NLPIP Lighting Answers

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Photovoltaic Lighting

Table of Contents

What is photovoltaic (PV) lighting?

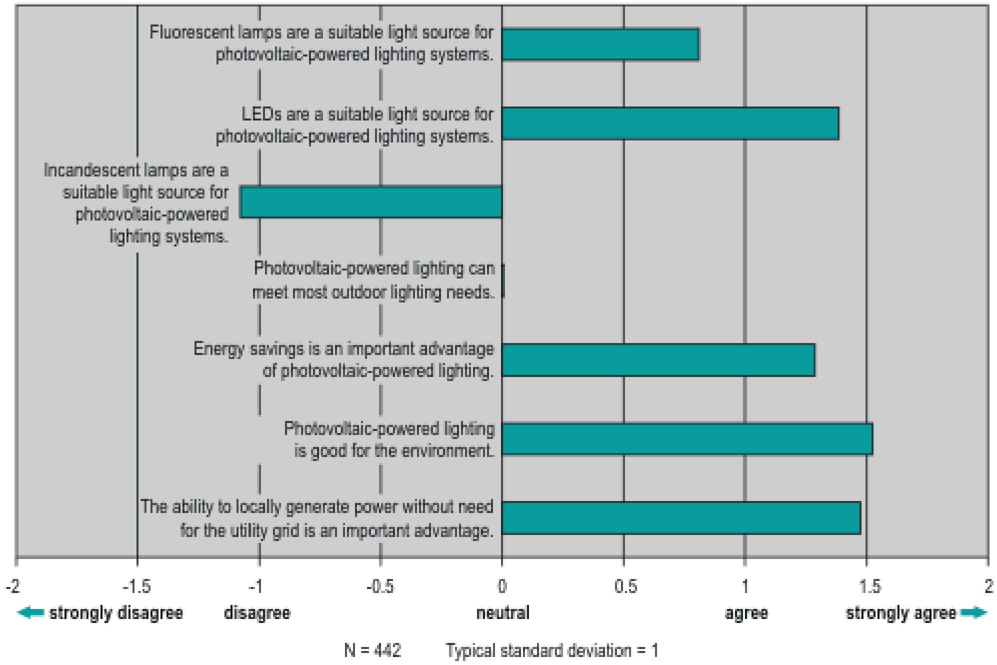
Photovoltaic (PV) lighting, or PV-powered lighting, is lighting that is at least partially powered by electricity generated from photovoltaic (PV) panels (often called solar panels). A popular example of PV lighting is the solar garden or pathway light. Other examples include post-top luminaires and parking lot luminaires carrying a solar panel on top. These PV lighting systems are usually off-grid, or "stand-alone" systems; their only power source is solar energy. Utility-connected and hybrid systems are more complicated because solar power is combined with other power sources such as a utility-generated grid, wind-powered generators, or fossil fuel-powered generators. This Lighting Answers considers only stand-alone/off-grid PV lighting technologies that are intended for nighttime lighting applications.

A PV lighting system collects solar energy using one or more PV panels, stores that energy in a battery or series of batteries, and then releases the energy to power light sources at night. Typically, PV lighting system components include PV panels, batteries, electronics (including battery charge controller, inverter or ballast/driver, and timer or switch), light sources (lamps), and luminaires. The initial purchase cost and maintenance cost for many of these components are high compared to traditional lighting systems powered by a grid. Designing and installing a PV lighting system are also more complicated than traditional grid-powered lighting systems. As a result, lighting applications suitable for PV lighting systems are currently somewhat limited. However, successful PV lighting applications can be developed through a carefully planned design process and educated choices between PV power and grid power. PV lighting applications are generally most successful where low light levels and limited electric power are acceptable and/or where access to a grid is expensive or difficult. Some examples of these types of applications are campgrounds, rural pathways, and parking lots in remote areas.

What are some common beliefs about PV lighting systems?

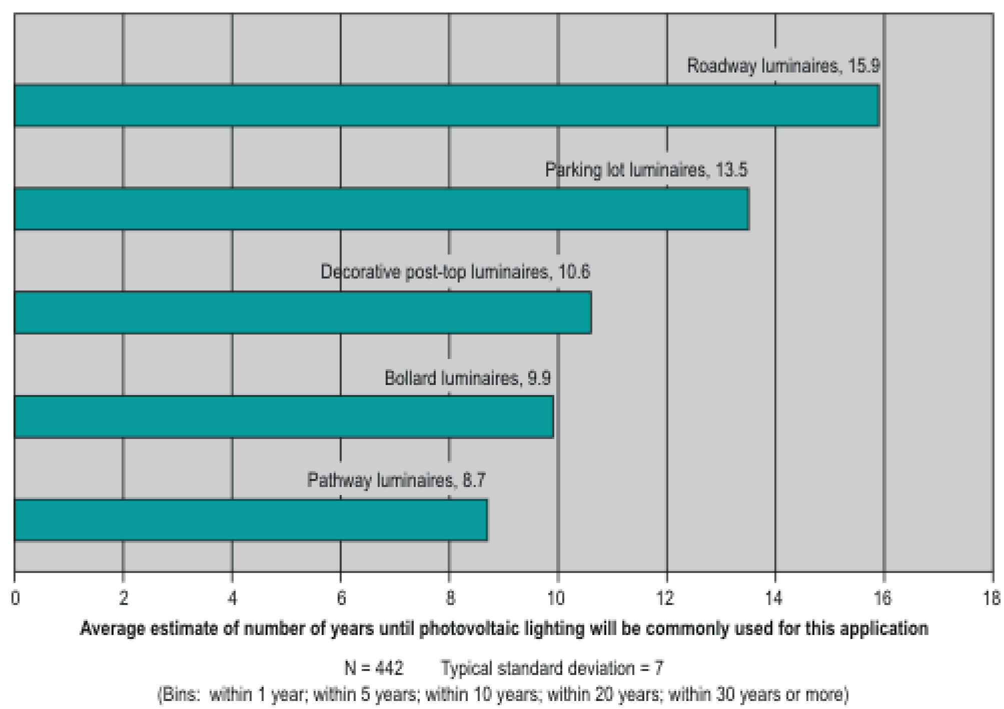
In 2005, NLPIP administered a survey to assess common beliefs among the public about photovoltaic (PV) lighting systems. The survey was sent via email to all subscribers of NLPIP Online. A total of 442 subscribers responded to the survey. These respondents felt that light-emitting diodes (LEDs) were the most suitable light sources for PV lighting applications, followed by fluorescent lamps. Incandescent lamps were not considered to be suitable for use in a PV lighting system. Respondents also selected three potential advantages of PV lighting systems: energy savings, environmental sustainability, and off-grid power generation. When asked if PV lighting systems could meet most outdoor lighting needs, the majority of survey participants responded neutrally, neither agreeing nor disagreeing with the statement. These results are shown in Figure 1.

Figure 1. Survey responses: beliefs about PV lighting systems



When asked to predict when PV lighting systems would be commonly used in various applications, survey respondents predicted that commonplace use is still a number of years away. They generally believed that PV lighting systems would first be commonly employed in applications such as pathway lighting, bollards, and decorative post-top **luminaires**, which generally use small, low-mounted luminaires, require low light levels, and use light sources with low power requirements. The use of PV lighting systems in applications such as parking lots and roadway lighting will be significantly farther into the future. Generally, survey respondents indicated that applications that use higher poles and greater illuminances (and therefore require more power) are less likely to be suitable for PV systems in the near term. These results are shown in Figure 2.

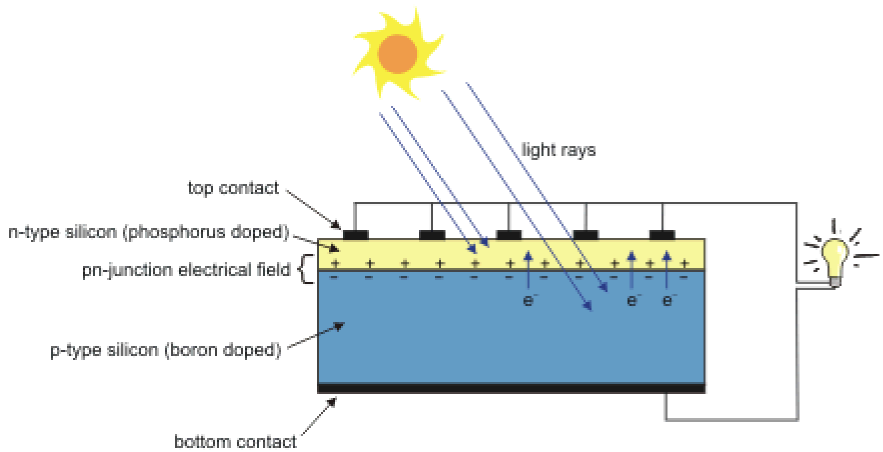
Figure 2. Survey responses: predictions of PV lighting acceptance for various applications



How do PV panels or PV cells work?

When light hits a surface, it may be reflected, transmitted, or absorbed. Absorption of light is simply the conversion of the energy contained in the incident **photon** to some other form of energy. Typically, this energy is in the form of heat; however, some absorbing materials such as **photovoltaic (PV)** cells convert the incident photons into electrical energy (Messenger and Ventre 2004). A PV panel has one or more PV modules, which consist of connected PV cells. Figure 3 shows the schematic structure and operation of a PV cell.

Figure 3. PV cell structure and operation schematic



Typically, a silicon PV cell contains two layers. The top layer consists of a thin sheet of phosphorus-doped (negatively charged or n-type) silicon. Underneath this sheet is a thicker layer of boron-doped (positively charged or p-type) silicon. A unique characteristic of these two layers is that a positive-negative **(pn) junction** is created when these two materials are in contact. A pn junction is actually an electric field that is capable of creating an electrical potential when sunlight shines on the PV cell. When sunlight hits the PV cell, some of the electrons in the p-type silicon layer will be stimulated to move across the pn junction to the n-type silicon layer, causing the p-type layer to have a higher voltage potential than the n-type layer. This creates an electric current flow when the PV cell is connected to a load. The voltage potential created by a typical silicon PV cell is about 0.5 to 0.6 volts dc under open-circuit, no-load conditions. The power of a PV cell depends on the intensity of the solar radiation, the surface area of the PV cell, and its overall efficiency (FSEC 2005).

