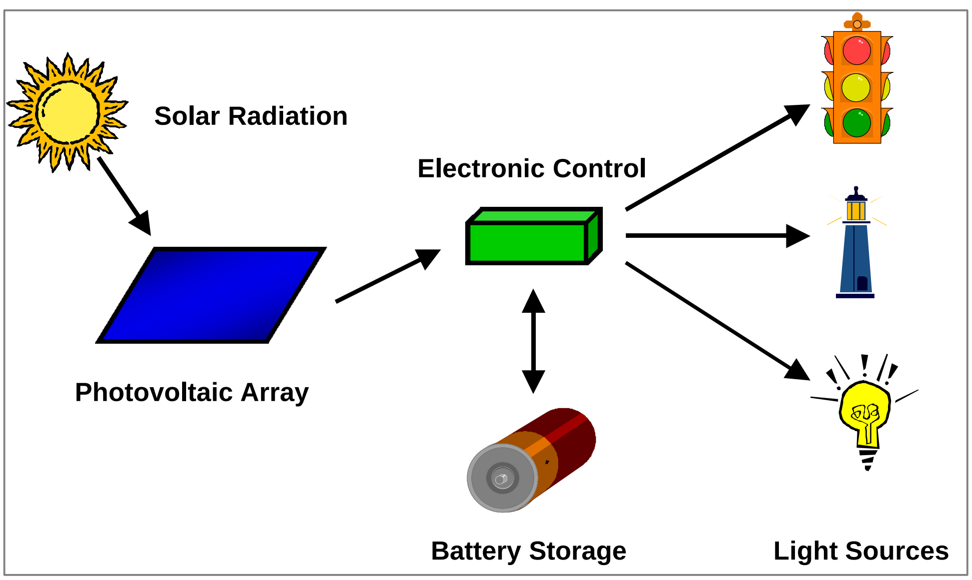



***Figure 1-1. PV lighting system advance organizer.***

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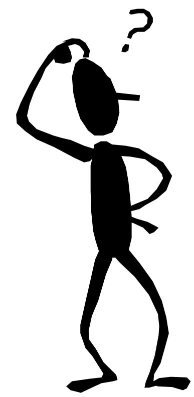
# 2. Evaluating the Potential for PV Lighting Applications

This section presents considerations for evaluating the potential of PV lighting applications. These guidelines are intended to help both buyers of PV lighting equipment, as well as those supplying systems and equipment, in identifying markets for their products.



For any given lighting application, there are a number of factors to consider in evaluating the potential for using PV power. In addition to the lighting requirement, these factors include whether or not the site and conditions are suitable for PV lighting, a cost comparison of the alternatives, and the consequences of not having light at all.

## 2.1 When Does PV-Powered Lighting Make Sense?

The first consideration in evaluating the potential for a PV lighting project is to determine whether the application makes sense and has justifiable value. Generally, PV lighting systems have the most practical application where the costs of providing utility electrical service are high, and moderate to low illumination levels are required in low ambient light areas. The following sections outline general criteria for evaluating potential PV lighting applications.

### *2.1.1 What Are the Lighting Requirements?*

- Are the required lighting levels (illuminance) and nightly duty cycle requirements reasonable (not excessive) for PV lighting equipment?
- Is lighting required all night, or just in early evening or "use" hours? Can the lighting use be controlled with a timer or sensors?

### *2.1.2 Is the Site Appropriate for PV Lighting?*

- Can the PV arrays be oriented with an unobstructed southerly and east-west sky exposure, and located away from tall trees and buildings to eliminate shading?
- Are there any prevailing meteorological conditions at the site that would require special considerations, such as high or low temperatures, corrosive conditions, or high winds?
- Are there special concerns such as safety or security that could not otherwise be met without PV lighting?
- Are there generally low ambient light conditions in the area that would make low-level PV lighting practical?
- Are there any planned utility extensions that would affect the expected future value of the PV lighting installation?

### 2.1.3 Is Existing Lighting Already Provided?

- What are the operating, maintenance and replacement costs for the current lighting equipment, and how does this compare with the proposed PV lighting alternative?
- Does or will the existing lighting equipment require replacement now or in the near future?
- Have energy conservation measures (efficient luminaires, automatic controls, etc.) been evaluated to reduce the existing electrical load?
- Are there any concerns about the power source (grid or generator) supplying the existing lighting, such as maintenance, reliability (outages), or electrical loading?

### 2.1.4 What are the Alternative Lighting Options?

- Are the possibilities for utility grid extension (transformers, trenching, cabling) impractical and cost-prohibitive?
- What are the present and projected costs of the grid-supplied energy to power the lights?
- What are the consequences of not having light at all?

### 2.1.5 Are There Other Application-Specific Issues to Consider?

- Is the application for temporary use such as for emergency purposes or construction sites where it may be necessary to eventually relocate lights and poles?
- Are there any particular reliability or safety issues to consider such as those lighting applications involving critical tasks, public safety, transportation or navigation?
- Are there high risks of vandalism or theft at the site that would require special equipment protection and security?
- Are there any building code, architectural, or aesthetic requirements for the lighting equipment to be installed at this site?
- Are there any issues related to endangered species (such as lighting restriction for sea turtle nesting areas) that warrant special attention?
- Is there restricted or otherwise difficult access to the site that would require special maintenance considerations?

# 3. PV Lighting Applications

PV lighting systems are used for a variety of applications, ranging from small consumer devices such as flashlights, portable lanterns and low-level walkway lights, to larger structurally-integrated independent power systems, designed to illuminate large surface areas or highway signs. Other PV lighting applications include flashing, signaling and warning devices where the primary function is the luminance, or brightness of the light. Perhaps the most significant application for PV lighting is for residential households and community centers in developing countries. Commonly called solar home systems (SHS), over one million systems have been installed around the world as part of rural electrification programs. Table 1 lists common PV lighting system applications and associated key user groups.

***Table 1. PV Lighting Application Matrix***

| Principal Function | Lighting Application | User Groups |
|---|---|---|
| | | |
| **Area Illumination** | | |
| | Parks and recreation areas | Federal, state and local government |
| | Parking lots | Public and private organizations |
| | Residential street lighting | Homeowners, developers and utilities |
| | Pedestrian and bike paths | Municipalities |
| | Bus stops and shelters | Municipalities and transportation officials |
| | Security lighting and remote illumination | Utilities and homeowners<br>Public and private organizations |
| | Storage yards | Public and private organizations |
| | Portable lighting systems | Contractors<br>Emergency management officials |
| **Sign Illumination** | | |
| | Highway information signs | Transportation officials |
| | Billboards | Advertisers and utilities |
| | Internally illuminated variable message boards | Transportation officials and contractors |
| **Flashing and Signaling Devices** | | |
| | Navigational aids | Navigational authorities |
| | Highway warning signals | Transportation officials |
| | Traffic and railway signals | Transportation and railway officials |
| | Transmission and antenna tower warning lights | Electric utilities<br>Telecommunications and aviation authorities |
| | Work area protection devices including flashing arrow boards and barricades, etc. | Transportation officials and municipalities<br>Construction contractors |
| | Signaling systems bridges and other general hazards | Maritime and transportation authorities<br>Public and private organizations |
| **Consumer Products** | | |
| | Low-level pathway and landscape lighting | Homeowners and builders |
| | Rechargeable flashlights | Vehicle and homeowners |
| | Portable lanterns | Emergency management officials<br>Development/conservation organizations<br>Homeowners |
| **Solar Home Systems** | | |
| | Rural residential lighting, remote cabins, restrooms | Development/conservation organizations<br>Rural electrification authorities<br>Homeowners |

## 3.1 Area Lighting Systems

Outdoor area lighting is one of the more popular applications for PV lighting systems. Wherever utility power is impractical or unavailable, and the need exists for low-level lighting in remote or inaccessible areas, PV outdoor area lighting systems may be a viable and cost-effective solution.

PV area lighting systems are usually designed as independent, stand-alone units with the PV system structurally integrated with a pole and lighting fixture(s). In most cases, the PV array is mounted at or near the top of the pole, out of harms way and with unobstructed solar access. Batteries and controls may either be located high on the pole near the PV array and light fixtures, at the base of the pole, or in an underground enclosure.

Figure 3-1 shows PV lighting systems illuminating an outdoor parking area at the Martin Luther King, Jr. National Historic Site in Atlanta, Georgia. Owned and operated by the National Park Service, thirty-nine individual systems are installed over a six-acre area. Each of these systems includes an array of PV modules mounted at the top of a thirty-two foot pole, two architectural light fixtures mounted just beneath the array, and batteries and controls located at the base of the pole in protective enclosures. Further information about this project is presented in a case study later in this document.

***Figure 3-1. PV area lighting systems at MLK, Jr. National Historic Site (NPS).***

Parking areas represent just one of many potential uses for PV-powered outdoor area lighting systems. Other applications include lighting for rural residential areas, parks and recreation areas, security lighting, bus shelter lighting, and many more remote area lighting needs. The figures on the following page show several of these common PV-powered area lighting systems and applications.

*Figure 3-2. Pathway PV lighting system at Brevard Community College.*

*Figure 3-3. PV pier lighting (Panama City Beach, FL).*

*Figure 3-4. PV security lighting (Florida Keys).*

*Figure 3-5. PV park lighting (Lakeland, FL).*

## 3.2 Sign Lighting Systems

Sign lighting is another popular application for PV lighting systems, with principal user groups including transportation officials and outdoor advertisers. Two classifications of sign lighting systems are those that are illuminated from external sources and those that are internally illuminated.

In sign lighting applications, the PV array is generally mounted on top of the sign structure or on an adjacent pole for solar access and vandal protection. The storage batteries and controls are usually mounted in a separate, lockable enclosure on or at the base of the sign structure for ease of access and maintenance.

### *3.2.1 Externally Illuminated Signs*

The illumination of highway guide signs represents a critical lighting application with public safety consequences. Many such signs are located on desolate stretches of highway, far from available utility power, thus making PV systems the only practical power source for these applications. Studies have shown that when directional highway signs are not illuminated, the potential risk for accidents is high. These circumstances make highway guide signs an extremely high-value PV lighting application.

Figure 3-6 shows one of many PV-powered highway guide sign lighting systems owned and operated by the Florida Department of Transportation. The PV arrays can be seen mounted on top of the sign structure, powering six fluorescent lamps located in front of and below the signs. In this application, the possibility of extending utility service to the site was considered cost-prohibitive. Without PV power, these signs would not be illuminated.

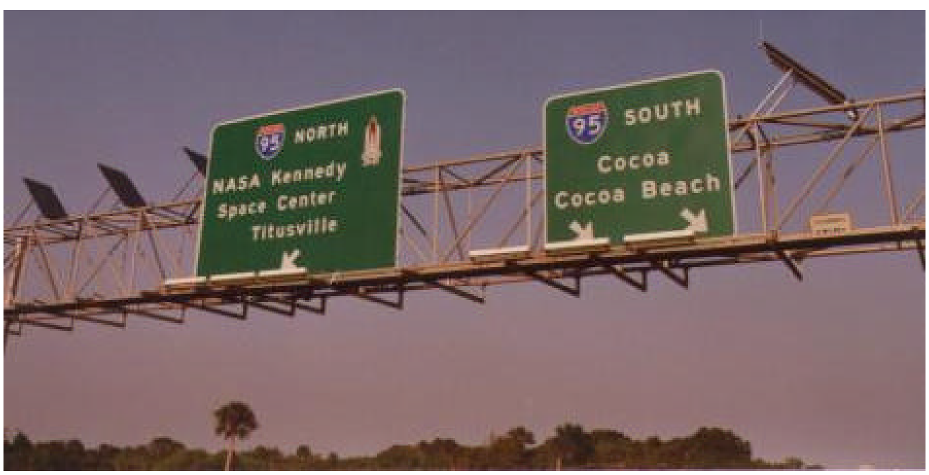



***Figure 3-6. PV-powered guide sign lighting, Brevard County, FL (FDOT).***

In the private sector, outdoor advertisers often use PV-power to illuminate billboards where utility service is unavailable.  Even when the grid is nearby, the cost of installing transformers, the service drop and metering even for a short distance can be too costly for a single sign light, making PV a worthy consideration.  Advertisers know how important it is to illuminate billboards, particularly to catch the attention of weary late-night travelers looking for accommodations.  Figure 3-8 shows a billboard lighting application with self-contained PV systems located in back of the board, powering light fixtures located in front of and beneath the advertisement.

Municipalities also use PV sign lighting systems, such as the sign shown in Figure 3-7 welcoming motorists to the City of Cocoa.  Figure 3-9 shows another PV-powered sign lighting application at Georgia Power's Shenandoah Solar Center near Atlanta.


***Figure 3-8.  PV-powered billboard lighting, (Solar Outdoor Lighting)***


***Figure 3-7.  Municipal sign lighting, Cocoa, Florida (Solar Electric Power Co.)***


***Figure 3-9.  PV sign lighting system at Shenandoah Solar Center (c. 1987, Georgia Power).***

### *3.2.2 Internally Illuminated Signs*

PV systems can power internally illuminated signs also. These types of signs are generally more energy-efficient than externally illuminated signs because the light source is more effectively utilized. Figure 3-10 shows a PV system powering an internally illuminated sign used by the City of Lakeland Electric and Water Utilities, which incidentally is located close to electrical transmission lines.

Another application for PV-powered internally illuminated signs are reflective-disk and LED-powered variable message boards, commonly used by roadway contractors and transportation officials to warn motorists of upcoming construction and other hazardous conditions. Figure 3-11 shows a portable PV-powered variable message board used to warn motorists of an approaching construction zone. Note the horizontally mounted PV array, rather than an optimally tilted south-facing array. Although a bigger array is required for a given light load, the horizontal array allows the portable message board to receive the same solar input in any position, eliminating the need for adjusting the array at each location.


***Figure 3-10. Internally-illuminated PV-powered sign (Lakeland Electric and Water).***

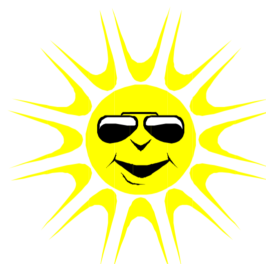


***Figure 3-11. PV-powered internally illuminated message board.***

## 3.3 Flashing, Signaling and Warning Lights

Flashing and signaling devices are common applications for PV lighting among transportation and navigational authorities. These applications are generally remote, inaccessible off-grid systems with a small electrical load, making PV power a cost-effective choice.

The U.S Coast Guard and other navigational authorities use PV to power nearly all offshore navigational aids worldwide. These occulting lights typically use either small incandescent lamps or arc strobes, and sometimes have automatic lamp changers to replace burnt out lamps between scheduled maintenance. These systems are usually over-designed somewhat due to the critical nature of the load. The battery is typically very large with respect to the size of PV array and lighting load, to minimize depth of cycling and to prolong battery cycle life. For reliability purposes, these systems often do not use battery charge controllers. Instead they use lower voltage PV modules to limit the output current as the battery voltage reaches full state of charge in what is called a "self-regulating" system.

The use of PV power for these navigational beacons has eliminated the high costs, frequent replacements, and disposal concerns of using primary batteries. Figure 3-12 shows a typical PV-powered flashing device on a navigational aid in Florida waters. Figure 3-13 shows another PV-powered beacon atop an Ocean Data Acquisition System (ODAS) buoy. In this application, the PV system is also used to power the monitoring equipment on the platform.


***Figure 3-12. PV-powered flasher on navigational aid, Kissimmee River, FL (SFWMD).***

***Figure 3-13. PV-powered ODAS buoy with beacon light.***

The highway transportation sector uses a number of flashing light systems to warn motorists of approaching danger and roadway conditions such as hazardous curves and steep grades, falling rock, high winds, fog-smoke, icy conditions, wrong-way and approaching stop. In many cases, these flashing lights are powered by PV systems. Depending on the application, these systems can be designed to flash all day, at night, or upon activation by vehicles or desired warning conditions. Figure 3-14 shows a PV-powered flashing device used by the Florida Department of Transportation to alert motorists to tune in to Highway Advisory Radio – another application which can be powered by PV – for the latest information on traffic conditions.

Another application for PV-powered flashing devices can be found in the communications, electric utility and aviation industries for aircraft warning beacons. These small, independent power systems can be installed at the tops of transmission and antenna towers to warn low-flying aircraft of the hazard, without the need for special transformers or external wiring. Figure 3-15 shows a PV-powered beacon installed on a transmission tower in the Florida Keys. An Osprey nest is located opposite to the PV module on the top left of the tower.


***Figure 3-14. PV-powered flashing light on Interstate 75, Broward County, Florida (FDOT).***

***Figure 3-15. Transmission tower beacon powered by PV in the Florida Keys.***

Portable flashing signals, such as those displaying text or directional arrows are a very cost-effective application for PV power among transportation departments and roadway contractors. In the past, noisy, maintenance-intensive diesel engine generators commonly powered these devices. Today, most of these signals are powered by silent PV systems, eliminating the need for refueling, maintenance and replacement of engine-generators.

Figure 3-16 shows a PV-powered portable flashing signal along the Florida Turnpike. As opposed to the horizontally mounted array on the portable variable message sign shown earlier, the PV array is tilted, requiring a southerly orientation to optimize the gain of solar radiation. Light sources used in these applications include quartz halogen incandescents and xenon arc lamps (inset).

PV-powered signal lights are also used by transportation and maritime authorities for clearance and channel markings under navigable bridges. These applications are generally difficult to service with utility power, especially for railway and vehicle bridges without utility service voltage available. Figure 3-17 shows a PV system powering a signal and gate at a railroad crossing maintained by the Florida East Coast Railroad.

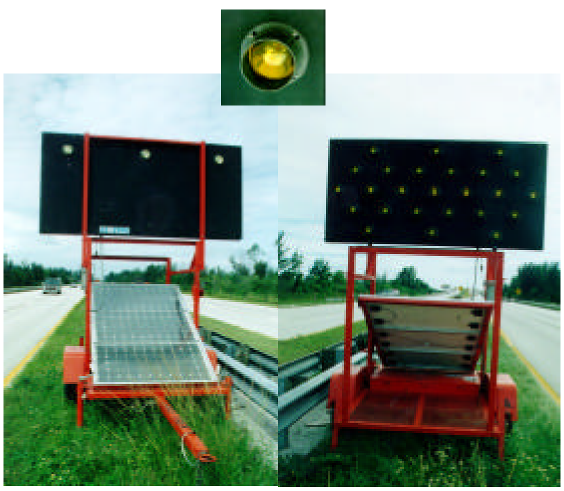


***Figure 3-16. PV-powered directional arrowboard.***

***Figure 3-17. PV-powered railway signals (FEC).***

## 3.4 Consumer Devices

A number of small PV lighting systems are targeted toward the general consumer, homeowner and outdoors enthusiast, including rechargeable flashlights, solar lanterns and landscape lighting. These PV-powered lighting applications generally use small lamps (less than 20 watts), are designed for low-level lighting requirements and are often portable.

PV-powered solar lanterns are becoming very popular, particularly among development and conservation organizations promoting small solar home lighting systems in developing countries. Thousands of these systems have been supplied to provide quality electric lighting in place of dirty and expensive to operate kerosene lanterns. Figure 3-18 shows a typical solar lantern using fluorescent lamps powered by a small battery in the base of the lantern and a small PV module for recharging.

***Figure 3-18. PV-powered solar lantern (Kyocera).***

## 3.5 Solar Home Systems

Solar home systems are one of the more significant applications for PV lighting, the primary use being for rural residential lighting in developing countries. With nearly one-third of the world's population not having access to electrical service and basic lighting, PV lighting systems have helped improve the quality of life, social interactions and education for many around the world.

Currently, many countries have rural electrification programs centered on solar home systems, typically financed by energy ministries and international development/conservation organizations. This market continues to grow at a significant rate, and if projections of one million solar home systems a year are installed each using a 50 Wp PV module, the demand created by this market alone will approach nearly one-half of the world PV production.

# 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
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magicpwr@magicnet.net
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ALTEN srl
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40068 S. Lazzaro di Savena
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Alternative Energy Engineering
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solarusa@bp.com
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http://www.scild.com/web/cran/

Cornette and Co.
P.O. Box 3443
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Tel: (813) 251-5915

Eco-Wise
110 W. Elizabeth
Austin, TX 78704
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Electro Solar Products, Inc.
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Golden Genesis (Photocomm)
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Real Goods Trading Co.
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Fax: (360) 435-2229
inverters@traceengineering.com
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FLORIDA SOLAR ENERGY CENTER®

# Stand-Alone Photovoltaic Lighting Systems

## A Decision-Maker's Guide

# Volume 2: PV Lighting Components and System Design


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**Publication Number**

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# STAND-ALONE PHOTOVOLTAIC LIGHTING SYSTEMS

***A Decision-Maker's Guide***

## Volume 2: PV Lighting Components and System Design

*Prepared for:*

**Florida Energy Office / Department of Community Affairs**

*By:*


**Florida Solar Energy Center**



***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

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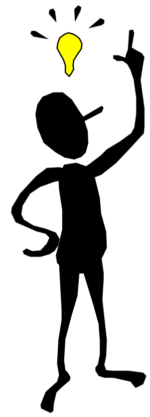
# 1. INTRODUCTION



***"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.

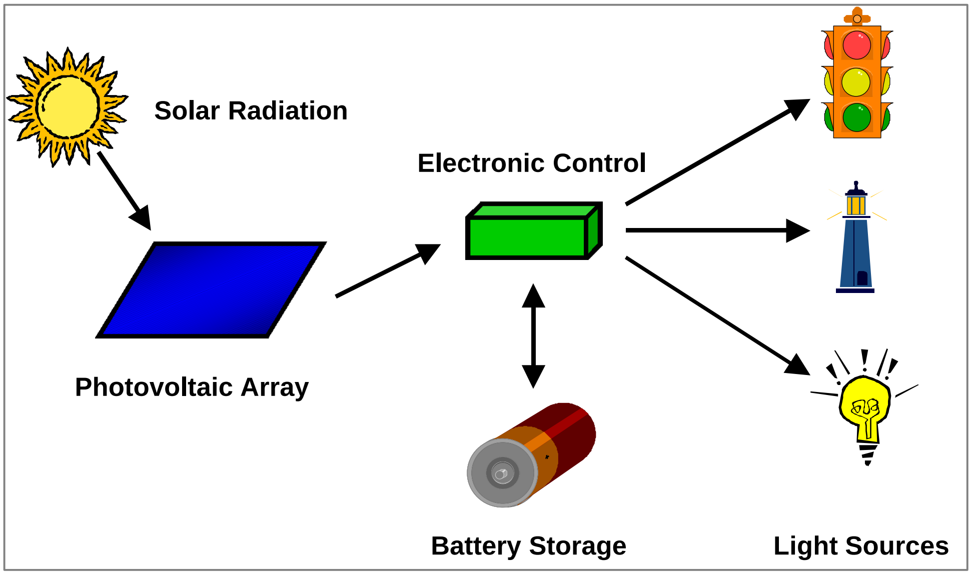



*Figure 1-1. PV lighting system advance organizer.*

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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.

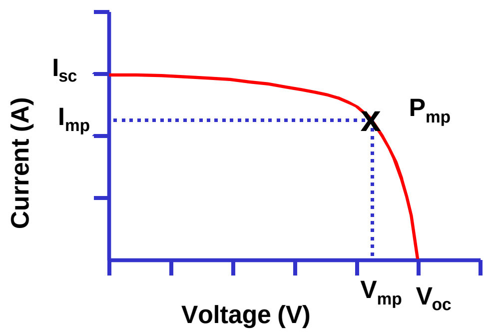



***Figure 2-2. I-V curve.***

*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.