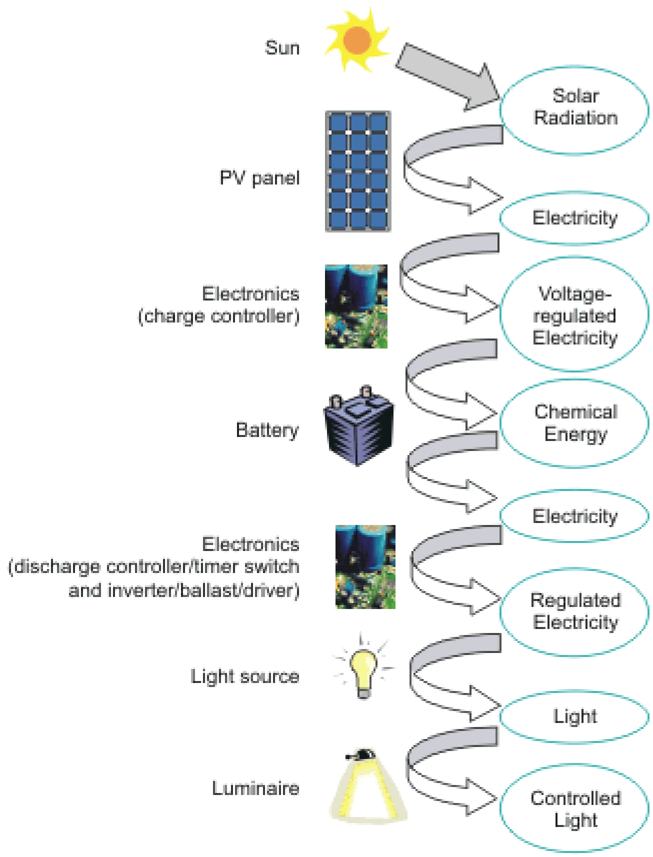
The efficiency of each individual PV cell directly determines the efficiency of the PV panel. PV cells can be categorized into different types according to their component materials and structural features. Efficiency of commercially available PV panels is typically 7-17% (Green et al. 2005).

How do PV lighting systems work?

In a **photovoltaic (PV)** lighting system, solar radiation replaces the burning of fossil fuels such as coal or natural gas or the harnessing of water power to generate the electricity necessary to power the lighting. A PV lighting system consists of a PV panel, battery, electronic circuits, light source (**lamp**), and **luminaire** (optics). Figure 4 illustrates the components in a typical PV lighting system.

PV panels transform solar energy into electrical energy. A PV panel is made up of many PV cells, which are created by semiconductor positive-negative **(pn) junctions** (see "How do PV panels or PV cells work?").

Figure 4. PV lighting system components and energy flow diagram



The electrical energy created by the PV cells can energize light sources (lamps) directly or be stored in a battery for later use. The dc current generated by the PV cell or the battery can be regulated and stabilized using an electronic circuit to energize dc light sources like incandescent, **light-emitting diodes (LED)**, or **fluorescent lamps** operated on dc **ballasts**; or they can be converted into 120 volts, 60 hertz ac to energize ac light sources such as fluorescent lamps operated on ac ballasts. Ac ballasts are more commonly available.

Electronic components, including charge controllers, timer switches, and ballasts for fluorescent lighting (or **drivers** for LEDs or **inverters** for ac lamps) provide regulation and control to the electric energy. The light source provides the light, and the luminaire that houses these components provides protection for the elements and optics to direct the light.

The light output of a PV lighting system depends on the amount of solar energy received and the efficiency or **efficacy** of its components, including the PV panel, battery, electronics, light source, and luminaire.

What kinds of batteries are used in PV lighting systems?

A battery is a device that converts chemical energy contained in its active materials directly into electrical energy by means of an electrochemical reaction. Batteries used in **photovoltaic (PV)** lighting systems must be rechargeable. Lead-acid batteries are the most common type of batteries used in PV systems, due to their wide availability in many sizes, their low cost, and their well understood performance characteristics. Lead-acid batteries are also commonly recycled. The most common types of lead-acid batteries used in PV systems are lead-antimony batteries, lead-calcium batteries, lead-antimony/lead-calcium hybrid batteries, and captive electrolyte lead-acid batteries, which include gelled batteries and absorbed glass mat (AGM) batteries (Dunlop 1997). Nickel-cadmium cells are used in some applications, but their high initial cost limits their use.

Batteries are the costliest and weakest components in stand-alone PV systems, if battery replacement is considered (Diaz and Lorenzo 2001; Diaz and Egido 2003). Battery capacity degrades over time, so batteries must be replaced at regular intervals. Providing an estimate for a "typical" battery life is difficult because of many factors, including battery type, correct sizing of the PV system, local climate, and proper operational management such as charge controllers and maintenance procedures. Generally, PV lighting systems store solar energy in the batteries during the day and release that energy as lighting at night. This is known as the battery's cycle (i.e., one charge and one discharge period). Batteries are sometimes specified in terms of cycle life. The cycle life of a battery denotes the number of cycles it is expected to last before being reduced to 80% of its rated capacity. Replacement should be considered when a battery reaches this point.

When selecting or specifying a PV lighting system, it is important to check that the battery capacity is sufficient to provide the energy needed to power the lighting system for the required amount of time. A battery's capacity is a measure of the amount of energy that a battery can store. This capacity is measured in ampere hours and indicates the amount of energy that can be drawn from the battery before it is completely discharged. A battery rated at 100 ampere hours, for example, should ideally provide a current of one ampere for 100 hours, or two amperes for 50 hours (or any combination of amperes and hours that give a product of 100).

The optimal type of battery for a PV lighting system is a deep-cycle (or deep discharge) battery that can be repeatedly drained of much of its energy and recharged (EREC 2001). The maximum depth of discharge for low-maintenance (sealed) batteries is 30% (Diaz and Egido 2003). The maximum depth of discharge of a battery is a measure (in percentage) of the amount of energy that can be removed from the battery during a cycle, without damaging the battery. Batteries should generally be located in a weather resistant, nonmetallic enclosure in order to prevent corrosion (Sandia National Laboratories 1995). Batteries should be maintained according to manufacturers' instructions, and it is important to keep them clean to ensure maximum performance over time.

What are the electronic components in a PV lighting system?

Electronic components for a **photovoltaic (PV)** lighting system typically include a battery charge controller, a timer switch, and/or an **inverter** or **ballast**/**driver**, depending on the size of the system and the type of light source used. For example, a solar garden light that uses **light-emitting diodes (LED)** of less than one watt may have the electronics on one circuit board; for larger systems, such as solar parking lot **luminaires**, the electronic components are most likely separated.

The primary function of charge controllers in a stand-alone PV system is to maintain the battery at the highest possible state of charge while protecting it from overcharge by the PV panels and from over-discharge by the loads (Dunlop 1997). The set points of a charge controller determine its operation. Charge controllers regulate a PV system using different methods. Each method has different performance characteristics and applicability.

Timer switches control when the light source should be turned on. This function is usually achieved by a timing device, a photocell, or the PV cell itself.

Light sources used in PV lighting systems typically require ballasts or drivers. PV lighting systems using ac light sources such as **fluorescent** or **high intensity discharge (HID)** lamps operated with ac ballasts require inverters. Inverters convert dc current into ac current; when used in stand-alone PV systems, inverters typically operate at 12, 24, 48, or 120 volts dc input and create 120 or 240 volts ac output at 50 or 60 hertz (Hz) (Sandia National Laboratories 1995).

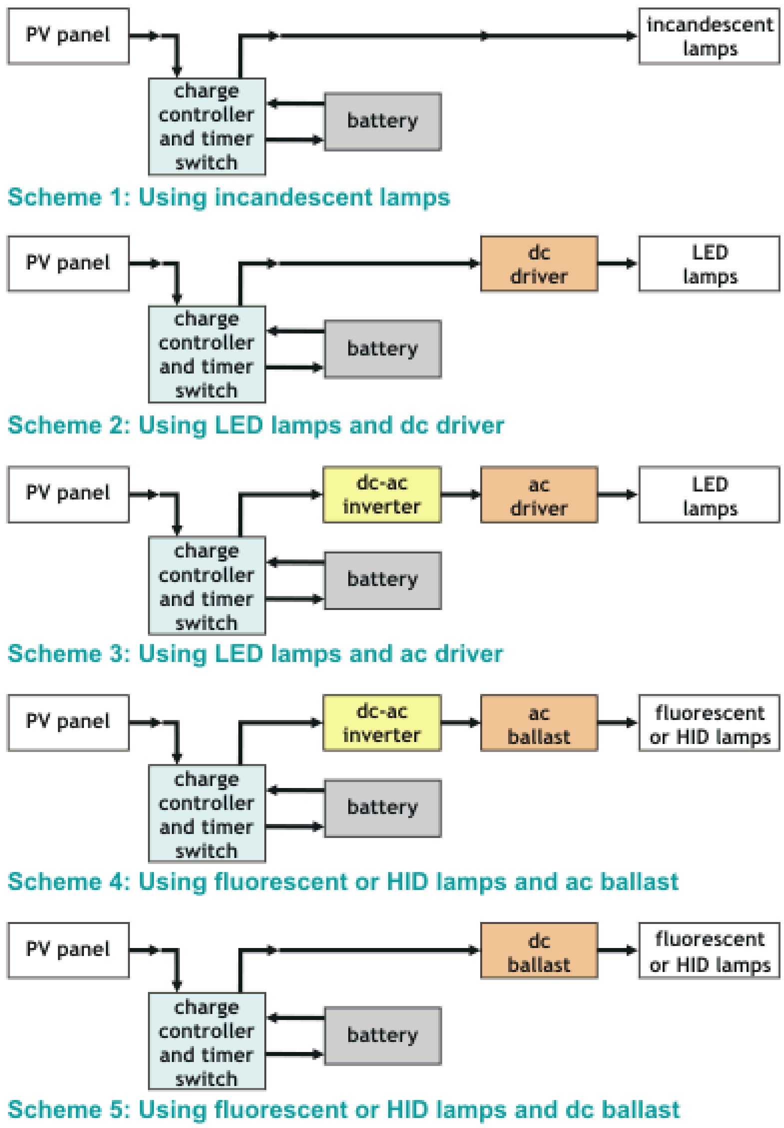
Most ac ballasts for fluorescent and HID lamps take 120 volts, 60 Hz ac as input, and some dc ballasts take low-voltage (12, 24, or 48 volts) dc as input. It should be noted that: ac ballasts convert 120 volts, 60 Hz ac to high-voltage high-frequency (> 20 kHz) ac, and dc ballasts convert dc to high-voltage, high-frequency ac directly.

While fluorescent and HID lamps require ballasts, LEDs require drivers. Both ac and dc drivers are available for LEDs. Ac drivers take 120 volts, 60 Hz ac as input, and are commonly used in LED lighting applications with ac grid power. Dc drivers take low-voltage dc as input and are typically used in PV lighting applications. Both ac and dc drivers maintain an appropriate, stable voltage to operate LEDs.

What kinds of light sources are used in PV lighting?

Light sources used in **photovoltaic (PV)** lighting systems can be divided into ac light sources and dc light sources. **Fluorescent** and **high intensity discharge (HID)** lamps are ac light sources; **light-emitting diodes (LED)** and incandescent (including **halogen** incandescent) lamps can be dc light sources. Configurations of the electronics in PV lighting systems differ for different light sources, as shown in Figure 5.

Figure 5. Configurations of PV lighting systems with different light sources



What factors should be considered when selecting a luminaire for PV lighting?