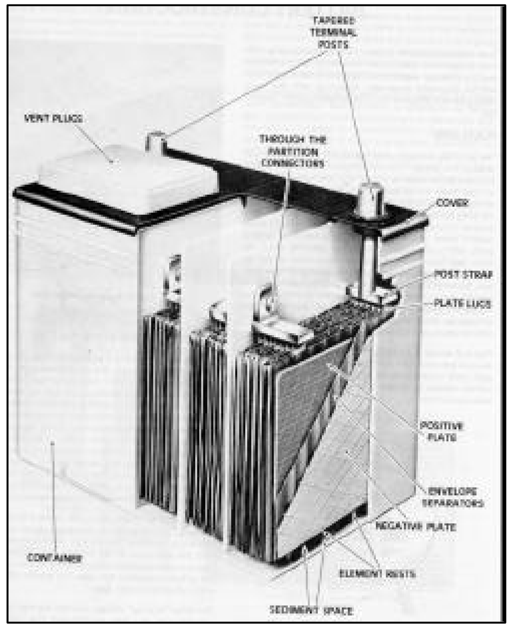



***Figure 2-4. Battery cut-away view.***

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.

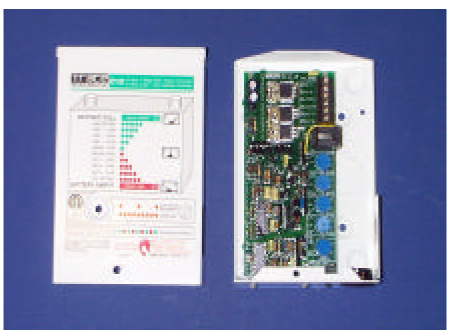


***Figure 2-5. PV lighting system controller (Trace Engineering).***


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

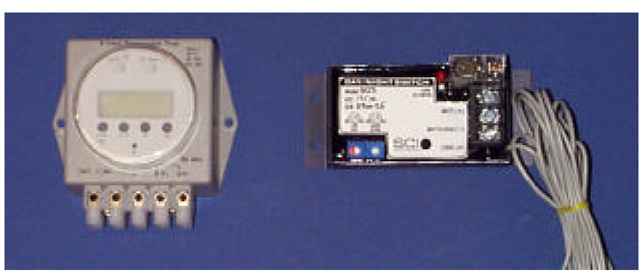


***Figure 2-7. PV lighting controls (SEPCO, SCI).***

### 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.

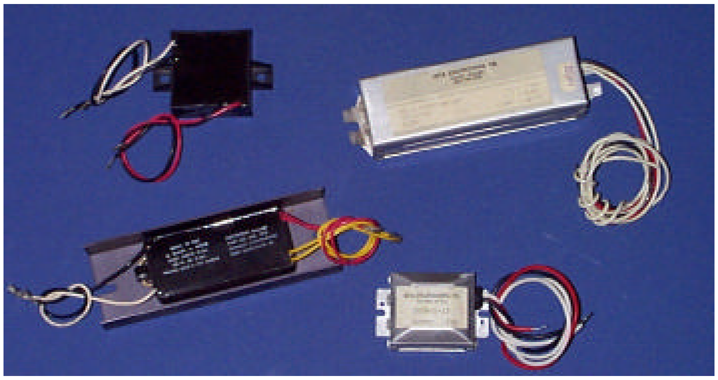
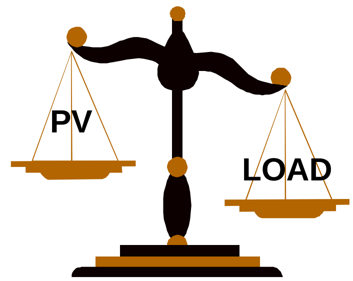


***Figure 2-11.  Low voltage DC ballasts (Sunalex, IOTA Engineering).***

# 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.

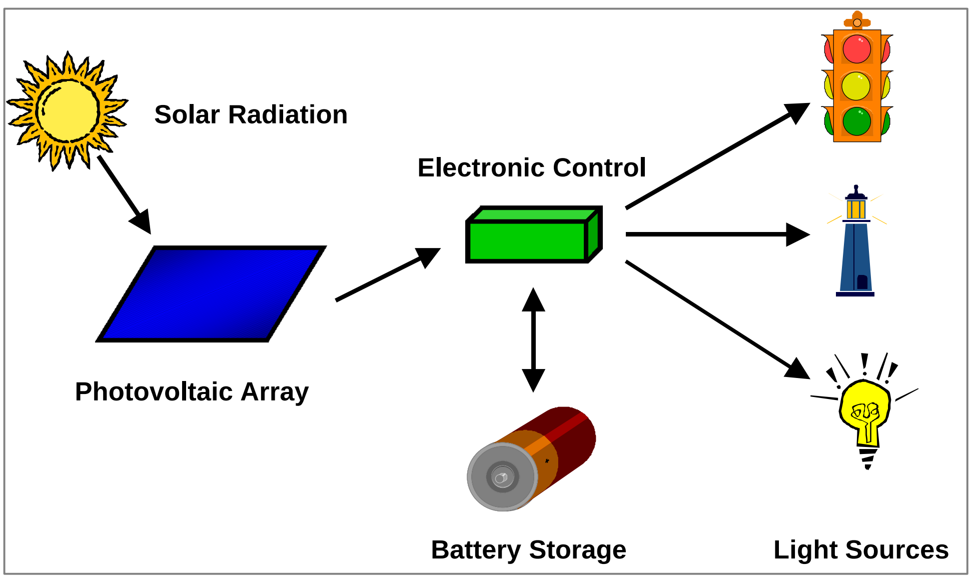



***Figure 3-1. PV lighting system advance organizer.***

## 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.

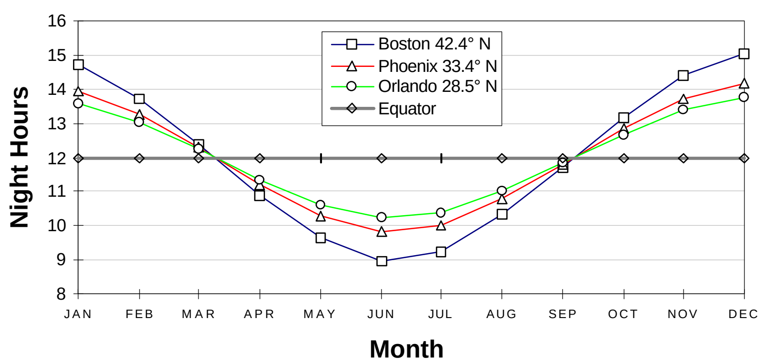



***Figure 3-2. Night hours vs. month for different latitudes.***

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.

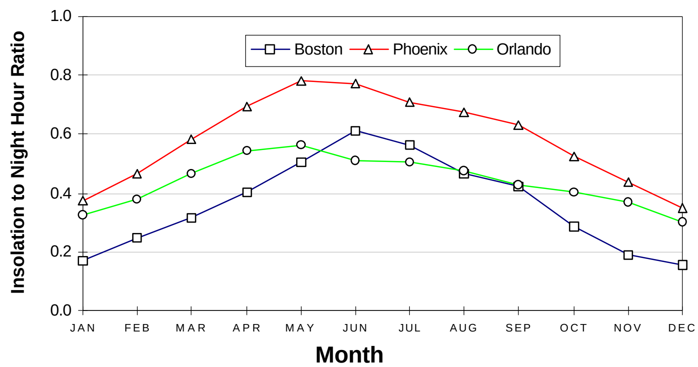



***Figure 3-3. Insolation to night hour ratios, latitude tilt surfaces.***

## 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 $^oC$ (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 $^oC$ 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 $^oC$ 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.

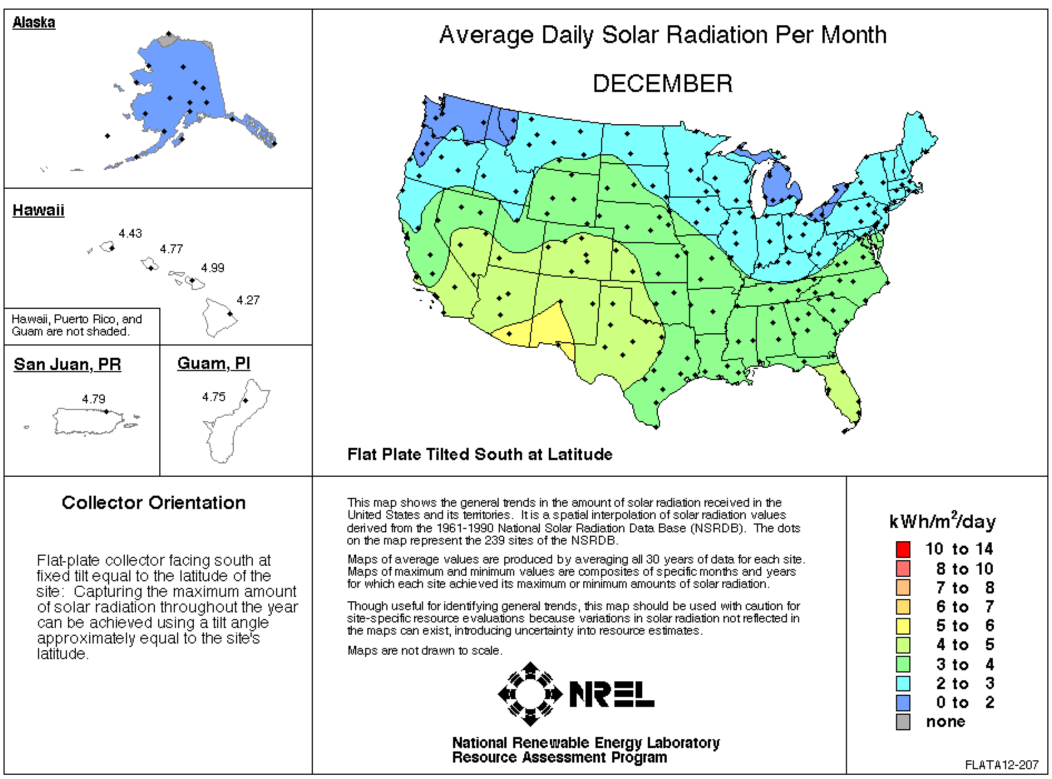



***Figure 3-4. U.S. solar radiation data map for latitude tilt surfaces in December (NREL).***

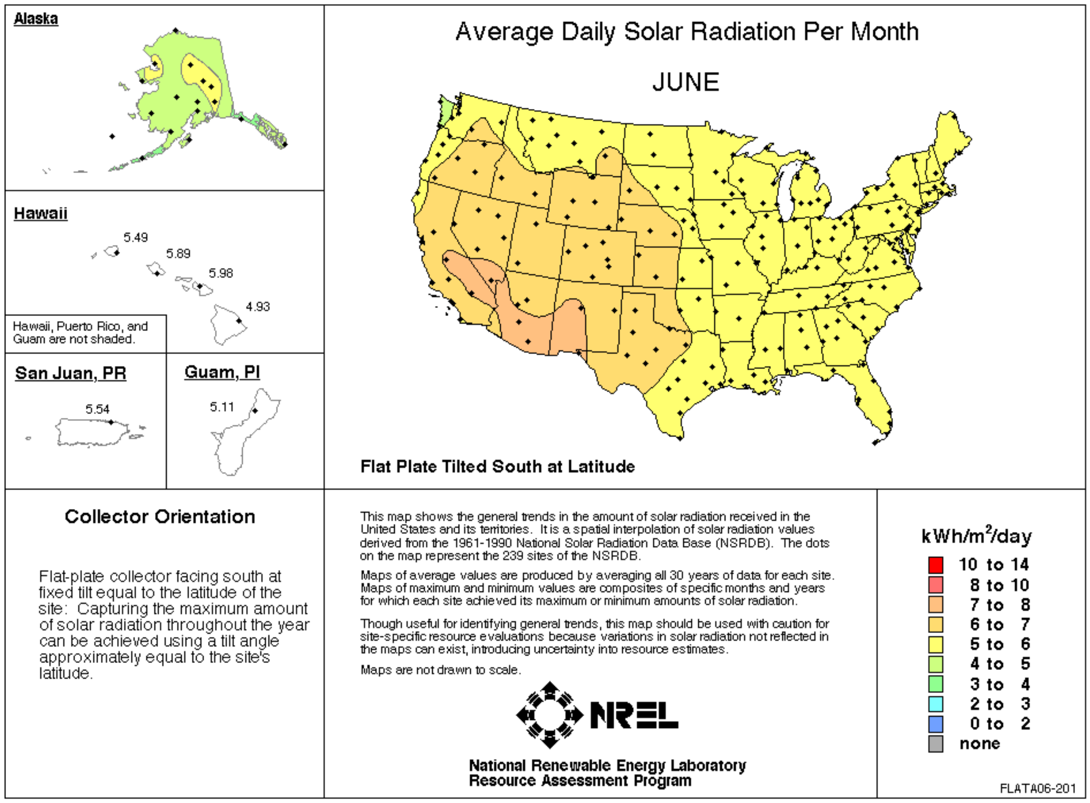



***Figure 3-5. U.S. solar radiation data map for latitude tilt surfaces in June (NREL).***

***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<br>**Latitude:** 28.5° 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 (°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/m²/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.