Luminaires for **photovoltaic (PV)** lighting systems are similar to those for other lighting systems; however, more components generally need to be included with PV-powered luminaires than with traditional **grid**-powered luminaires. The main functions of a luminaire for a PV lighting system are to:

- House some or all of the system components, i.e., PV panels, batteries, electronics, and light source
- Control the light output from the light source so it is directed where it is needed to light a particular area effectively

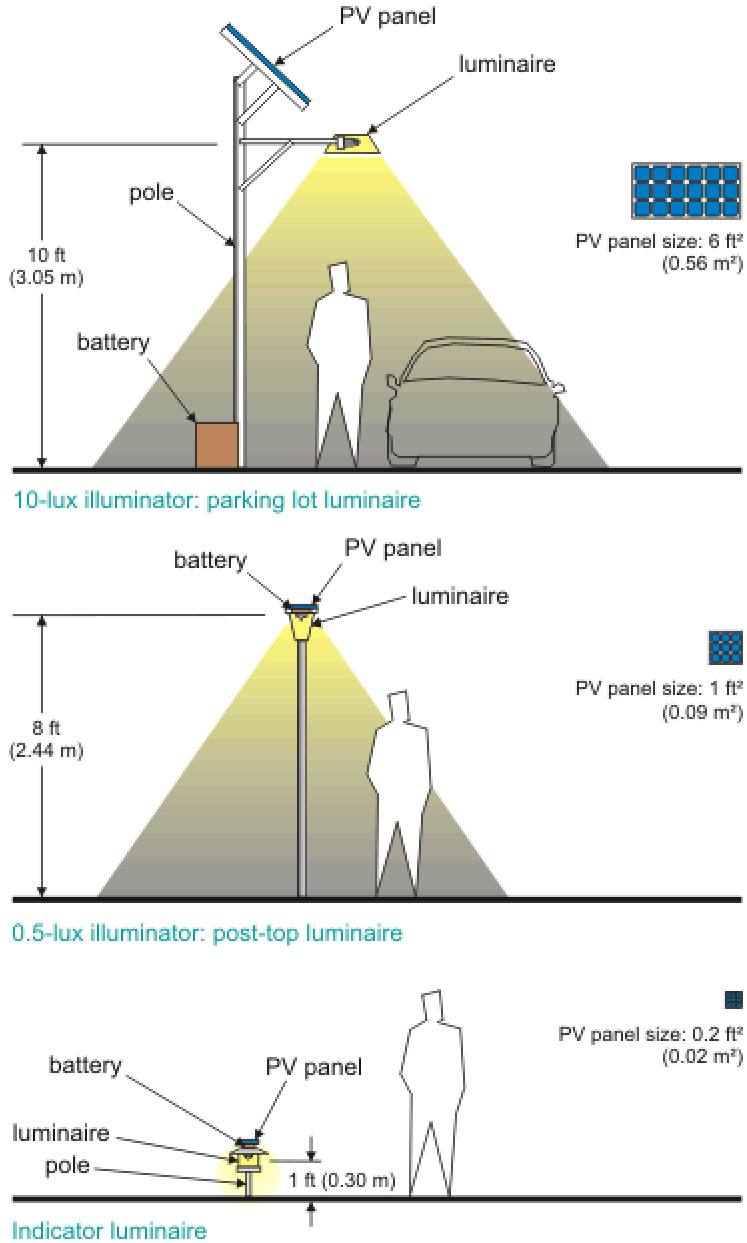
Light output control is generally a function of the luminaire's optical components (i.e., reflector and lens). These components typically are the same for PV-powered luminaires as for grid-powered luminaires. The optical efficiency of a luminaire determines what portion of the light output from the light source can be delivered out of the luminaire. The higher the optical efficiency, the better; however, issues such as **glare**, light distribution, and **illuminance** uniformity must also be considered.

A major difference between PV-powered and grid-powered luminaires is the need to house additional components within or adjacent to PV-powered luminaires. Some of these components, such as PV panels and batteries, can be relatively large. In small PV-powered luminaires such as garden path lights, these components are generally incorporated directly into the luminaire itself. In larger luminaires such as parking lot and roadway luminaires, various components are generally attached to the pole or other structure that supports the luminaire.

The illustrations in Figure 6 represent the approximate size of PV lighting systems required to provide two different light levels on the ground beneath a pole-mounted luminaire: 10 **lux** or 100 moonlights and 0.5 lux (5 moonlights). This assumes a luminaire that has a single light source and an optical efficiency of 50%, which uniformly distributes all light output on a circular area with a radius equal to the pole height.

A system able to provide sufficient **luminance** to act as an indicator light, such as garden pathway luminaire, is also illustrated. Figure 6 provides a means to compare the relative size of the PV panel, mounting structure, and battery necessary for each of the three systems.

Figure 6. Illustration of three PV lighting systems



As seen in Figure 6, the PV panels required to power larger scale luminaires designed to provide 10 lux (100 moonlights) or more on the ground tend to be relatively large in comparison to the luminaire itself. This may present some aesthetic concerns, especially in applications where decorative luminaires are used or in historic areas, where the public expects luminaires with a traditional style. The mounting pole for larger scale PV lighting systems typically will need to be stronger to support the PV panel and handle the wind load on the system. Finally, a weather-tight compartment of some type will be needed to house the battery required by the system. All of these components add to the cost of the lighting system.

In comparison, the smaller-scale post-top luminaire designed to provide 0.5 lux (5 moonlights) on the ground is much more compact, and both the PV panel and battery are small enough to be incorporated directly into the design of the luminaire itself. Because of the small size of this luminaire, the mounting pole can also be smaller.

When low light levels such as 0.5 lux (5 moonlights) are considered, only **light-emitting diodes (LED)** and incandescent **lamps** are available in lumen packages small enough to provide these levels effectively. It is interesting to note that while respondents on the survey conducted by NLPIP felt that LEDs were suitable light sources for PV lighting systems, they did not consider incandescent lamps to be suitable (see "What are some common beliefs about PV lighting systems?"). This holds true in applications requiring high light-levels and/or using high-mounted luminaires because a large PV panel would be needed to meet the power requirements of the light sources, which would be expensive and cumbersome. However, in situations using lower mounting heights (8 ft [2.4 m] or less), where less than five moonlights are required, incandescent lamps become a viable option because they can provide the suitable lumen package to meet the required light levels at low mounting heights. However, LEDs are able to provide moonlight levels most efficiently over the widest range of mounting heights. This is because the light output provided by each individual LED light source can be very small, and can be easily adjusted by adding additional LEDs to a luminaire design to increase the light output when needed.

A final consideration when selecting a luminaire for a PV lighting system is electrical safety. This is similar to a grid-powered luminaire, and care should be taken that the luminaire and other PV lighting system components meet all applicable safety codes and standards.

What are some important considerations in choosing PV lighting?

Amount of solar irradiance

Solar **irradiance** for **photovoltaic (PV)** power is affected by location, weather, time of year, and surrounding structures. The solar radiation received by the earth's atmosphere is 1367 watts per square meter (Messenger and Ventre 2004), but this amount is reduced when the solar radiation passes through the air mass. Solar radiation is the radiant energy emitted by the sun. The term "solar irradiance" refers to the amount of radiant flux incident on any surface, including buildings. The solar irradiance is lower at sea level, for example, than it is on a mountain top. It is also generally true that the farther away a location is from the equator, the lower the solar irradiance will be available at ground level. In summer, solar irradiance is available longer than in winter. Weather also affects the amount of solar irradiance. Cloud cover, for example, will reduce solar irradiance. Finally, solar irradiance may be blocked by buildings, trees, or snow and dirt on the PV panels (see "How does solar radiation vary by location?").

Aesthetic and structural concerns

Some of the components in PV lighting systems, such as the PV panels, tend to be large and awkward. Structural support and wind load should be considered to ensure that the PV panel does not pose a safety hazard to people. A smaller PV panel may reduce both aesthetic and structural concerns but will limit the power capacity of the PV panel.

Cost vs. performance

Cost is an important factor in any investment. From the end-user's point of view, PV lighting systems include more components and therefore are more expensive to purchase than traditional, **grid**-powered lighting systems. However, in areas where electricity from the grid is not accessible, extending the power lines is often prohibitively expensive. For example, it would be economically ineffective to extend a power line to a remote mountain area only for powering **luminaires** at a campground's parking lot. In these types of remote locations PV power may be a good alternative for providing lighting at night.

The performance of a PV lighting system is related to the quality of its components. Generally, the higher the quality, the more expensive the system. Technologies associated with PV lighting are not fully mature (at time of publication), and some components may not be reliable even if they are expensive. These costs and risks have often pushed PV lighting out of consideration for use in a wide variety of lighting applications. However, the increasing desire for energy independence and the rising cost of energy may change this situation in the future. By carefully matching PV lighting to appropriate **applications**, PV lighting may find its way to more lighting markets and thereby reduce both the costs and risks associated with these systems (see "How does the cost of PV lighting systems compare to grid-powered lighting systems?").

How does the cost of PV lighting systems compare to grid-powered lighting systems?

The best analysis of the cost of owning a **photovoltaic (PV)** lighting system compared to a **grid**-powered lighting system can be made through a life cycle cost (LCC) analysis. LCC analysis is an evaluation method that takes into account all of the costs of owning a product or system over a period of time (normally over its lifetime). LCC analysis includes the time value of money and calculates the present value (or present worth) of all costs expected to occur.

The costs of owning a lighting system include acquisition or capital costs (C), maintenance costs (M), energy costs (E), and replacement costs (R). This is expressed as a formula:

$$LCC = C + M_{pw} + E_{pw} + R_{pw}$$

where the "pw" subscript refers to the present worth of each cost.

(Sandia National Laboratories 2002; Messenger and Ventre 2004)

When comparing PV lighting systems to grid-powered lighting systems in applications where the electric grid is readily accessible, where the lighting must operate reliably throughout the night at all times of year, and where relatively high nighttime light levels are required (e.g., 1 **lux** or greater), it is generally difficult to justify the higher life cycle cost of the PV lighting system. This is primarily because the higher capital cost of the PV system cannot be offset by the energy cost savings attained by the system.

Both a PV lighting system and a grid-powered lighting system will require a **luminaire**, a pole or other mounting system, and a **lamp**. It is difficult to make a simple comparison of these particular costs because in some cases, they may be the same for each system and in other situations, the costs may differ. For example, in the case of a large PV lighting system, the pole and foundation may need to be significantly stronger to handle the weight and wind load on the PV panel. This will add to the system's cost. However, the cost comparison shown in Table 1 considers these particular costs to be the same for each system.

In addition to a pole, luminaire, and lamp a PV lighting system will also require the purchase and installation of a PV panel, a battery (which generally must be replaced every five years), and other electronic equipment such as a controller. The grid-powered lighting system will require wiring to connect the system to the grid. The maintenance costs of the PV lighting system will also generally be higher because of battery replacement labor, and because the PV panel is an extra surface that needs cleaning. A comparison of the life cycle costs for a 10 lux (100 moonlights) illuminator (a parking lot luminaire designed to provide approximately 10 lux on the pavement) over a period of 10 years is summarized in Table 1 below. This comparison assumes a luminaire that has a single light source and an optical efficiency of 50%, which uniformly distributes all light output on a circular area with a radius equal to the pole height.

Table 1 summarizes a 10-year life cycle cost comparison of one PV-powered luminaire and one grid-powered luminaire located 50 ft (15.2 m) from an electric grid connection. The luminaire in this example uses an 11-watt compact fluorescent lamp (CFL), operating eight-hours per night. A more detailed analysis can be found in the Case Study: Life Cycle Cost.