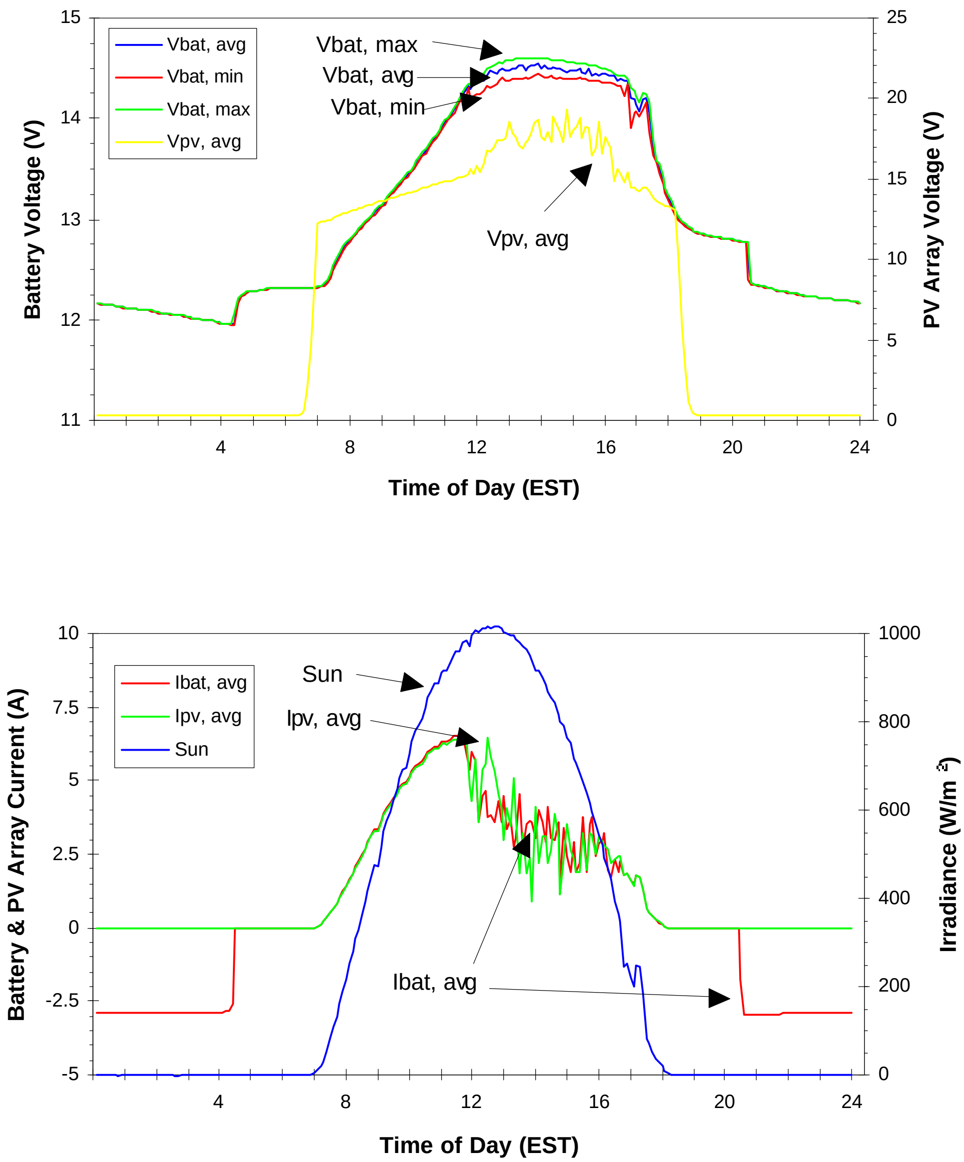



*Figure 3-6. Daily operational profile for PV lighting system.*

# 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
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FLORIDA SOLAR ENERGY CENTER®

# Stand-Alone Photovoltaic Lighting Systems

## A Decision-Maker's Guide

# Volume 3: Technical Specifications and Case Studies

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# STAND-ALONE PHOTOVOLTAIC LIGHTING SYSTEMS

***A Decision-Maker's Guide***

## Volume 3: Technical Specifications and Case Studies

*Prepared for:*

**Florida Energy Office / Department of Community Affairs**

*By:*

**Florida Solar Energy Center**

***First Edition September 1998***

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## *Abstract*

This document provides considerations for developing PV lighting system technical specifications and includes suggestions for top-level functional requirements and equipment specifications. Case studies of two PV lighting projects are also presented as an example of specific system requirements. This information is intended to help prospective buyers of PV lighting equipment establish their requirements and to help ensure that system suppliers have a clear understanding of customer expectations.

# *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

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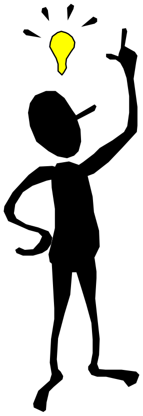
# 1. INTRODUCTION



***"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.

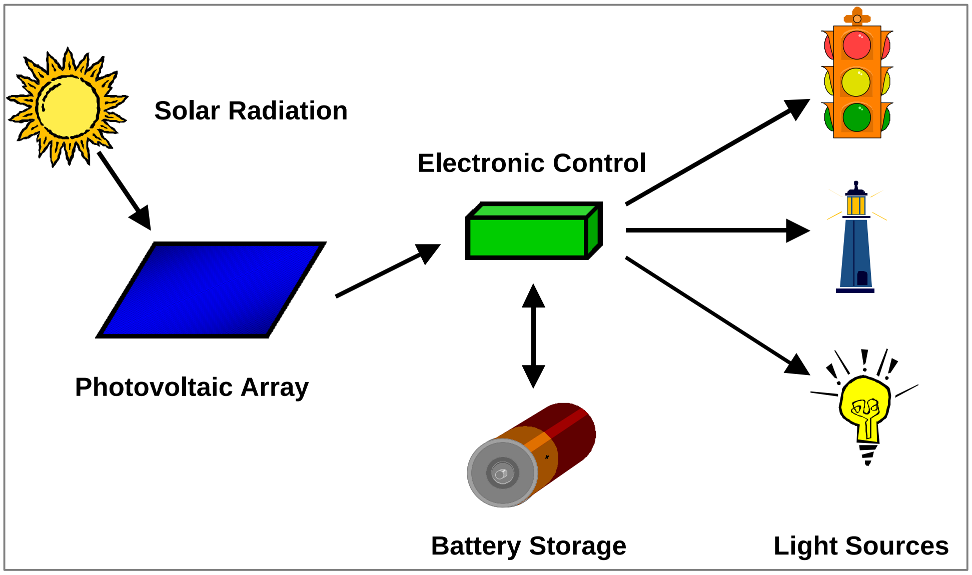



*Figure 1-1. PV lighting system advance organizer.*

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# 2. Developing Technical Specifications for PV Lighting Systems

This section presents guidelines for the specification and procurement of PV lighting systems and equipment. These guidelines are intended to help both buyers of PV lighting equipment as well as those supplying systems and equipment.

A well-written specification for a PV lighting project helps ensure the buyer purchases the equipment they need, and gives the system supplier a clear understanding of customer expectations. Depending on the lighting application, these project specifications will include a combination of design and performance-based requirements. In all cases, PV lighting specifications should include the primary functional and operational requirements for the end-use product – the quantity and quality of lighting provided by the systems. The following provides an overview of issues to consider in specifying PV lighting systems and equipment.

***The Buyer Should Provide the Following Information***

- Specification of system functional, operational and performance requirements
- Magnitude, duration, variation and critical nature of lighting application
- Applicable codes, standards, permits, qualifications and other requirements
- Autonomy or battery storage capacity
- Auxiliary systems, controls and backup provisions
- Site-specific information, data and other requirements.

***The Buyer Should Insist on the Following***

- Photometric data for lighting fixtures and overall design
- System and component warranty information
- System and component specifications (parts lists and product literature)
- Electrical and mechanical drawings
- Operation, maintenance and diagnostic procedures
- Service, repair and safety information
- User/operator training
- Acceptance tests to verify delivered system meets specified performance
- Complete documentation package including all of the above information.

## 2.1 What Should the Buyer Consider?

Once a decision has been made to pursue a PV lighting application, the buyer must establish project constraints and tradeoffs. The constraints establish necessary and essential criteria for the project such as budget, schedule, and performance. Tradeoffs are variables that allow flexibility in the design and performance of the systems.

### 2.1.1 *What are the Project Constraints?*

- What are the maximum initial and life cycle target costs for the lighting project?
- What is the projected schedule and what are the target dates for procurements and completing the installation?
- What are the requirements for minimum light levels, time of operation, availability or other factors?
- Are there any regulatory requirements such as product listings or approvals, contractor licensing, permitting or inspections that are required for the project?

### 2.1.2 *Consider Key Tradeoffs*

The size and costs of PV lighting equipment for a given light application are directly related to the energy required for light, in other words the amount of illumination and the time of operation required. For this reason, the buyer may want to:

- Consider automatically controlling the light operation (duty cycle) based on time of day, time of operation, time after dusk, or occupancy (presence) sensing.
- Consider alternative designs and configurations for array mounting, type, height and installation requirements for light poles, location and accessibility to battery/control enclosures.
- Consider initial versus life cycle cost tradeoffs such as the system sizing (size of battery/autonomy period, array to load ratio), and the quality, expected life, warranties and maintenance requirements for individual components.

### 2.1.3 *Provide Site-Specific Information*

The buyer should provide as many details as possible about the site and prevailing conditions, to ensure the designs offered by system suppliers meet or exceed performance and reliability expectations. Site specific information includes but is not limited to:

- Description and/or drawings of the site identifying the area to be illuminated, suggested/required lighting fixture locations, elevations, soil conditions, and the potential for flooding.
- Meteorological conditions at the site, including temperatures, wind speeds, humidity and solar radiation data.
- Solar exposure at the site and any particular shading concerns such as tall trees or nearby buildings.
- Establishing the potential risk of vandalism, theft, and personal injury.
- Any special installation concerns such as limited site access or preparation requirements.

### 2.1.4 *Establish Proposal Requirements*

Bid specifications should clearly indicate the requirements for responsive proposals. In addition to the total price, the buyer should include additional proposal requirements that help in selecting the most qualified response. Proposal requirements may include:

- Experience, qualifications and capabilities of system supplier
- Field experience and reliability of the same or similar designs
- Total price and schedule
- Electrical and mechanical drawings
- Product literature and specifications for major system components
- Lighting system layout and illuminance calculations
- System sizing and design computations.

## 2.2 Top-Level Functional and Operational Requirements

Top-level requirements are those specifications that deal primarily with the overall function and operational performance of the PV lighting systems. Top-level functional and operational requirements include:

- Lighting quantity and quality requirements
- Lighting time of use requirements
- System maintenance requirements
- System and component cycle life requirements.

### 2.2.1 *Specifying the Quantity and Quality of Lighting*

The quantity and quality of light should always be specified and are key to achieving the visual acuity requirements for the lighting application. Generally, these requirements are related to some established standard or recommended practice for the given lighting application. For area and sign lighting applications, the lighting requirement is usually based on minimum and average illuminance levels, not to exceed a limit of average to minimum illuminance ratio (uniformity) over a certain surface area. For flashing and signaling devices and internally illuminated signs, the lighting requirement is usually based on the luminance (brightness) of the device, as observed at a specified distance, and the contrast between the device and the background. In addition to uniformity or contrast, other light quality features such as color, luminaire distribution type and glare reduction may be specified. The buyer should request photometric information from the system supplier for individual systems as well as the overall photometrics where more than one individual system is required for the application.