Table 1. 10-year life cycle cost comparison of luminaires
(located 50 ft [15.2 m] from grid)

System Type	Illuminance	LCC	Capital Costs	Maintenance $Costs_{pw}$	Energy $Costs_{pw}$	Replacement $Costs_{pw}$
PV–powered	10 lux	$1303	$710	$479	$0	$114
Grid–powered	10 lux	$1252*	$1010*	$192	$31	$19

* Includes cost of power line extension

In the example above, the luminaire was located close to the electric grid. However, if the lighting **application** were in a remote area that required extending the electric grid for one mile (1.6 km) or more, the life cycle costs of the grid-powered lighting system would increase dramatically. The cost of extending the power grid is estimated to be $30,000 per mile (EERE 2005). A comparison of the life cycle costs for a parking lot lighting system located one mile (1.6 km) off-grid, using 10 luminaires that contain a 11-watt CFL in each, and owned over a period of 10 years is summarized below. A more detailed analysis can be found in the Case Study: Life Cycle Cost.

Table 2 summarizes the life cycle cost comparison of a PV-powered lighting system containing 10 luminaires and a grid-powered lighting system containing 10 luminaires located one mile (1.6 km) from an electric grid connection.

Table 2. Life cycle cost comparison of lighting systems with 10 luminaires
(located one mile [1.6 km] from grid)

System Type	Illuminance	LCC	Capital Costs	Maintenance $Costs_{pw}$	Energy $Costs_{pw}$	Replacement $Costs_{pw}$
PV–powered	10 lux	$13,033	$7100	$4789	$0	$1144
Grid–powered	10 lux	$34,571*	$32,100*	$1916	$364	$192

* Includes cost of power line extension

In Tables 1 and 2, the lighting systems were designed to provide about 10 lux (100 moonlights) on the ground and were operated eight hours per night, on average. The power requirements per luminaire were relatively modest, at 13 watts including lamp and ballast. Any changes in system requirements will also change the economic comparison between the PV and grid-powered lighting options. For example, if the application parameters were changed to require that the lighting systems provide higher light levels over a wider area, for a longer period of time, the grid-powered lighting system may become a more attractive option due to its ability to power higher wattage light sources. The costs of the PV lighting system, on the other hand, may rise substantially due to the need for larger PV panels and increased battery capacity. The capital costs associated with PV lighting systems are the most likely costs to push these systems out of consideration when application requirements (e.g., high light levels and long operating times) begin to stretch a PV system's capacity to meet these requirements economically. Conversely, higher expenses for extending the grid such as for easements, difficulty terrain, or repaving, will favor PV systems.

In some areas of the United States, subsidies may be available to help offset the cost of the purchase and installation of PV lighting systems. These subsidies will often help to bring down the initial costs of a PV lighting system, making it a more attractive option for end users. A system specifier or end user will want to consider all of the parameters discussed above when performing an economic comparison of lighting system options.

Because light level requirements will affect the overall costs of both PV-powered and grid-powered lighting systems, a life cycle cost analysis was performed for a 0.5 lux (5 moonlights) illuminator (a post-top luminaire designed to provide approximately 0.5 lux on the ground) using a one-watt white **light-emitting diode (LED)** as the light source. For this example the use of a one-watt LED is based on the assumption that the luminous efficacy of this white LED is 25 lumens per watt (LPW). However, with the rapidly improving efficacy of LEDs, the wattage of the LED lamp can be lowered significantly in the near future. For example, with today's premium LED products at 40 lumens per watt, only a 0.6-watt LED would be needed to provide this light level.

Table 3 summarizes the life cycle cost comparison of one PV-powered luminaire and one grid-powered luminaire located 50 ft (15.2 m) from an electric grid connection. This comparison assumes a luminaire that has a single light source and an optical efficiency of 50%, which uniformly distributes all light output on a circular area with a radius equal to the pole height.

Table 3. Life cycle cost comparison of luminaire
(located 50 ft [15.2 m] from grid)

System Type	Illuminance	LCC	Capital Costs	Maintenance Costs_{pw}	Energy Costs_{pw}	Replacement Costs_{pw}
PV–powered	0.5 lux	$414	$155	$239	$0	$19
Grid–powered	0.5 lux	$995*	$895*	$96	$4	$0

* Includes cost of power line extension

In this example, the life cycle costs of the PV lighting system are less than that of the grid-powered system. This is due to the added costs of extending the power line from the grid as well as a substantial decrease in the capital cost associated with the PV lighting system. The lower light level requirements allowed these costs to be reduced significantly because smaller system components (e.g., PV panel, battery) could be used. Table 4 summarizes the life cycle cost comparison of a PV-powered lighting system providing approximately 0.5 lux (5 moonlights) on the ground containing 10 luminaires and a grid-powered lighting system containing 10 luminaires located one mile (1.6 km) from an electric grid connection.

Table 4. Life cycle cost comparison of lighting systems with 10 luminaires
(located one mile [1.6 km] from grid)

System Type	Illuminance	LCC	Capital Costs	Maintenance Costs_{pw}	Energy Costs_{pw}	Replacement Costs_{pw}
PV–powered	0.5 lux	$4,135	$1,550	$2,395	$0	$191
Grid–powered	0.5 lux	$31,950*	$30,950*	$958	$42	$0

* Includes cost of power line extension

The cost of the PV lighting system in this example is significantly lower because it avoids the costs associated with extending the power grid one mile (1.6 km). However, the lower light level requirements have also reduced the costs of the PV lighting system by over $8,800 compared to the previous 10-lux (100 moonlights) system. In contrast, the costs of the grid-powered lighting system were reduced by just over $2,600 due to the lower light level requirements.

What are the most suitable applications for photovoltaic lighting?

In remote locations such as mountain areas, nature preserves, national and state parks, or rural villages and towns, where the electric **grid** is far away, providing lighting at night is usually difficult. Under very dark visual conditions found in remote areas, moonlight, or even star light, often provides enough lighting for people's basic needs such as walking or finding a house or car. In many pathway lighting **applications**, for example, the lighting system needs only to provide enough light to strike the surface of the path at very low levels. Similar light levels are appropriate for a garden or residential landscape. The same can be true for a parking lot in a remote area. Because car headlights will generally provide enough light for a driver to navigate the parking lot safely, fixed luminaires need only provide sufficient light levels to reduce the risk of tripping for pedestrians as they locate and walk to and from their cars. In these types of applications, moonlight illuminance can be used as a reference value for setting expectation of suitable light levels in remote locations.

Based on the average **luminance** (2500 candelas/square meter) and diameter of the moon (347,900 meters), and the distance between the moon and the earth (384,385,000 meters), the **illuminance** on the ground on a full moon night with clear sky condition is approximately 0.1 **lux**. Because this prediction is based on an average moon luminance, actual illuminance from moonlight will vary based on lunar phase, atmospheric conditions, time of year, and other variables. Empirically, the earth's surface **illumination** from moonlight can vary from 0.005 to 0.5 lux (Courter 2003; Krisciunas and Schaefer 1991). For convenience, the illuminance level of 0.1 lux can be defined as one unit of "moonlight." Although this light level may seem low, an average illuminance of between 0.1 and 0.5 lux is sufficient to read a newspaper. While higher nighttime light levels may be desirable in heavily trafficked or hazardous areas, a wide range of lighting applications can be lighted safely to less than 0.5 lux, including residential areas, gardens, parks, and landscapes where people may walk at night, provided, people are able to see the path and any hazards that might be on the ground.

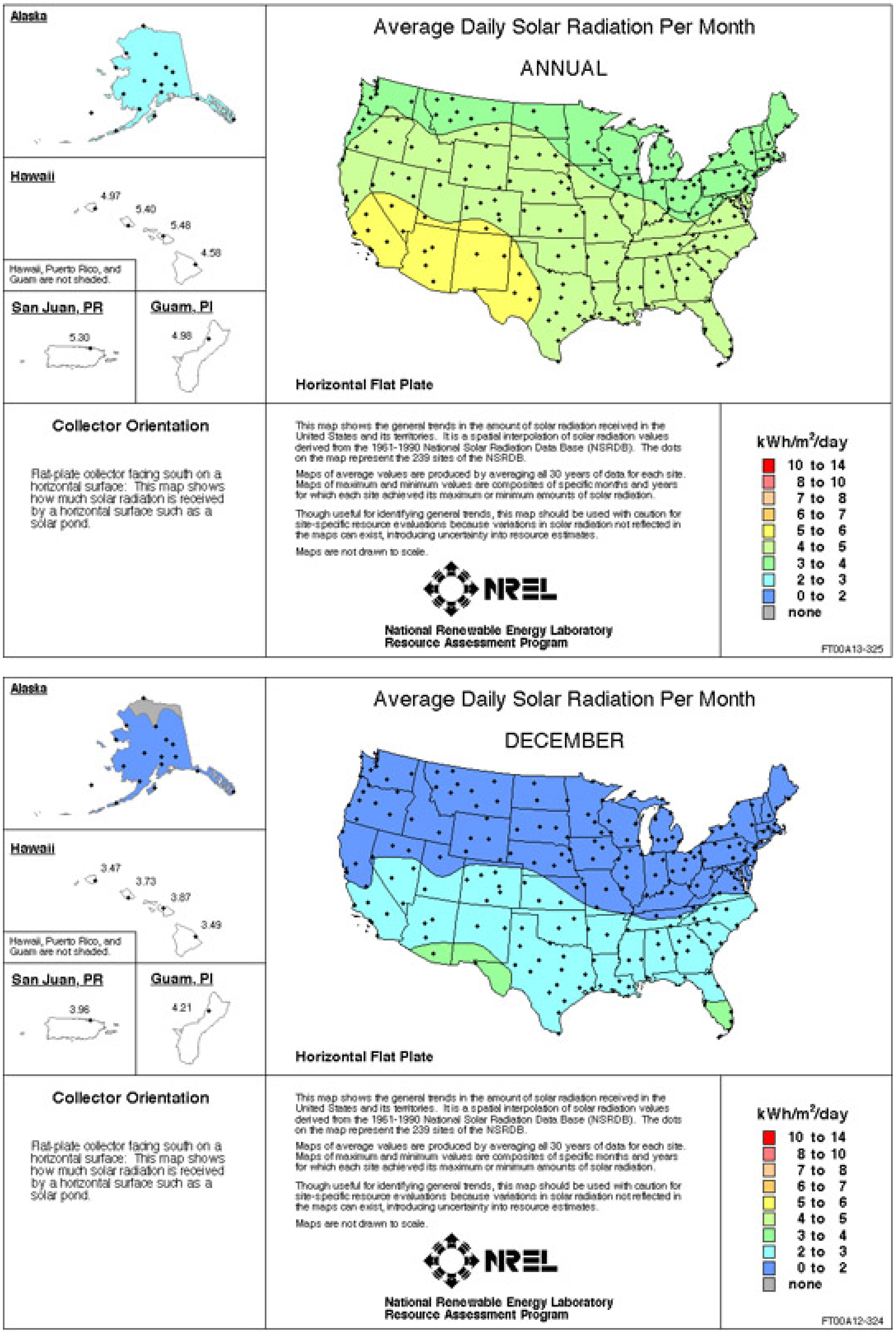
In campgrounds, as well as state and national parks that people use at night, it is often desirable to maintain low levels to allow people to see the stars while providing lighting where needed for navigation, direction, and safe passage. Dock and waterfront areas along oceans, lakes, and rivers can also be lighted effectively at low levels, if these areas are used only intermittently at night and are not heavily trafficked.

Lighting applications requiring "moonlight" levels are generally well suited for **photovoltaic (PV)** lighting systems. In these situations, only a small quantity of dc power needs to be stored in a battery to provide a low level of light over a limited period of the night. This allows PV panels to be smaller in size, less expensive, and more easily integrated into the design of a luminaire. This also allows batteries to be smaller and less expensive.

How does solar radiation vary by location?

The amount of solar radiation is affected by the geographic location, the season, and the climate conditions of the location. For example, the amount of available solar radiation in Phoenix, Arizona is greater than that in New York City. If we install two lighting systems located in these two cities with the same components, the system in New York City will require a larger solar panel to power the system reliably. The National Renewable Energy Laboratory (NREL) has detailed statistical information about the amount of solar radiation at different locations across the U.S. Figure 7 shows two examples of NREL solar radiation data. The first example shows the average daily amount of solar radiation on horizontal flat panels on an annual average. The second example shows the same information for the month of December only.

Figure 7. Examples of NREL solar radiation data



Source: National Renewable Energy Laboratory (NREL) Resource Assessment Program

NREL also provides data on daily total solar radiation for different months in various US cities. Using these data, NLPIP performed a comparison of the relative size of **photovoltaic (PV)** panels needed for different PV lighting systems in different months of a year for various US cities. The results of this evaluation are shown in Figure 8. These comparisons provide two examples of PV lighting systems. The first system is a parking lot **luminaire** mounted at a height of 10 ft (3.0 m) that will provide approximately 10 **lux** or 100 moonlights **illuminance** on the ground; the second is a post-top luminaire mounted at 8 ft (2.4 m) that will provide about 0.5-lux (5 moonlights) illuminance. The comparisons assume a luminaire that has a single light source and an optical efficiency of 50%, which uniformly distributes all light output on a circular area with a radius equal to the pole height.

The assumptions for both of these PV lighting systems are:

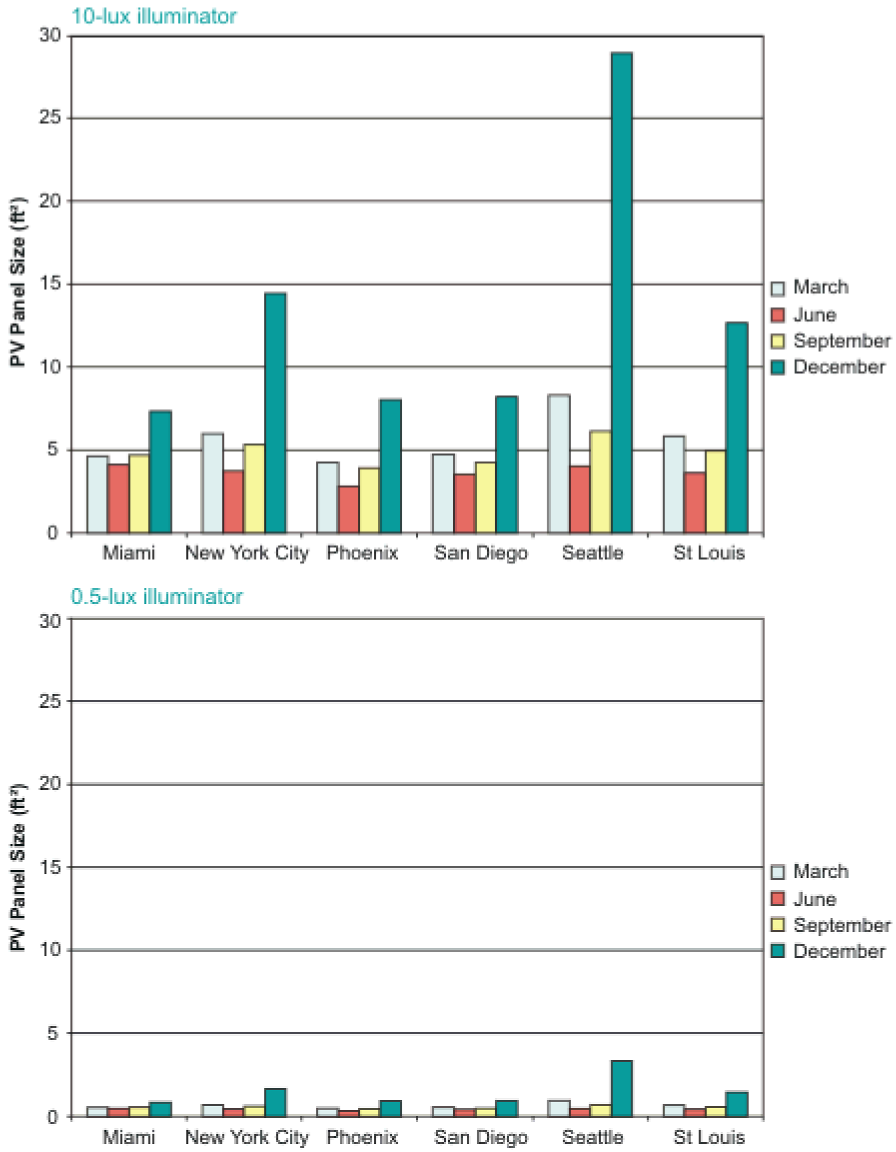
- The lighting will be turned on for 8 hours of operation at night, per day.
- PV panel conversion efficiency is 10%.
- A fixed-direction horizontal (facing up) flat PV panel is used.
- Electronics efficiency (including charge controller and dc **ballast** for the **compact fluorescent lamp [CFL]** or dc **driver** for the **light-emitting diode [LED]**) is 80%.
- The battery is sufficiently sized and has a battery charge/discharge efficiency, including conduit loss, of 60%.
- The light source efficacy is 65 **lumens** per watt (LPW) for the CFL and 25 LPW for the LED.

The parking lot luminaire uses an 11-watt CFL powered by a dc ballast, with a total system wattage of 13 watts. The post-top luminaire uses a 1-watt white LED powered by an LED driver, with a total system wattage of 1.5 watts.

The numbers quoted above are typical values for PV-powered luminaires. They assume that the battery capacity of the system is large enough to allow necessary discharge for powering the lamp. Rural roads and parking lots are often unpaved and create a lot of dust, which can block solar irradiance. In northern locations, snow may cover PV panels, blocking much of the solar **irradiance**. For the purposes of this example, the PV panel was assumed to be cleaned regularly and therefore free of dust and snow, so its conversion efficiency remains stable throughout the year. These two systems were selected for comparison to illustrate the difference in the size requirements for PV systems designed for two different types of lighting applications. The parking lot luminaire, designed to provide 10 lux (100 moonlights) on the ground, uses a CFL because this is the most efficient source currently available that can provide this light level at the selected mounting height of 10 ft. (3.0 m). 10 lux (100 moonlights) is similar to light levels found in many parking areas that are not heavily trafficked at night.

The post-top luminaire is designed to provide a much lower light level, 0.5 lux (5 moonlights), at a mounting height of only 8 ft (2.4 m). This luminaire uses an LED because it is the most efficient source capable of providing this light level. CFLs, for example, are not available in lumen packages small enough to provide a light level this low at this mounting height. This post-top luminaire would be appropriate for pathways and other types of lighting applications in rural or remote areas where the surrounding nighttime conditions are very dark.

Figure 8. PV panel size requirements in different months for different US cities



($ft^2 = 0.09\ m^2$)

As seen in Figure 8, the luminaire providing 10 lux (100 moonlights) on the ground needs a much larger PV panel than that needed by the luminaire providing 0.5 lux (5 moonlights). All locations need larger PV panels in December than they do in June because daylight hours are shorter in winter, giving the system less time to recharge. The sun's energy is also less intense in the winter. This decreased solar irradiance affects the ability of the PV panel to collect sufficient energy to power the lighting throughout the night, thus necessitating a larger panel size.

This analysis also indicates that Seattle needs significantly larger PV panels than nearly all other locations, especially in winter. Using the 10-lux (100 moonlights) luminaire as an example, a PV panel of approximately 29 square ft (2.7 square m) would be needed to power the lighting system reliably for Seattle's winter. This is too large to be practical for a parking lot luminaire. Therefore, other adjustments would be needed to the lighting system to make it more practical and realistic. These adjustments could include lowering the wattage of the light source or downsizing the energy requirements of the system in some other way. Conversely, in Miami, a PV panel of less than 7.5 square ft (0.7 square m) could comfortably power the 10-lux system throughout the year. A solar panel of this size could more easily be mounted on a luminaire pole, making PV lighting a much more viable option in this location.

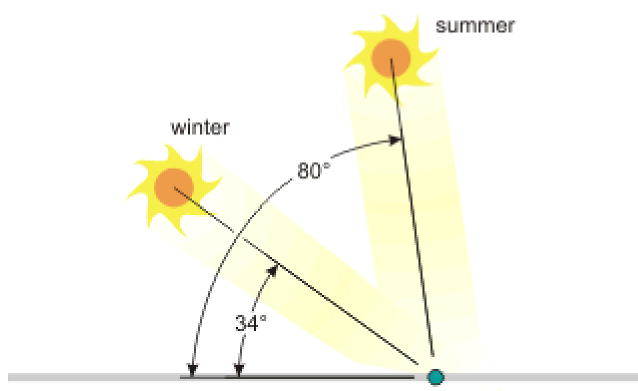
When the light level requirements are reduced to 0.5 lux (5 moonlights) the size requirements of the system components reduce dramatically across all locations. This will significantly reduce the system's cost. In most areas of the country 0.5 lux (5 moonlights) of illumination could comfortably be provided by a luminaire with a PV panel of 1 square ft (0.09 square m) or less. A PV panel of this size could easily be incorporated directly into the design of a luminaire. For illustrations of these systems, see Figure 6 in "What factors should be considered when selecting a luminaire for PV lighting?."

The solar panel size estimates shown in Figure 8 are based upon average solar radiation for the various months listed. When calculating the size requirements for a solar panel, using average solar radiation data for the month with the least sunshine will ensure that the panel will provide the power required to operate the lighting system, even during the winter months. However, this does not cover a "worst-case-scenario" in which a location might receive little or no sunlight for a higher than average number of consecutive days. If a PV lighting system is installed in a location where it is critical that the system operate fully every night of the year, a system specifier may want to "over design" the size of the PV panels to help to ensure that it will provide the required power under all possible sky and weather conditions.

How does the tilt angle and/or orientation of the PV panel affect system performance?

Photovoltaic (PV) panels collect solar radiation directly from the sun, from the sky, and from sunlight reflected off the ground or area surrounding the PV panel. Orienting the PV panel in a direction and tilt to maximize its exposure to direct sunlight will optimize the collection efficiency. The panel will collect solar radiation most efficiently when the sun's rays are perpendicular to the panel's surface. The angle of the sun varies throughout the year, as illustrated in Figure 9. Therefore, the optimal tilt angle for a PV panel in the winter will differ from the optimal tilt angle for the summer. This angle will also vary by latitude.