### 2.2.2 *Specifying the Light Operation Time*

The required light operation time can be prescribed by the total hours per night, number of hours after dusk, or dusk to dawn operation. Other variations may include specifying a lower number of operational lamps or illumination levels after a certain time each night, or using other automatic or manual controls to operate the light. Note that the nightly hours for dusk-dawn operation vary seasonally, especially at higher latitudes. Manual control presents the greatest uncertainty about the energy requirement for the lights.

### 2.2.3 *Specifying System Maintenance and Life Cycle Requirements*

In general, PV lighting systems should require little maintenance except for simple replacement of lamps, ballasts and batteries at projected intervals. Any required maintenance and replacements should be specified or requested from the system supplier. With the exception of batteries, a complete inventory of spare parts may be specified for expected or required replacements. In the absence of qualified, on-site personnel, a service contract may also be established between the system supplier, installer or a local contractor. The buyer will also want to ensure that the specified light output is maintained over time and under the range of operating conditions experienced at the site, such as high or low temperature, factoring in lamp lumen depreciation and dirt accumulation in and on the fixture.

## 2.3 Equipment Specifications

### 2.3.1 *Request System and Component Warranties*

To help ensure long-term reliability, the buyer should insist on both system and component warranty information from the supplier. The methods for implementing a warranty provision should be clearly established and handled by the system supplier (or local designee) as the single point-of-contact for warranty service. The buyer may also specify certain warranty requirements beyond the typical conditions offered by the system supplier. These issues may be negotiated in the contract for purchase.

System-level warranties include assurances for the specified performance and operation of the overall system. Complete system-level warranties are usually for a shorter period (one to three years) than individual component warranties. Warranties for individual components (PV modules, batteries and lights) are generally based on maintaining a certain percentage of initial rated performance. For example, performance warranties on PV modules may be for no more than twenty percent power output degradation over twenty-five years. Battery performance warranties will be tied closely to the operating regimes, temperatures and maintenance, and may be expressed in terms of maintaining a certain percentage of initial rated capacity over a period of years.

PV lighting system warranties should consider:

- Complete system-level warranty for the no-cost replacement of defective components for a nominal period.
- Individual warranties for major system components such as PV modules, batteries, lamps, ballasts, and controls.
- Extended warranty or service contract beyond baseline warranties offered by the system supplier.

### 2.3.2 *Specifying Luminaires (Lamps, Ballasts and Fixtures)*

Issues to consider when specifying luminaires 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.

### 2.3.3 *Specifying Photovoltaic Modules and Array*

Any type of PV module is generally acceptable for PV lighting systems. However, for many applications, array surface area must be limited due to mechanical and wind load constraints, especially if the arrays are mounted to light poles. In these cases, higher efficiency modules may be desirable to minimize array area requirements. The PV module/array may be integrated in the light fixture for small systems, installed on a pole mount for area lighting applications, or mounted to the ground, a roof or independent structure for larger systems.

Issues to consider when specifying modules and arrays for PV lighting systems include:

- Preferred cell technology (e.g., crystalline, thin-film, etc.)
- Electrical performance (rated, guaranteed 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 the array
- Cost, lifetime and warranty.

### 2.3.4 *Specifying Batteries*

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

- Preferred battery technology (e.g., flooded lead-acid, gelled, AGM, etc.)
- 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)
- Costs (initial and replacements)
- Availability.

### 2.3.5 *Specifying System Control Requirements*

The following control requirements should be considered in 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 and thresholds
- 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.

### 2.3.6 *Specifying Spare Parts Requirements*

Spare parts may be requested with system procurement, or sources for the equipment should be identified. Examples of spare components that may be provided with the system include lamps, ballasts, fuses, and spare PV modules. Batteries are not suitable items for spare parts inventories.

## 2.4 Specifying Electrical Design Requirements

Safe and reliable electrical practices should be adhered to in the design and installation of any PV lighting system. For most applications, the National Electrical Code (NEC) establishes the minimum electrical design and safety requirements for PV lighting systems. A good system electrical design not only ensures safety but can also improve the reliability of the system performance.

Examples of electrical design requirements include:

- Specifications requiring the use of approved or listed equipment for the intended application.
- Specifications for the types, sizes and ratings of conductors based on location, temperature, ampacity and voltage drop.
- Specifications and appropriate ratings for required disconnect and overcurrent protection devices such as switches, fuses and circuit breakers. In all cases, some means of isolating the battery should be provided.
- Specifications for electrical system grounding and surge suppression. All PV systems, regardless of operating voltage, must have an equipment ground connecting the exposed metal frames and enclosures to earth. For systems operating above 50 volts, the NEC requires that a current carrying conductor in the electrical circuit be grounded. Surge suppression may be specified to provide some level of lightning protection for ballasts, controllers and other sensitive system components.

## 2.5 Specifying Mechanical Design Requirements

Mechanical design specifications for stand-alone PV lighting systems should typically require:

- Calculation of structural loads
- Compliance with applicable standards and building/structural codes
- Use of appropriate and compatible materials to avoid degradation
- Use of appropriate enclosures for batteries, controls and lighting equipment to protect from the elements and to minimize temperature high/low temperatures
- Ease of installation and access for maintenance
- Optimum array mounting design and orientation to improve thermal performance, to gain maximum solar exposure and to avoid shading of the array
- Aesthetics and architectural compatibility of the complete installation
- System design that offers low risk for vandalism, theft and personal injury
- Tradeoffs to reduce first and life-cycle costs.

## 2.6 Specifying System Documentation Requirements

To ensure long-term system performance and reliability of PV systems, it is essential that the system supplier provide a complete documentation package to the buyer. As a new technology, maintenance personnel are often not as familiar with PV lighting systems as they are with common, conventional equipment.

At a minimum, the following items should be required as part of the system documentation package.

- Component and system specifications, part lists
- Electrical and mechanical drawings
- Description and requirements for operation, maintenance, diagnostics and safety
- Acceptance test procedures.

# 3. PV Lighting Project Case Studies

This section presents case studies of two PV lighting projects. The first case study is for PV area lighting systems installed at the Martin Luther King, Jr. National Historic Site in Atlanta, Georgia. The second case study is a PV-powered overhead highway guide sign lighting system operated by the Florida Department of Transportation near Orlando, Florida. These case studies are intended to provide an example of the specifications and design considerations for two popular PV lighting applications.

## 3.1 PV Area Lighting for the Martin Luther King, Jr. National Historic Site

This case study presents an example of specifications used in the procurement of 65 PV lighting systems that were installed at the Martin Luther King, Jr. National Historic Site in Atlanta, Georgia in June 1996 (Figure 3-1). The specific application was to provide PV-powered lighting for a six-acre parking area, meeting certain illumination levels with an aesthetically pleasing and architecturally compatible design. This section provides an overview of the project requirements, specifications and resulting hardware.

***Figure 3-1. PV lighting at MLK, Jr. National Historic Site.***

### 3.1.1 *Project Requirements*

- Design and size photovoltaic-powered outdoor lighting systems
- Specify layout of the systems in parking area
- Deliver, assemble and install the systems
- Provide appropriate documentation
- Provide on-site technical assistance and user training during acceptance testing
- Meet or exceed the lighting requirements
- Require no regular maintenance except for periodic replacement of lamps and batteries
- Reduce the risk of vandalism, theft and personal injury
- Make the design and layout aesthetically pleasing.

#### 3.1.1.1 Hardware and Documentation Required

- Complete photovoltaic-powered outdoor lighting systems
- Spare parts: 1 module, 2 controllers, 2 lamps and ballasts and 1 luminaire (per 20 systems):
- Parts, materials, and source lists
- Assembly, installation and checkout instructions
- Operation and maintenance manual
- Electrical and mechanical drawings
- Product literature and specifications for major components.

### 3.1.1.2 Illumination Requirements

- A minimum illuminance of 0.4 footcandle is required
- A uniformity ratio (average to minimum illuminance) of 4:1 should not be exceeded.

### 3.1.1.3 Site Conditions

- The total area to be illuminated is approximately six acres
- Solar access is good except near buildings in the southeast corner of the parking area
- No shading from trees or vegetation is expected above 20 feet
- December should be used as the design month for all array tilt angles
- NREL solar radiation data for Atlanta, Georgia should be used for sizing the systems
- Risk of vandalism, theft and personal injury in a high crime area.

### 3.1.1.4 Schedule

- Installation and operation must be complete before the summer Olympics.
- Contractor must coordinate schedule with the National Park Service.

### 3.1.1.5 Warranties Required

- Three-year limited warranty on systems
- Spare parts supply replenished at end of warranty period
- Two-year, no-cost replacement warranty on batteries
- Ten-year unlimited manufacturer's warranty on modules.

## 3.1.2 *Equipment Specifications*

### 3.1.2.1 Fixture, Pole and Lamp

- Olympic design and architectural requirements require pre-approved design. Bidders should factor these special design requirements in their proposals.
- Lighting fixtures and PV arrays should be mechanically integrated on the pole, at a height no lower than 20 feet above grade.
- Fluorescent, high-pressure sodium and metal halide lamps are acceptable.
- Polarized connections on ballasts required.

### 3.1.2.2 Photovoltaic Modules and Array

- Photovoltaic modules must be UL-listed or meet or exceed the latest draft qualifications standard.
- Crystalline or polycrystalline silicon cells are preferred but not required.
- Flat-plate arrays are required.
- No restrictions are placed on the array tilt angle.

### 3.1.3 *Batteries and Charge Control*

- Sealed, maintenance-free batteries are required.
- Batteries must be properly matched with charge controllers.
- All batteries (and lamps) will typically be replaced at the same time.
- Battery subsystems are required to provide five days of autonomous operation.
- Battery enclosures should be designed to minimize large internal temperature swings.
- Battery subsystem design and location should minimize the risk of vandalism, theft and personal injury.
- The preferred location for the battery subsystem is either high on the pole or below ground level.
- Charge controllers are required and must be properly matched with batteries.
- Proposals must include manufacturer, model number, charging algorithm and set points.
- Proposals which do not clearly indicate proper matching of charge controllers and batteries will be rejected.

### 3.1.4 *Lighting Operation and Control Requirements*

- Systems should be adequately sized to operate the lights for a minimum of eight hours after dusk year round.
- The on-off lighting control algorithm must be specified, and a procedure for changing the duty cycle must be provided.
- Provision for turning the lights on during the day must be provided for maintenance and check out.

### 3.1.5 *System Sizing, Lighting Design and Photometric Calculations*

- PV system sizing computations and methodology must be provided.  These computations will be reviewed and verified to help ensure that the systems are properly sized.
- Proposals must specify the entire lighting system layout, including the locations and number of fixtures (systems), and fixture mounting height.
- Illuminance predictions must be provided for a single fixture as well as the entire lighting system design.
- Some bidders may be asked to verify photometric data.  The costs for performance verification via testing should be included in the project budget.

### 3.1.6 *Electrical and Mechanical Design*

- Designs must comply with all applicable sections of the National Electrical Code.
- Voltage drops between array, battery and ballasts should be less than four percent.
- Provision for isolating the battery subsystem must be provided.
- Electrical components must be dc-rated, labeled and accessible.
- Metal module frames, poles, supports and enclosures must be properly grounded.
- Mechanical loads due to the weight of the array, wind forces on the array, the array attachment to the poles and the footings for the poles should be computed using ANSI/ASCE 7-93.
- Direct contact between dissimilar metals must be avoided.
- Untreated wood, common steel and corrosion/weather susceptible materials will not be accepted.

### 3.1.7 *Acceptance Testing, Performance Monitoring and User Training*

- A third-party agent (to be selected by buyer) will conduct acceptance testing to ensure that project specifications have been met.
- Measurements will include array performance, verification of proper charge control operation and light control function, and ground-level illuminance.
- Selected systems will be monitored for at least one year to document performance.
- The contractor is required to provide eight hours of training to National Park Service.
- Topics will include component descriptions and specifications, theory of operation, maintenance requirements and schedule, instrumentation and test points, diagnostics and troubleshooting, safety precautions and record keeping.