Figure 9. Range of midday sun angles at 33° north latitude



In some PV lighting systems such as solar garden lights or small post-top **luminaires**, the PV panels are incorporated directly into the luminaire housing and cannot be moved or oriented in a particular direction. In these types of systems, the PV panels are typically oriented horizontally, facing the sky. However, many larger PV lighting systems are designed to allow a system installer to tilt the PV panel at an angle from horizontal and to orient the PV panel in a particular direction. In these types of systems, a system specifier or installer should first determine the optimal tilt angle and orientation of the PV panel for the system's location.

The first step in determining optimal PV panel orientation and tilt angle is to review the site where the PV lighting system will be installed. Trees, large buildings, or other structures or obstructions surrounding the site might cast shadows onto a tilted PV panel at various times of day or during winter months when the sun is at a low angle in the sky. Therefore, it may be best to orient the PV panels horizontally to face the sky directly. This may allow the panels to collect the maximum amount of solar radiation with the least obstruction. However, a horizontal panel will get dirty faster.

However, if the site surrounding the PV lighting system is relatively free of obstructions, a lighting specifier can orient the system's PV panel in a particular direction and up at a selected angle. In this case, the PV panel should always face toward the equator. In the Northern Hemisphere the panel should face south and tilt from horizontal at an angle approximately equal to the site's latitude (NREL 2005). For example, if the system were located in San Diego, California, the PV panel should face south and tilt up at an angle of approximately 33°.

These recommendations for tilt angle represent an average, taking into account the angle of the sun over the entire year. However, if a PV lighting system at a northern latitude is designed to be used throughout all four seasons, it may be advantageous to tilt the PV panel at an angle that optimizes its performance in the winter, when solar radiation is likely to be at its lowest. As a general rule, to optimize the performance of PV panels in the winter, they should be tilted up from horizontal at an angle 15° greater than the latitude. For example, the calculation (in "What is the process to determine the appropriate size of PV panels for a particular application?") shows that a panel tilted to 48° in San Diego (latitude 33°) will allow a reduction of panel size by 43%, compared to a horizontal panel.

Conversely, if a PV lighting system is going to be used only in summer, (e.g., at a campground or state park that is used seasonally), it may be most advantageous to optimize the performance of the PV panel for summer. For optimal summer performance, the panel should be tilted 15° less than the latitude (NREL 2005). Unfortunately, good historical data does not exist on the actual improvement in system performance that can be achieved through proper orientation and tilt of a PV panel. Most recommendations for panel orientation are made based upon computer simulations and mathematical models. Estimates of performance improvements based on optimizing PV panel orientation and tilt angle range from 10-40% (Landau 2002).

How is system efficacy calculated for PV lighting systems using various light sources?

When calculating the total **efficacy** of a **photovoltaic (PV)** lighting system, take into account the efficacies and/or efficiencies of all of its individual components (Zhou and Narendran 2005). This calculation is relevant to sizing the PV system (see What information is needed to specify a PV lighting system?). One of these components is the light source. When selecting a light source for a stand-alone PV lighting system the following factors should be taken into consideration:

- **Lumen (lm)** package (total light output of the light source)
- Power requirements (total watts required to power the light source)
- System efficacy (efficacy of the light source and any **ballast** or **driver** needed to operate it)
- Environmental issues (impacts the system will have on the environment such as disposal of components and reduction in atmospheric pollution from lower power plant emissions)
- Climate (effect of high or low temperatures on the light source's light output and life)
- **Lumen maintenance** (ability of the light source to sustain its light output over time)
- Life of the light source (amount of time over which the light source will operate reliably).

The total system efficacy of a PV lighting system is associated with the efficacy of the light source and the efficiencies of the other system components. The typical luminous efficacies of various light sources are:

- White **light-emitting diodes (LED)** = 25 lumens per watt (LPW), excluding driver losses
- **Halogen** incandescent **lamps** = 20 LPW
- **Compact fluorescent lamps (CFL)** with ballast = 65 LPW
- Linear **fluorescent** lamps (LFL) with ballast = 85 LPW

(Zhou and Narendran 2005)

Note: LED lamp efficacy has improved rapidly in recent years, and a series of premium white LED products are now achieving efficacies about 35 to 40 lumens per watt (at time of publication).

The formula below can be used to calculate the overall system efficacy for a stand-alone PV lighting system:

$$\mathbf{E = \phi / P}$$

Where:

- ϕ: Light output from PV lighting system (in lumens)
- **P**: Input solar power (in watts)

Since

$$\phi = P * \eta_{PV} * \eta_{bat} * \eta_{ele} * E_{src} * \eta_{lum}$$

We have

$$E = P * \eta_{PV} * \eta_{bat} * \eta_{ele} * E_{src} * \eta_{lum} / P$$
$$= \eta_{PV} * \eta_{bat} * \eta_{ele} * E_{src} * \eta_{lum}$$

Where:

η_{PV}: PV panel efficiency, assume η_{PV} = 15%

η_{bat}: Battery efficiency, assume η_{bat} = 80%

η_{ele}: Product of efficiencies of all electronics, which may include efficiency of charge controller (η_{cha}), inverter (η_{inv}), and ballast/driver (η_{dri})

E_{src}: Efficacy of light source, as lumens per watt

η_{lum}: Luminaire efficiency, as the ratio of total output lumens from the luminaire to total lumens from the lamps

We assume that η_{PV}= 15%, η_{cha}, = 90%, η_{bat} = 80%, and the battery is large enough to meet the maximum power demand of the system. The PV efficiency of 15% is on the high end, which may be achieved with premium level PV panels available on the market. The battery efficiency of 80% is also on the high end, which implies high-quality batteries and little conduit loss. Table 5 shows the remaining assumptions used to calculate system efficacies for different system configurations.

Table 5. Assumptions used to calculate total system efficacy

White LED		Halogen		CFL		LFL	
η_{dri}	85%	No inverter or regulator necessary		η_{inv}	80%	η_{inv}	80%
E_{src}	25 LPW	E_{src}	20 LPW	E_{src}	65 LPW	E_{src}	85 LPW
η_{lum}	85%	η_{lum}	75%	η_{lum}	60%	η_{lum}	70%
η_{lum}	85%	η_{lum}	80%	η_{lum}	70%	η_{lum}	80%

Note that in this table, CFL and LFL (linear fluorescent lamp) **luminaire** efficiencies are higher in general lighting **applications** than in directional lighting applications. This is important to consider because outdoor lighting applications, especially those using low light levels, tend to favor directional lighting and allow a user to aim or focus the light where needed.

To illustrate the calculation listed above, consider the case of a PV lighting system using white LEDs as the light source. The system efficacy in directional lighting applications, expressed as lumens per watt (LPW) of solar power reaching the PV panels, can be calculated as follows:

$$E_{LED} = \eta_{PV} * \eta_{bat} * \eta_{cha} * \eta_{dri} * E_{src} * \eta_{lum}$$
$$= 15\% \times 80\% \times 90\% \times 85\% \times 25 \text{ LPW} \times 85\%$$
$$= 2.0 \text{ LPW}$$

In comparison, a lighting system using a CFL as the light source does not need a dc current regulator, but it does need a dc-to-ac inverter. The system efficacy can be calculated as follows:

$$E_{CFL} = \eta_{PV} * \eta_{bat} * \eta_{cha} * \eta_{dri} * E_{src} * \eta_{lum}$$
$$= 15\% \times 80\% \times 90\% \times 80\% \times 65 \text{ LPW} \times 60\%$$
$$= 3.4 \text{ LPW}$$

Note that the efficacy values above were calculated for every watt of solar power that arrives at the PV panels. The ideal solar radiation power is 1000 watts per square meter at sea level, which is approximately 100 watts per square ft.

Using similar calculations, NLPIP obtained the results found in Table 6 (in "What factors should be considered when selecting a luminaire for PV lighting?"), which summarizes the system efficacy (LPW) for PV lighting with different light sources in directional lighting applications. Since LED technology is rapidly evolving, the efficacies of LED are expected to increase significantly over the next 15 years. According to U.S. Department of Energy's roadmap on solid-state technology (U.S. Department of Energy 2005), for example, the efficacy of white LEDs is expected to reach 100 lumens per watt by the year of 2010, and 140 lumens per watt by 2015. Therefore, Table 6 contains projections of system efficacy using white LED lamps in future years.

Table 6. System efficacy for stand-alone PV lighting with different light sources (with projection for future years)

Year	White LED efficacy (lumen/watt)	PV System Efficacy (lumens per watt received from solar) dc light sources		ac light sources	
		White LED	Halogen	CFL	LFL
2003	25	2.0	1.7	3.4	5.1
2006	40	3.2	1.7	3.4	5.1
2010	100	7.9	1.7	3.4	5.1
2015	140	11.1	1.7	3.4	5.1

In the survey conducted by NLPIP (see "What are some common beliefs about PV lighting systems?") respondents indicated that LEDs were the most suitable light sources for PV lighting applications followed by fluorescent lamps, while halogen light sources were considered not suitable for PV lighting applications. However, given current lamp efficacies, PV lighting systems using fluorescent lamps are the most efficient. PV lighting systems using white-light LEDs are considerably more efficient than systems using halogen lamps, but neither is as efficient as those using fluorescent lamps.

In addition to system efficacy, the impact of the outdoor environment on the PV lighting system also needs to be evaluated. For example, even though ac light sources such as fluorescent lamps have a higher luminous efficacy than LEDs or incandescent lamps, they may have starting problems and/or reduced light output in low temperature environments.

Lumen maintenance and lamp life should also be considered when choosing a light source for a PV lighting system. CFLs and LFLs tend to have very good lumen maintenance (up to 90% or greater) and long average rated lives (ranging from 6000 to over 20,000 hours). However, these projections are based on lamps operating under ideal power conditions. Because the power conditions provided by PV lighting systems may vary much more than those provided by grid-powered lighting systems, it may be reasonable to assume that both the life and lumen maintenance of these sources would be reduced. There are no data available to end users concerning the performance of these light sources under PV power conditions, so the risks of using them in PV lighting systems increases. LEDs and incandescent light sources, on the other hand, are generally less affected by variable power conditions than their gas discharge (fluorescent and HID) counterparts.

CFLs and LFLs also have relatively high total lumen output per lamp and are relatively high wattage (e.g., 9 watts or greater). LEDs and incandescent lamps, on the other hand, are available in very low-wattage versions, providing very low light output. White-light LEDs, for example, are available in versions requiring as little as 0.2 watts. These low power requirements and low total light output are well suited to low light level PV lighting applications because they allow for the use of low-mounted luminaires with small PV panels and small battery capacity. Therefore, assuming low light levels are acceptable for the application, PV powered luminaires using these light sources (LEDs or incandescent lamps) are a much more viable option than larger, high-mounted luminaires using CFLs or LFLs.

What are the application issues related to PV lighting systems?

Installation

Installing a solar yard light is not necessarily difficult; however, installing a large-scale **photovoltaic (PV)** lighting system such as a 40-watt solar street **luminaire** with 12 square feet of PV panels is not a simple task. A survey of PV installations conducted in 2002 showed that 50% of PV systems (stand-alone, interconnected, hybrid, and multi-mode) in the U.S. were installed improperly. This resulted in deficiencies in safety, durability, and/or performance (Wiles et al. 2002). Stand-alone PV systems are more technically complex than electric **grid**-connected systems (DOE 2003).

In order to avoid installation problems associated with PV lighting systems, it is important to work with trained and experienced PV designers and installers, and to use well-established PV module technology and reliable equipment, while following the best available information and codes such as the National Electrical Code (NEC).

System integration

All components of PV lighting systems need to be well designed and matched to provide satisfactory system performance. If system components are not well matched, the system will likely be inefficient and the life of the components will be compromised. An automobile battery, for example, is a poor choice for a PV lighting system. An automobile battery is designed to supply high current for a short duration. Taking too much energy out of this type of battery before recharging it is likely to damage the internal components. A PV lighting system will repeatedly remove large amounts of a battery's energy capacity. Therefore, a specialized type of battery, called a deep discharge battery, is better suited to a PV lighting system.

If a PV lighting system uses a **fluorescent** or **high intensity discharge (HID)** lamp, a dc **ballast** may be used to replace two components: the dc-ac **inverter** and the ac ballast. This will improve the overall efficiency of the PV system, if the efficiency of the dc ballast is higher than the efficiency of the combination of the other two components. However, few dc ballasts exist for these light sources. For **light-emitting diode (LED)** lamps, a dc driver (current regulator) is a better choice than the combination of a dc-ac inverter and an ac driver. The dc driver for LED lamps in PV lighting systems is sometimes considered unnecessary because the output voltage from PV panels can be designed to match the required driving voltage of the LED lamps. However, it is normally poor practice not to use a dc driver, since unexpected changes in the circuit condition such as voltage or current fluctuations are likely to occur.

Maintenance

PV panels degrade over time, and the cover glass may collect dirt. Although panels are becoming more robust, a study in 2000 warned that PV modules may delaminate due to oxidization, thus resulting in reduced efficiency, and the cover glass could crack due to hail damage or thermal cycling (Quintana et al. 2000). Exposure to atmospheric oxygen, high current density, and elevated temperatures contribute to solar cell degradation (Riesen and Bett 2005). High aluminum content of PV modules also contributes to degradation. Many types of solar cells need high aluminum content in the window layer to ensure transparency, but layers with high aluminum content are prone to oxidation. Layers with lower aluminum content tend to be more stable (Riesen and Bett 2005). Moisture can also cause damage in thin-film PV modules, including material delamination and electrochemical corrosion (Mon et al. 1988).

Batteries also degrade over time. After eight years, battery capacities typically drop to just three to 50% of their initial value (Diaz and Egido 2003). Also, a battery's capacity decreases under lower ambient temperature. For example, a battery's capacity may drop 25% when the ambient temperature drops from 25° to 0° C (Sandia National Laboratories 1995).

Aesthetics

PV lighting sometimes causes aesthetic concerns. The PV panel is usually large compared to the luminaire itself, and may be considered an eyesore by some people. A designer for a PV lighting system should integrate the PV panel into the architectural and environmental surroundings as much as possible. This will help to avoid objections from people who live in the area where the system is being installed. With low-power PV lighting systems, the size of PV panel should be small, and aesthetics may not be as much of a concern because it can be more easily incorporated into the luminaire and/or its supporting structure. Figure 10 shows an example of PV-powered luminaires along a pedestrian pathway located alongside a public street.

Figure 10. PV-powered luminaires used to illuminate a pathway

Conversely, the use of a PV lighting system may illustrate that the system's owner is sensitive to the environment and is interested in the use of "cutting-edge," environmentally sustainable technology. In this case the PV panels may be viewed as a positive feature of the luminaire, which the owner may wish to showcase. However, it is still a good idea to try to integrate the PV panel into the design of the luminaire or mounting structure in a way that is visually pleasing and structurally sound.

What are the environmental and safety benefits and concerns surrounding PV lighting systems?

According to the NLPIP survey, people think **photovoltaic (PV)** lighting is good for the environment (see "What are some common beliefs about PV lighting systems"). Traditionally, electricity was transformed (or generated) by burning coal or other fossil fuels, which gives off harmful gases such as carbon dioxide (CO_2) and sulphur dioxide (SO_2), or by harnessing water power, which affects the biological environment for living organisms in the water mass. In 2002, the 100 largest US power producers, who produced nearly 90% of the nation's electricity, emitted approximately 9.7 million tons of SO_2, 4.2 million tons of nitrogen oxide (NO_x), 45 tons of mercury, and 2.3 billion tons of CO_2 into the atmosphere (CERES et al. 2004). Since PV lighting systems use solar radiation to generate electricity, they do not contribute to any of these environmental concerns.

Manufacturing the components of PV lighting systems, however, does consume energy and may cause a certain degree of environmental pollution. The manufacturing process and materials used can also create hazardous waste. Using PV lighting systems may cause other concerns as well, including battery disposal problems. The most common batteries used in PV systems are lead acid batteries, which, as their name suggests, contain lead and other potentially toxic materials. These batteries should be recycled at the end of their life.

Wind force represents a major force acting on PV arrays. In order to minimize potentially dangerous structural failure, it is important to design the arrays and mounting systems to withstand the maximum local wind speed expected in the areas where they are to be installed.

What information is provided in manufacturers' literature?

photovoltaic (PV) lighting system manufacturers' catalogs do not normally include sufficient technical information to understand the performance of a PV lighting system. Some manufacturers' product literature includes battery type, battery output voltage and capacity in amp-hours, lamp type, lamp wattage, lamp light output, and estimated run time per night. Other manufacturers' literature includes only information on lamp type, the color characteristics of the light sources (correlated color temperature [CCT] and color rendering index [CRI]), or estimated light output in watts, which often refers to the light output of an incandescent lamp with equivalent wattage.

Limited information makes it difficult to select appropriate PV lighting systems, especially if system efficacy, operational life, maintenance, and reliability are a concern. If considering installing a PV lighting system, contact the equipment manufacturer for additional technical information.

What information is needed to specify a PV lighting system?

In many ways, specifying a photovoltaic (PV)-powered lighting system is similar to specifying a grid-powered lighting system. However, expectations and design parameters must be altered if PV systems are to provide illumination effectively and economically. Additional information is also necessary to ensure that the PV system will supply the power needed to meet the requirements of a particular lighting application reliably. Some of the necessary information is provided in manufacturers' literature. The remainder can usually be obtained from a manufacturer's representative or distributor.

Determining application lighting requirements

The first step in specifying a PV lighting system is to determine if a PV system can realistically and economically meet the lighting needs of the application. In order to make this determination it is important to determine the application's lighting requirements. If the application requires relatively high nighttime light levels (greater than 1 lux on the ground) that is distributed uniformly over a large area for a long period of time (e.g., throughout the entire night), and is located in an area where the electric power grid is readily and easily accessible, a PV lighting system will most likely not be able to meet the lighting requirements reliably and cost effectively. An example of this type of application might be a parking lot or roadway that is located in an urban area and is used throughout the night.

A PV lighting system will most likely be able to meet the needs of a lighting application if one or more of the following points apply:

- Lower light levels, no more than 0.5 lux (5 moonlights), are considered appropriate for the application.
- The lighting system needs to operate for only a few hours (no more than eight) per night.
- Lighting needs to be provided only in limited areas of a site (e.g., to outline a path or pedestrian walkway).
- Small-scale luminaires are desirable for the application.
- The site is located in an area of the country where solar irradiance is plentiful throughout the year, or the site is only used when the solar irradiance is plentiful (i.e., summer).
- The electric power grid is not readily accessible and/or it would be costly to bring power to the site.
- The luminaires can be located in an area that will have non-shaded access to the sun for a majority of daylight hours and in which dirt is not likely to accumulate quickly on the PV panels.
- Financial subsidies are available through an electric utility, state energy office, or other entity, which would offset a significant portion of the capital costs for the PV lighting system.

If several of these points apply to the site under consideration, a lighting specifier may want to determine if a PV lighting system can meet the needs of the particular application cost effectively.

Selecting appropriate PV lighting equipment

When selecting lighting equipment for a particular application, it is important to understand the light output and distribution requirements of each luminaire. Once these requirements have been determined, a lighting specifier can select PV lighting equipment that will meet these specifications. Usually PV lighting equipment is purchased as a system that has already been assembled by a manufacturer, which contains the PV panel, batteries, electronics, luminaire, and other necessary components. In this case, a lighting specifier may want to check that the system will meet the lighting requirements of the application under consideration. The following information will be helpful.

System capacity

The information listed in the process below is needed in order to determine the system capacity or size requirements of a PV lighting system. The various system components (i.e., lamps, PV panels, electrical components) will degrade over time; therefore, a lighting specifier may need to over-design a PV lighting system (design it to exceed the minimum requirements of an installation) to ensure that it will continue to operate reliably over a long period of time.

Before determining energy requirements, first determine appropriate light levels for the application under consideration. For example, a high activity area may require a 10-lux system. A rural pathway, on the other hand, may need only a system with 0.5 lux illumination.

Step 1 - Determine energy requirements of the lighting system

The proper sizing of a PV lighting system depends on the watt-hours needed to operate the system each night. This is a function of the optical efficiency of the luminaire and the total number of **lamp lumens (lm)** needed, which will in turn determine the number of watts needed to provide those lumens. Once the total wattage of the lighting system (lamp and ballast or driver) is determined, this must be multiplied by the number of hours the system will operate each night. Therefore, the following information is needed:

- Luminaire efficiency
- Total number of lumens the lamp must produce (over time)
- Total wattage of the lighting system (lamp plus **ballast** or **driver**)
- Number of hours the lighting system will operate each night

Step 2 - Determine efficiency of system electronics

To ensure that the PV panels and batteries can provide the required energy for the lighting system, it is necessary to account for any losses that will occur in the system's electronics, such as charge controllers or dc-ac **inverters**. The efficiency of system electronics is usually given as a percentage. This will allow estimating how much of the battery's capacity will actually be available to power the lighting system. Therefore, it is necessary to know the efficiency of all system electronic components throughout their useful life.

Step 3 - Determine required battery storage capacity

Batteries are typically specified by the number of ampere- (amp) hours they are able to provide. To determine the number of amp-hours needed to provide the number of watt-hours required by the lighting system, it is necessary to know the voltage of the system. To convert watt-hours to amp-hours, divide the watt-hours by the voltage of the system. This will provide a rough estimation of the battery storage capacity needed for a particular system. It is also important to know how much of a battery's capacity is actually available for use. This is sometimes listed in manufacturer's literature as the battery's "usable amp-hours." Many batteries should only discharge 30% of their total storage capacity before being recharged. To check if the battery provided by the manufacturer is sized appropriately to meet the needs of a particular application or to specify battery capacity, the following information is needed:

- System voltage
- Usable amp-hours capacity of the battery (over time)
- Number of cycles for different discharge percentages

Step 4 - Determine the size of the solar panel needed

A crucial step in specifying a PV lighting system is to determine the size of the solar panel that will be needed to power the system reliably. This will vary based upon the area of the country in which the application is located (see "How does solar radiation vary by location?") and whether the design is for "worst case" or average solar radiation availability. Information available on solar radiation charts typically specifies the number of kilowatt hours (kWhs) that can be produced per day in a particular location by a solar panel of one square meter. To determine if the solar panel you are considering is large enough to provide the energy required by a particular system, the following information is needed:

- The location of the lighting application
- The conversion efficiency of the solar panel being considered (over time)

What is the process to determine the appropriate size of PV panels for a particular application?