### 3.1.8 *Proposal Requirements and Award Criteria*

At a minimum, each proposal shall include:

- Total price
- Complete design and system sizing calculations
- Electrical and mechanical drawings
- Product literature and specifications for major system components
- Illuminance calculations for single fixture and entire layout
- Bidder capability information - experience and qualifications, field experience and references
- Proposed schedule for complete design, installation and training.

Evaluation criteria for proposals shall be weighted according to:

- Quality of the design in meeting the performance requirements and in reducing the risk of vandalism, theft, and personal injury (20%)
- Prospects for minimizing maintenance and maximizing reliability (20%)
- Total price (20%)
- Capability of the bidder to satisfactorily implement the project (20%)
- Aesthetics (20%).

### 3.1.9 *Design Summary*

Table 1 on the following page summarizes the system sizing and components delivered for the PV lighting systems at Martin Luther King, Jr. National Historic Site.

*Table 1. Design Summary for MLK PV Lighting System.*

| MLK PV Lighting System Summary | |
|---|---|
| ***Location*** | Atlanta, Georgia 33$^0$ N |
| ***Design Month*** | December |
| ***Design Insolation*** | 3.7 kWh/m2/day, south-facing 45$^o$ tilt surface |
| **LOAD** | |
| ***System, Load Voltage*** | 24-volts DC |
| ***Lighting Load*** | 36-watt compact fluorescent fixtures, 2 per system, 1.5 amps each, 3 amps total load |
| ***Time of Operation*** | 8 hours after dusk each night, year round |
| ***Average Daily Load*** | 24 amp-hours at 24-volts DC |
| **BATTERY** | |
| ***Battery Bank*** | Deka Gel-Tech gelled lead-acid: 6-volt, 190 amp-hour (4 in series) |
| ***Rated Battery Capacity*** | 190 amp-hours at 24 volts, C/20 rate, 25 $^o$C |
| ***Average Daily DOD*** | 12.6 percent |
| ***Maximum DOD*** | 80 percent |
| ***Maximum Charge/Discharge Rates*** | Discharge rate C/60, maximum charge rate C/22 |
| ***Autonomy Period*** | 5 days |
| **PV** | |
| ***PV Module and Array*** | ASE-50-AL/16: Imp = 2.8 amps @ STC (2 series x 3 parallel) |
| ***Array Rating*** | 8.4 Imp @ STC |
| ***Array Design Month Output*** | 31 amp-hours per day |
| ***Minimum PV to Load Ah Ratio*** | 1.3 (December) |

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## 3.2 PV-Powered Highway Guide Sign Lighting System

In 1987, 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 3-2. Located on a remote stretch of highway, this site is located several miles from the nearest utility service, making the cost of grid extension cost-prohibitive. One of the first few systems of this type to be installed in the U.S., this project illustrates many of the considerations in the specification and design of PV lighting systems.

The following presents an overview of the project, including the selection of a light source, system sizing, and electrical and mechanical design considerations.

***Figure 3-2. PV-powered highway guide sign lighting system.***

### 3.2.1 *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 below in Table 2 for low, medium and high ambient light area [ref]. To achieve acceptable contrast with the surrounding background, higher lighting levels are required for signs located in high ambient light areas. For this application, the low ambient light requirements apply.

***Table 2. Recommended Luminance and Illuminance Levels for Highway Signs.***

| Ambient Light | 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 higher than 6:1 over the sign face, with a ratio of 4:1 desirable. 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.

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 to characterize the light sources being considered. A number of high-pressure sodium, fluorescent and mercury-vapor lighting systems were evaluated. The final choice was a 32-watt T-8 fluorescent lamp based on energy efficiency, availability, ballast requirements, lifetime and cost. Six of these light fixtures were required to meet the minimum required illumination and uniformity levels.

***Figure 3-3. Photometric measurements.***

## 3.2.2 *Sizing and Load Analysis*

After the light source had been selected, the second objective was to develop the load profile and size the battery and PV array accordingly. Since the light was required to operate all night, December was defined as the critical design period. Using the equations presented earlier, the nightly light operation time was determined to be 13.4 hours. Using the peak load of 9 amps (at 24 volts DC) for all six luminaires, the total daily load during the critical design period was calculated to be 120 amp-hours per day. The battery selected for this application was a deep-cycle design, so we used 80 percent as the allowable maximum depth of discharge limit. The desired autonomy period was seven days.

Table 3 on the following page shows the results of the system sizing process and component requirements for the PV-powered highway sign lighting system.

*Table 3.  Sizing Example for PV Higway Sign Lighting System*

| PV Guide Sign Lighting System Sizing Worksheet | |
|---|---|
| **Application:** Highway Guide Sign Lighting System | |
| **Location:** Orlando, Florida<br>**Latitude:** 28.5$^{o}$ N | |
| **Electrical Load Estimation** | |
| **A1:** Total Load DC Current Requirement (amps) | 9 |
| **A2:** Average Daily Load Usage, Design Month (hours) | 13.4 |
| **A3:** Average Daily Load Energy Requirement, Design Month = A1x A2 (amp-hours) | 120 |
| **A4:** Nominal Load (System) DC Voltage (volts) | 24 |
| **A5:** Maximum Load DC Current (amps) | 9 |
| **Battery Sizing** | |
| **B1:** Autonomy Period, Days of Storage (days) | 7 |
| **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) | 1312 |
| **B6:** Nominal Capacity of Selected Battery (amp-hours) | 1350 |
| **B7:** Nominal Voltage of Selected Battery (volts) | 2 |
| **B8:** Number of Batteries Required in Series = A4 / B7 (#) | 12 |
| **B9:** Number of Batteries Required in Parallel = B5 / B6 rounded up to next integer (#) | (0.97) 1 |
| **B10:** Total Number of Batteries Required = B8 x B9 (#) | 12 |
| **B11:** Total Battery Capacity = B9 x B6 (amp-hours) | 1350 |
| **B12:** Battery Average Daily Depth of Discharge = (A3 *100) / B11 (%) | 8.9 |
| **B13:** Battery Maximum Discharge Rate = B11 / A5 (hours) | 150 |
| **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) | 120 |
| **C5:** Load Adjustment Factor for System Inefficiencies (decimal) | 0.85 |
| **C6:** Adjusted Design Month Average Daily Load = C4 / C5 (amp-hours) | 141 |
| **C7:** Selected Module Maximum Power Current Output at STC, Imp (amps) | 3.5 |
| **C8:** Module Output Derating Factor (decimal) | 0.9 |
| **C9:** Adjusted Module Maximum Power Current Output = C7 x C8 (amps) | 3.15 |
| **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) | 12.7 |
| **C11:** Number of Parallel Modules Required = C6 / C10 rounded up to next integer (#) | (11.1) 12 |
| **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 (#) | 24 |
| **C14:** Nominal Rated PV Module Output (watts) | 60 |
| **C15:** Nominal Array Rated Output = C14 x C13 (watts) | 1440 |
| **Sizing Summary** | |
| Lighting Load (Ah/day) | 120 |
| Design Autonomy Period (days) | 7 |
| Selected Battery Series/Parallel Configuration (S x P) | 1 x 12 |
| Total Number of Selected Batteries (#) | 12 |
| Battery Storage Capacity (Ah) | 1350 |
| Allowable Depth of Discharge Limit (%) | 80 |
| Average Daily Depth of Discharge (%) | 8.9 |
| Selected Module Series/Parallel Configuration (S x P) | 2 x 12 |
| Total Number of Selected Modules (#) | 24 |
| Estimated PV to Load Ah Ratio for Design Month = (C7 x C11 x C2) / C4 | 1.41 |

### 3.2.3 *Electrical Design*

The electrical design of the PV lighting system included selection of appropriate wire types and sizes, and selection and location of overcurrent protection, disconnect devices, surge protection and grounding.

Due to the long wire runs from the array to the battery and from the battery to the lights, special attention was given to select wire sizes to limit the overall voltage drop to less than four percent. Each of the 12 two module series strings and each of the six luminaires were wired separately to minimize the wire sizes required and to allow for easier troubleshooting. Each two-module sub-array was terminated at a junction box through a fuse and blocking diode and connected in parallel with the other sub-arrays. Fused disconnect switches were installed at the system controller connections to the PV array, battery and lighting load. Figure 3-5 shows the control room housing the batteries, combiner boxes, disconnects and system controller.

The control design for the system includes battery overcharge and over discharge protection, and dusk to dawn lighting control. System status indicators on the controller provide active operational mode, and a digital display reads battery voltage, and battery, PV array and load currents.

### 3.2.4 *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.

In order to reduce the potential for vandalism and shading, the array was mounted on top of the sign structure. This required special considerations for 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. With the given dimensions and tilt angle of the array mounting assemblies, a spacing of 80 inches was required between sub-arrays to prevent shading in the winter months. Figure 3-4 shows the array mounting design.

***Figure 3-5. Guide sign lighting battery and control room.***

***Figure 3-4. Array mounting design.***

### 3.2.5 *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 for five miles. 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, a simple economic procedure was used assuming a 30-year PV system lifetime and expected 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 4 summarizes the results of the economic analysis.

***Table 4. PV guide sign economic comparisons.***

| Power Option | Present Life Cycle 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 with the PV and generator options.

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# 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
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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 USA
Tel: (407) 869-5300

Work Area Protection Corp.
2500-T Production Dr.
P.O. Box 87
St. Charles, IL 60174 -0087 USA
Tel: (630) 377-9100
Fax: (630) 377-9270

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# Stand-Alone Photovoltaic Lighting Systems

## A Decision-Maker's Guide

# Volume 4: Lighting Fundamentals and Equipment

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# STAND-ALONE PHOTOVOLTAIC LIGHTING SYSTEMS

***A Decision-Maker's Guide***

## Volume 4: Lighting Fundamentals and Equipment

*Prepared for:*

**Florida Energy Office / Department of Community Affairs**

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***First Edition September 1998***

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## *Abstract*

This document provides an overview of lighting fundamentals and equipment, and is intended for those individuals that specify, design, and/or integrate photovoltaic (PV) lighting systems. The information includes definitions of photometric properties and laws, description of common light sources, and the basics of lighting system design.

# *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

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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.

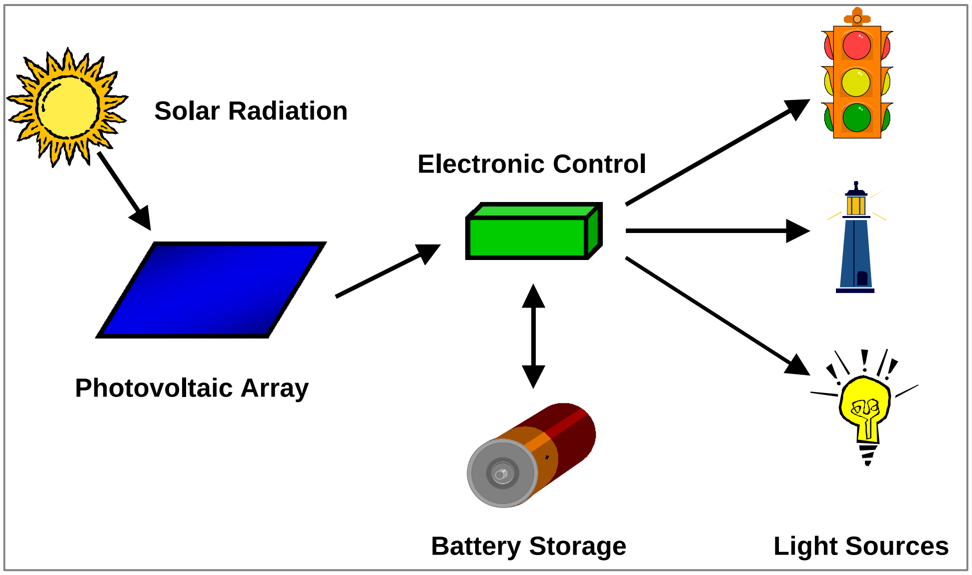


***Figure 1-1. PV lighting system advance organizer.***

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# 2. Lighting Fundamentals

Knowledge of basic photometric properties, light sources, and lighting requirements are an important part of specifying the performance of photovoltaic-powered lighting systems. The information presented in this section is intended to provide an overview of these topics for those specifying, designing and/or installing PV lighting systems.

## 2.1 Photometric Properties

The following technical definitions describe the more important photometric properties and laws.

***Illuminance (E).*** Illuminance or the illumination, is the luminous flux density *incident* on a surface. Illuminance is generally expressed in units of *footcandles* (lumens/ft$^2$), or in international units of *lux* (lumens/m$^2$). One footcandle is the illumination at a point on a surface, which is one foot from and perpendicular to a uniform point source of one candela (Figure 2-1). In most cases, lighting levels are expressed in terms of the average and uniformity of illuminance over a given area. For unit conversions, one footcandle equals 10.76 lux.

***Luminance (L).*** Luminance or photometric *brightness* represents light that is *reflected or emitted* from a surface, as opposed to the light flux *incident* on a surface (illuminance). A surface that 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.

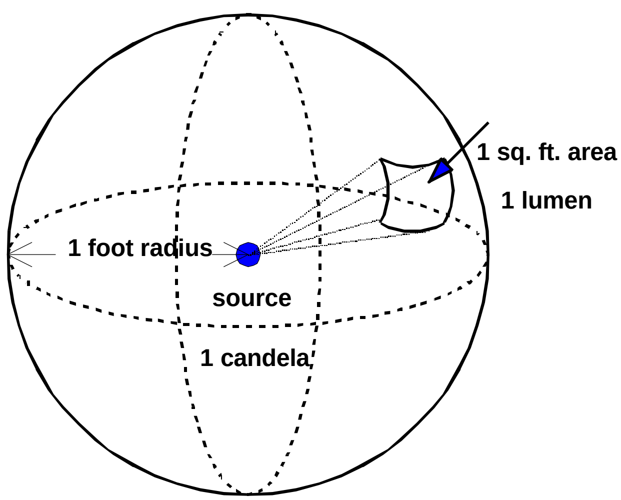



*Figure 2-1. Luminous flux and intensity.*

***Luminous Intensity (I):*** The luminous intensity is the light density of a source, measured in a specified direction and within a very small solid angle. The candela (cd) is the basic unit of luminous intensity. An ordinary wax candle has a luminous intensity in a horizontal direction of one candela. The luminous intensity of a light source expressed in candelas is its candlepower (cp). *Candlepower distribution curves* represent the luminous intensity of a light source in many directions, and are used in lighting system design to determine illuminance distribution patterns on surfaces. An approximation of candlepower can be estimated by multiplying the normal flux in footcandles by the square of the distance in feet.

***Luminous Flux (ƒ):*** The total luminous power emitted from a source is expressed in units of *lumens* (lm). One 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 (Figure 2-1). The lumen is a measurement of light flux, and is used to express the total output of a source, incident light over a specified area or region, or the amount of light reflected, absorbed or transmitted.

***Reflection, Transmission and Absorption.*** When light rays strike a surface, they can be reflected, transmitted, and/or absorbed. *Reflectance* ($\rho$) is defined as the ratio of light reflected from a surface to the incident light. Reflections can be either specular or diffuse, depending on the nature of the surface. Reflectance is normally expressed as the ratio of the brightness in footlamberts and the illuminance in footcandles. Reflection properties have importance in lighting fixture design and the materials used on externally illuminated signs. The *transmittance* ($\tau$) is defined as the ratio of light transmitted through a material to the incident light. Transmission of light is an important feature of lens materials for lighting fixtures. Light rays passing through transparent or translucent materials are *absorbed* if they are not reflected of transmitted. The *absorptance* ($\alpha$) is defined as the ratio of light absorbed in a material to the incident light. By definition, the sum of the reflectance, transmittance and absorptance equals one.

***Refraction.*** Light rays that pass obliquely from one medium to another, for example from air through a glass or water interface, are *refracted*. The *refractive index* of a material or medium defines the extent to which light rays are bent when passing through the material.

***Color.*** The spectral content or wavelength determines the color of light. The visible spectrum consists of the colors of a rainbow, ranging from violet at one end to red at the other end. Wavelengths in the visible spectrum range from about 0.4 to 0.7 micrometer (µm). Ultraviolet light has wavelengths shorter than 0.4 µm, while infrared radiation has wavelengths longer than 0.7 µm. The color of light sources is an important consideration in lighting design.

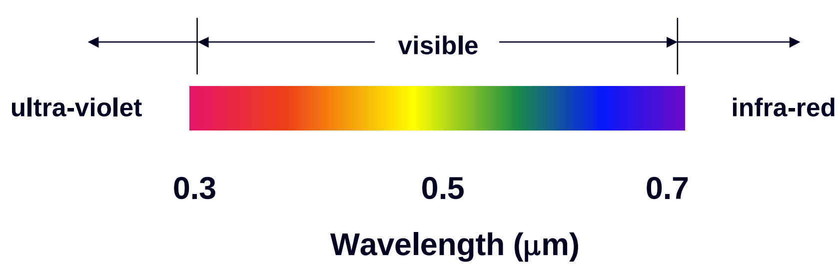



***Figure 2-2. Visible spectrum.***

## 2.2 Photometric Laws

Two basic photometric laws are used in almost all lighting design practice – the *Inverse Square Law* and the *Cosine Law of Incidence*.

### 2.2.1 *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 is one quarter of the illumination level at one foot away. Similarly, the illumination three feet away from a source is one ninth of the illumination one foot away. The inverse square law generally applies if the distance at which measurements are taken is at least five times the greatest dimension of the light source. Figure 2-3 illustrates the inverse square law.

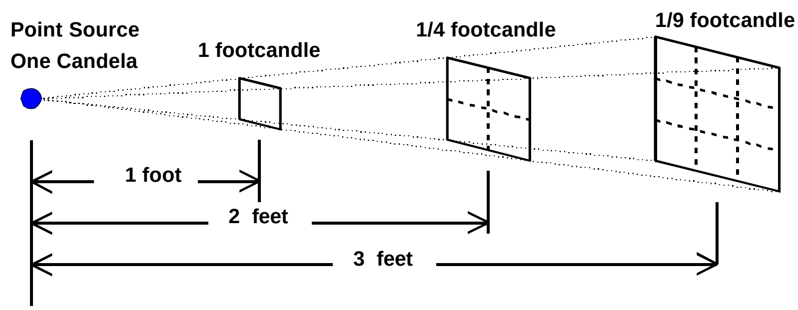
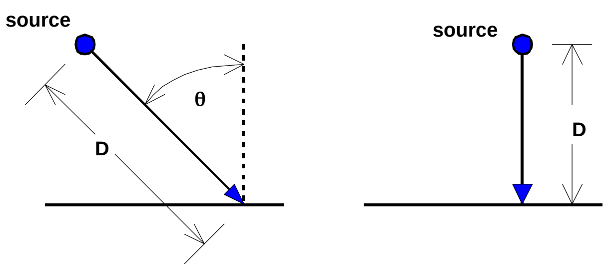



***Figure 2-3. Inverse square law.***

### 2.2.2 *Cosine Law of Incidence*

The *cosine law of incidence* 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 the perpendicular (normal) to the surface. Figure 2-4 illustrates the cosine law of incidence.




$$E = \frac{I \times \cos\theta}{D^2}$$

$$E = \frac{I}{D^2}$$

**for perpendicular incidence**

**Where,**

**E = illuminance in footcandles**
**I = source intensity in candelas**
**D = distance in feet**
**θ = angle of incidence**

***Figure 2-4. Cosine law of incidence.***

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## 3. Lighting Equipment and Terminology

Lighting equipment consists of lamps, sockets, fixtures or housings, reflectors/diffusers, lenses, ballasts, controls, power source and mounting hardware. The following defines some basic for lighting equipment.

***Source.*** Common terminology for a light source, lamp or luminaire.

***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 and LEDs do not require a ballast for starting or operation.

***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.

***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 lamp(s) alone. The CU quantifies the efficiency of a lighting application.

***Lamp Lumen Depreciation (LLD).*** Sometimes referred to as lumen maintenance, LLD refers to a lamp's lumen output reduction over its lifetime, generally expressed as a percentage of initial rated output as a function of lamp burn hours. For some types of lamps, depreciation of lamp lumen output makes it practical 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. In particularly dirty environments such as cities and dusty areas, periodic maintenance and cleaning may be required to maintain illumination levels.

***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, emitting 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), fluorescent lamps range between 3,000 and 7,000$^{o}$ K, and incandescent lamps range between 2,000 and 4,000$^{o}$ K. Note that color temperature is not a measure of actual temperature, only an approximation of light source color.

***Chromaticity and Color Rendition.*** Chromaticity refers to color, or spectral composition of the light source. Chromaticity coordinates give a specific, quantifiable representation of the color and spectral constant of a light source. Color rendition refers to the manner in which a lamp's light output affects color perception, as compared with color perception when viewed under natural daylight.

## 3.1 Light Sources

The choice of light source is an important decision in any lighting system design, particularly for PV lighting applications where the energy efficiency of the light affects the size and cost of the power source. Factors to be considered in lamp selection include efficacy, color, lifetime and lumen depreciation.

Light sources can be categorized into three groups - incandescents, fluorescents and high intensity discharge (HID) sources. HID lamps include four major categories - high-pressure sodium, metal halide, mercury vapor and low-pressure sodium. Common lamp types used in PV lighting systems include standard and compact fluorescents, low-pressure sodium and some metal-halide lamps. Due to their lower efficacies, incandescent lamps are generally only used in PV powered flashing and signaling applications. Table 1 lists general characteristics of common lamp types and Table 2 compares the efficacies of various light sources.

***Table 1. Light Source Comparison***

| Lamp Type | Efficacy (lm/W) | Typical Lifetime (hr) | Lumen Maintenance | Color Rendition | Size Range (W) |
|---|---|---|---|---|---|
| **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 | Fair | 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, manufacturing and operational environment.*

***Table 2. Efficacies of Various Light Sources***

| Light Source | Lumens per Watt<br>*Lamp Only |
|---|---|
| **Candle (Luminous Efficacy Equivalent)** | 1.4 |
| **Oil Lamp (Luminous Efficacy Equivalent)** | 0.3 |
| **Original Incandescent Lamp (1879)** | 1.4 |
| **60-Watt Carbon Filament Lamp (1905)** | 4.0 |
| **60-Watt Coiled Tungsten Filament Lamp (1968)** | 15 |
| **40-Watt Fluorescent Lamp (1968)** | 80* |
| **400-Watt Metal Halide Lamp** | 85* |
| **1000-Watt Metal Halide Lamp** | 100* |
| **400-Watt High Pressure Sodium Lamp** | 125* |
| **180-Watt Low Pressure Sodium Lamp** | 183* |

### 3.1.1 *Incandescent Lamps*

Incandescent lamps are generally constructed with a wire-wound tungsten filament and enclosed in an evacuated or gas-filled glass bulb. When power is applied, the resistive filament is heated to incandescence by the flow of electric current through it. The filament essentially becomes 'white-hot', emitting a continuous spectrum of long-wave visible radiation. The higher the temperature of the filament, the greater the portion of emitted energy that lies in the visible spectrum. Figure 3-1 shows common incandescent lamps.

***Figure 3-1. Incandescent lamps.***

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 for higher filament temperatures and higher efficiencies. While incandescent lamps are inexpensive and convenient to use because they do not need a ballast, they generally have low efficiencies and short lifetimes compared to electric discharge lamps. For these reasons, incandescents are seldom used in PV applications except for short duration or flashing type signals, such as navigational aids.

### 3.1.2 *Fluorescent Lamps*

Fluorescent lamps are electric discharge devices that utilize an arc between two cathodes to excite a low-pressure mercury vapor, resulting in the emission of ultraviolet (UV) radiation. The UV radiation is then 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 a fluorescent 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 color characteristics for fluorescent lamps.

Standard fluorescent lamps with lengths from 6 to 96 inches are commonly used in PV lighting applications. A "T" designation is used for these lamps, which refers to the tube diameter in eighths of an inch. For example, the F40-T12 CW lamp designation refers to a 40-watt cool-white fluorescent lamp with a tube diameter of 1-1/2 inches. The length of a fluorescent lamp is related to its power rating, typically about 8-10 watts per foot for standard lamps. For example, an 18-inch tube is typically rated at 12-15 watts and a 48-inch tube is rated at 32 to 40 watts, depending on the type of lamp.

Compact fluorescent lamps are very popular in PV lighting due to their small size, high efficacy, long life and simple ballast design requirements (Figure 3-2). Typical power ratings for these compact fluorescent lamps include 5,7,9,13, 24 and 36 watts, although other wattages are available in dual- or quad-tube lamp arrangements. The light output from a 13-watt compact fluorescent is often compared with that of a 60-watt incandescent lamp, and has approximately ten times the rated life.

***Figure 3-2. Compact fluorescent lamps.***

Fluorescent lamps typically convert twenty percent of the input power to visible light, compared with incandescents, which are generally less than ten percent efficient. The efficacy for larger fluorescent 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. Original fluorescent lamps developed in 1938 were the preheat type, requiring a separate starter which supplied a few seconds of current flow through the cathodes to preheat them prior to lamp ignition. When the cathodes are heated, thermionic emission aids in liberation of electrons from the cathode, and allows the lamp arc to be initiated at lower voltages. Instant start lamps, on the other hand, rely on ballasts to supply a high enough voltage to strike the arc, without the need for preheating. Rapid start lamps utilize windings in the ballast to heat the cathodes, and start almost as smoothly as instant start ballasts; however they are less efficient. Ballasts are required on all fluorescent lamps to limit the arc current after the lamp is started.

The lifetimes of many types of fluorescent lamps exceed 10,000 hours, compared with 1,000 hours for typical incandescent lamps. During the first 100 hours of operation, the lumen depreciation for fluorescent lamps may be as much as ten 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 produced by the cathodes. Rated lifetime for fluorescent lamps is decreased for shorter burn cycles (more frequent starts) – the primary reason why they are not used for high frequency on-off or flashing applications. A 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.

### 3.1.3 *High Intensity Discharge Lamps*

High intensity discharge (HID) lamps produce light by an electric arc passing through a vapor or gas inside a quartz tube, rather than through a wire filament as with incandescent lamps. Unlike fluorescent lamps, it is the arc that primarily produces the light, not phosphors inside the bulb. 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 and lifetimes up to 24,000 hours (Figure 3-5).

#### *Metal Halide Lamps*

Another HID lamp and similar in operation to mercury vapor lamps, metal halide lamps contain metal iodides added to 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. They have lifetimes up to 20,000 hours (Figure 3-3).

#### *High Pressure Sodium Lamps*

High-pressure sodium (HPS) lamps use metal sodium as the main ionizing gas in the arc tube (Figure 3-4). The high gas pressure broadens the otherwise monochromatic sodium radiation spectra of 0.59 $\mu$m (yellow light), which is characteristic of low-pressure sodium lamps. High-pressure sodium lamps have fair color rendition, high efficiencies and long lifetimes up to 28,000 hours.

***Figure 3-5. Mercury-vapor lamps.***

***Figure 3-3. Metal-halide lamps.***

***Figure 3-4. High-pressure sodium lamps.***

### 3.1.4 *Low Pressure Sodium Lamps*

The low-pressure sodium (LPS) lamp is the most efficient light source available, with efficiencies as high as 200 lumens per watt. The lamp design and construction keep thermal and radiant losses to a minimum, resulting in the high efficacies. For this reason, they are often used in PV lighting applications. LPS lamps have lifetimes between 12,000 and 18,000 hours while achieving nearly 100 percent lumen maintenance.

The inner tube of the LPS lamp contains condensed sodium and neon starting gas. The space between the inner and outer tubes is highly evacuated. In operation, an electrical arc ionizes the neon gas causing a red glow during the first few minutes of operation. As the lamp reaches temperature, the sodium is vaporized and ionized by the arc, creating a monochromatic 0.59 $\mu$m (yellow light) source. Because of this monochromatic color, LPS lamps are used in applications where color rendition is not important. As with other arc discharge lamps, a ballast is required with LPS lamps to limit the arc current and supply the minimum open-circuit voltage required for starting the lamp. LPS lamps must also be operated in a specified orientation.

***Figure 3-6. Low pressure sodium lamps.***

### 3.1.5 *Light Emitting Diodes (LEDs)*

Commonly used as indicator lamps and in digital displays, light emitting diodes are becoming popular for internally-illuminated signs and even for some task lighting needs. While individual LEDs operate at low voltages and at low light output, arrays of LEDs can be wired in series and parallel to operate at 12 volts DC and produce reasonable light output for some low-illumination tasks. Although most LEDs in the past were red, green or other color, new generation ‘white light’ LEDs offer considerable promise. LEDs are a potentially attractive light source because they do not require a special ballast (they operate with DC power) and have projected lifetimes up to 100,000 hours.

## 4. Photometry and Basics of Lighting Design

Lighting system design involves consideration of many variables, including the *quantity* and *quality* of illumination required, the purpose or application, economic factors and other issues. *Photometry* refers to the data that quantifies the light output characteristics of a luminaire, and is essential information in lighting system design. Any lighting system design begins with the following steps:

- Defining the visual task
- Identifying the illuminance category
- Establishing illuminance and uniformity target values.

### 4.1 Quantity of Light

The most significant 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 long hours working with small parts such as electronics assembly require high illumination levels, while parking lots and storage yards require less illumination due to the nature of the anticipated activity. For signal lighting applications, the luminance (brightness) of the source is the quantitative measure of system performance. Table 3 gives recommended values of illumination for various activities. Table 4 lists representative levels of illumination from common sources such as daylight.

***Table 3. Recommended Illumination Levels***

| Area/Activity | Range of Illumination (fc) |
|---|---|
| **General** | |
| Classroom | 50 - 100 |
| Reading | 20 - 100 |
| Stairways | 20 - 10-20 |
| Wash rooms | 10 - 20 |
| Building exteriors | 1 - 5 |
| Residences | |
| *general* | 5 - 10 |
| *kitchen and bath* | 20 - 100 |
| **Assembly, inspection** | |
| *simple* | 20 - 50 |
| *difficult* | 100 - 200 |
| *exacting* | 500 - 1000 |
| **Recreation activities** | |
| *tennis* | 10 - 30 |
| *baseball* | 15 - 150 |
| *football* | 10 - 100 |
| *parks* | 2 - 20 |
| **Roadways** | 0.6 - 2 |
| *bus stops* | 2 - 10 |
| *billboards, signs* | 15 - 100 |
| *parking lots* | 0.5 - 4 |
| Storage yards | 0.2 - 20 |

*Table 4. Representative Levels of Illumination*

| Source | Footcandles |
|---|---|
| Starlight | 0.0002 |
| Moonlight | 0.02 |
| Street Lighting | 0.06-1.8 |
| Daylight | |
| *At North Window* | 50.200 |
| *In Shade (Outdoors)* | 100-1000 |
| *Direct Sunlight* | 5000-10000 |
| Office Lighting | 70-150 |

## 4.2 Qual*i*ty of Light

Adequate quantity of light does not necessarily ensure good illumination. Other factors such as glare, color and uniformity of distribution are some of the more important quality features. Maintaining adequate distributions is at least as important as illumination levels. Proper selection of lamp types and luminaires can generally achieve the quality requirements of most lighting installations. Light sources without good reflectors and diffusion generally exhibit poor light quality. Good quality illumination helps keep visual tasks easy to perform over prolonged periods.

## 4.3 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 any surface can be calculated from candlepower distribution data on the source given the luminaire geometry with respect to the surface. Where the inverse square law applies, the illumination at a given point 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 4-1 shows a typical candlepower distribution curve for a street lighting luminaire in the horizontal plane.

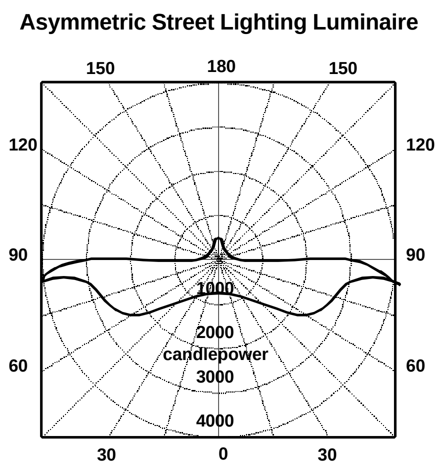


*Figure 4-1. Horizontal candlepower distribution*

## 4.3.1 *Iso-Footcandle Diagrams*

An *iso-footcandle or iso-lux diagram* is a quantitative measure of a lighting system design, produced from either measured data or calculations from system layout and candlepower distribution curves. These diagrams provide contours showing regions receiving the same amount of illumination on the working surface, as shown in Figure 4-2.

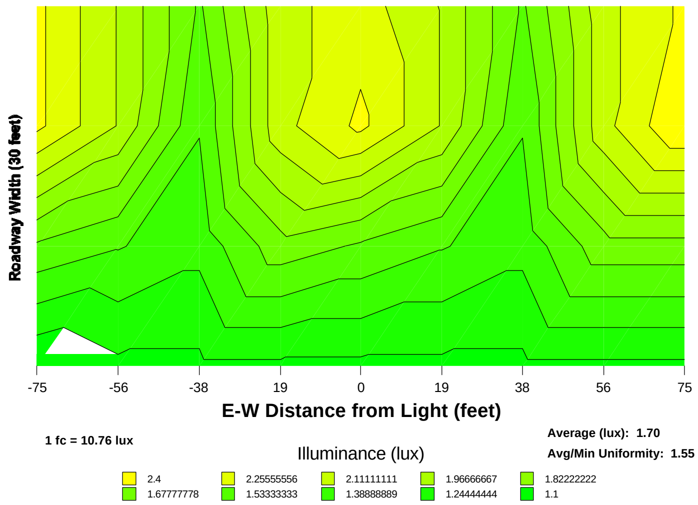


***Figure 4-2. Iso-footcandle diagram for roadway lighting application.***

Figure 4-3 shows a type of iso-footcandle diagram where 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.

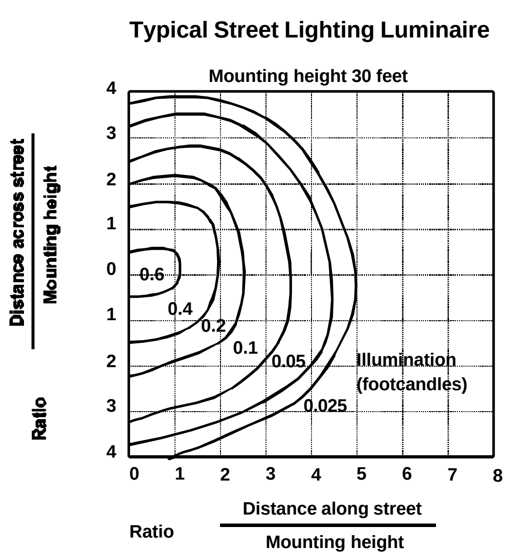


***Figure 4-3. Iso-footcandle diagram.***

## 4.4 Photometric Instruments and Measurements

### 4.4.1 *Illuminance Meter*

A basic photometric instrument, an illuminance meter utilizes a light-sensitive photovoltaic cell that produces a small current when illuminated. The current output can be calibrated to read directly in units of *foot-candles* 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. Figure 4-4 shows two typical illuminance meters.

***Figure 4-4. Illuminance meters.***

### 4.4.2 *Luminance Meter*

Luminance meters measure light reflected or emitted from a surface, in units of footlamberts or candelas per square meter. The instrument is aimed directly at the test surface, and a photoelectric tube produces a current that 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. Figure 4-5 shows a luminance meter.

***Figure 4-5. Luminance meter.***

# 5. 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
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eco@ecowise.com
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Precision Solar Controls
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Real Goods Trading Co.
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Ukiah, CA 95482-5576 USA
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http://www.realgoods.com/

Quasar Solar Electric Co.
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Siemens Solar Industries
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Work Area Protection Corp.
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