Two examples are given below to demonstrate the process involved in determining the size of **photovoltaic (PV)** panels for a particular PV lighting system. The first is a parking lot **luminaire** that provides approximately 10-**lux illuminance** on the ground. The second is a post-top luminaire that will provide about 0.5-lux illuminance (assuming a luminaire that has a single light source and an optical efficiency of 50%, which uniformly distributes all light output on a circular area with a radius equal to the pole height.)

These are the same examples used in the previous section (see "How does solar radiation vary by location?"); however, in this example they are specified for a particular location: San Diego, California.

Example 1:

The first example uses the following assumptions:

- The lighting system is a PV-powered parking lot luminaire.
- The light source is an 11-watt **compact fluorescent lamp (CFL)** powered by a dc **ballast** with a total system wattage of 13 watts.
- The CFL will be turned on for eight hours of operation at night per day.
- PV panel conversion efficiency is 10%.
- A flat PV panel is used.
- Electronics (including charge controller and dc ballast) efficiency is 80%.
- Battery charge-discharge efficiency including conduit loss is 60%.
- The location is San Diego, California (33° N latitude).

The wattage of this example system (13 W), was determined through lighting calculation, considering parameters such as the required illuminance on the ground, size of area to be lighted, and luminaire efficiency. This same calculation is needed for **grid**-powered lighting systems. A CFL was selected for this application because it is the most efficient light source, considering the required light output, to produce the illuminance needed on the ground from the mounting height selected. Once the light source wattage has been determined, the following steps should be performed:

Step 1 - Calculate the daily energy consumed by the light source in watt-hours.

$$E_{\text{Daily Consumed}} = \text{Lamp Wattage} \times \text{Daily Operating Hours}$$
$$= 13 \text{ watt} \times 8 \text{ hours/day}$$
$$= 104 \text{ watt-hours/day}$$

Step 2 - Calculate the electric energy that the PV panels need to produce each day.
Assume the battery capacity of the system is large enough to allow necessary charging and discharging for powering the lamp.

$E_{\text{PV Produced}} = E_{\text{Daily Consumed}}$ / (Electronics Efficiency × Battery Charge/Discharge Efficiency)
= (104 watt-hours/day) / (80% × 60%)
= 217 watt-hours/day

Step 3 - Calculate the amount of solar radiation that the PV panels need to collect each day.
$E_{\text{Solar Radiation Needed}} = E_{\text{PV Produced}}$ / (PV panel conversion efficiency)
= (217 watt-hours/day) / 10%
= 2170 watt-hours/day

Step 4 - Find the average daily solar radiation at the location for the seasons in which this lighting system will be used, or for the season with the lowest amount of solar radiation if designing for use year-round.
In December, the 30-year-average of monthly solar radiation on a horizontal, flat panel in San Diego is 2900 watt-hours/square meter/day. For a flat panel tilted to an angle of latitude plus 15 degrees (facing south), it is 5000 watt-hours/square meter/day.

Step 5 - Calculate the size of the PV panels needed.
If the PV panel is in a horizontal position:
Size of PV Panels = $E_{\text{Solar Radiation Needed}}$ / Daily Solar Radiation
= (2170 watt-hours/day) / (2900 watt-hours/square meters/day)
= 0.75 square meters
= ~8.2 square ft

If the PV panel is tilted with an angle of latitude plus 15 degrees (facing south):
Size of PV Panels = $E_{\text{Solar Radiation Needed}}$ / Daily Solar Radiation
= (2170 watt-hours/day) / (5000 watt-hours/square meters/day)
= 0.43 square meters
= ~4.6 square ft

It is advantageous to tilt the PV panel to an angle of latitude plus 15 degrees (facing south). Therefore, this lighting system in San Diego in December requires 4.6 square ft of PV panels (tilted as described above), in order to collect enough solar energy to power this parking lot luminaire, providing approximately 10 lux (100 moonlights) on the pavement throughout the night for one year.

Example 2:

This example uses the following assumptions:

- The lighting system is a PV-powered post-top luminaire.
- The light source is a one-watt **light-emitting diode (LED)**, powered by an LED **driver**, with the system wattage of 1.5 watts.
- The LED will be turned on for eight hours of operation at night per day.
- PV panel conversion efficiency is 10%.
- A flat PV panel is used.
- Electronics (including charge controller and LED driver) efficiency is 80%.
- Battery charge-discharge efficiency including conduit loss is 60%.
- The location is San Diego, California.

The wattage of this system was again determined through lighting calculation, considering the same parameters as those in Example 1. In this case, an LED is the most efficient light source able to provide the required light output to produce the desired illuminance on the ground from the mounting height selected. CFLs are not available in small enough lumen packages (i.e., with low enough total light output ratings) to be used in this application.

Step 1 - Calculate the daily energy consumed by the light source in watt-hours.

$E_{Daily\ Consumed}$ = Lamp Wattage × Daily Operating Hours
= 1.5 watt × 8 hours/day
= 12 watt-hours/day

Step 2 - Calculate the electric energy that the PV panels need to produce each day.

Assume the battery capacity of the system is large enough to allow necessary charging and discharging for powering the lamp.

$E_{PV\ Produced}$ = $E_{Daily\ Consumed}$ / (Electronics Efficiency × Battery Charge/Discharge Efficiency)
= (12 watt-hours/day) / (80% × 60%)
= 25 watt-hours/day

Step 3 - Calculate the amount of solar radiation that the PV panels need to collect each day.

$E_{SolarRadiationNeeded}$ = $E_{PV\ Produced}$ / (PV panel conversion efficiency)
= (25 watt-hours/day) / 10%
= 250 watt-hours/day

Step 4 - Find the average daily solar radiation at the location for the seasons in which this lighting system will be used, or for the season with the lowest amount of solar radiation if designing for use year-round.

Using the same information as shown in Example 1, the amount of daily solar radiation is 2900 watt-hours/square meter/day for a horizontal, flat panel. For a flat panel tilted to an angle of latitude plus 15 degrees (facing south), it is 5000 watt-hours/square meter/day.

Step 5 - Calculate the size of PV panels needed.

If the PV panel is in horizontal position:

Size of PV Panels = $E_{Solar\ Radiation\ Needed}$ / Daily Solar Radiation
= (250 watt-hours/day) / (2900 watt-hours/square meters/day)
= 0.09 square meters
= ~1 square foot

If the PV panel is tilted with an angle of latitude plus 15 degrees (facing south):

Size of PV Panels = $E_{Solar\ Radiation\ Needed}$ / Daily Solar Radiation
= (250 watt-hours/day) / (5000 watt-hours/square meters/day)
= 0.05 square meters
= ~0.5 square foot

Again, it is advantageous to tilt the PV panel to an angle of latitude plus 15 degrees (facing south). Therefore, 0.5 square foot (0.45 square meter) of PV panels are needed (tilted as described above) for this lighting system in San Diego in December, in order to collect enough solar energy to power this 0.5-lux (5 moonlights) illuminance post-top luminaire. If designing for reliable year-round operation, then the appropriate size of PV panels for this system should be at least 0.5 square foot (0.45 square meter).

Case Study: Life Cycle Cost

Various scenarios are provided in this case study that use a life cycle cost (LCC) analysis to compare the cost-effectiveness of **photovoltaic (PV)**-powered lighting systems to **grid**-powered lighting systems for a variety of **applications**.

Assumptions:

- 10-year analysis period
- 3% inflation rate
- 4% discount rate
- No salvage cost at the end of 10 years
- $0.10 per kWh electricity cost (unless otherwise specified)
- Grid-powered systems require a 50-ft extension of the power line at a cost of $800 (unless otherwise specified)
- Eight hours of operation per night
- The 10-**lux** illuminator parking lot **luminaire** (see Figure 6 in "What factors should be considered when selecting a luminaire for PV lighting?") uses an 11-watt **compact fluorescent lamp (CFL)** with a system wattage of 13 W that costs $10 and must be replaced every three years. The luminaire hardware (luminaire, pole, and supporting hardware) costs $200.
  When powered by PV, the system requires a $300 50-watt (peak power) PV panel, $100 of electronic components (including charge controller and dc **ballast**), a $100 rechargeable battery that must be replaced every five years, and $50 of annual maintenance (including **lamp** and battery replacement and PV-panel cleaning). When powered by the grid, the maintenance cost is $20 per year.
- The 0.5-lux illuminator post-top luminaire (see Figure 6 as above) uses a 1-watt **light-emitting diode (LED)** with a system wattage of 1.5 watts that costs $15. The luminaire hardware costs $80. When powered by PV, the system requires a $30 PV panel, $10 of electronic components, a $20 rechargeable battery that must be replaced every five years, and $25 of annual maintenance (including lamp and battery replacement and PV-panel cleaning). When powered by the grid, the maintenance cost is $10 per year.
- The indicator luminaire (see Figure 6 as above) uses a 0.2-watt LED. When powered by PV, the system uses a $20 self-contained solar LED garden luminaire. When powered by the grid, the luminaires cost $5 each. The maintenance cost is negligible in both cases.

Scenario 1: One 10-lux illuminator: parking lot luminaire

	PV-powered lighting	Grid-powered lighting
Component	**Present worth ($)**	**Present worth ($)**
PV panel	300	-
Electronics	100	-
Battery 0 yr.	100	-
Battery 5 yr.	95	-
Luminaire hardware	200	200
Lamp 0 yr.	10	10
Lamp 3 yr.	10	10
Lamp 6 yr.	9	9
Maintenance	479	192
Electricity	-	31
Grid line extension (50 ft)	-	800
TOTAL	**$1303**	**$1252**

(Note: For all tables in this case study, 'Present worth' represents the value or 'worth' of a future cost, given a prevailing rate of interest and inflation.)

The LCC analysis in the table above shows that the PV and grid power systems are nearly the same. Increasing the electricity cost to $0.15 per kWh only increases the LCC of the grid-powered system by $15, so the options are still comparable in the total cost.

Scenario 2: One 0.5-lux illuminator: post-top luminaire

	PV-powered lighting	Grid-powered lighting
Component	**Present worth ($)**	**Present worth ($)**
PV panel	30	-
Electronics	10	-
Battery 0 yr.	20	-
Battery 5 yr.	19	-
Luminaire hardware	80	80
Lamp 0 yr.	15	15
Lamp 3 yr.	-	-
Lamp 6 yr.	-	-
Maintenance	239	96
Electricity	-	4
Grid line extension (50 ft)	-	800
TOTAL	**$414**	**$995**

In this scenario, the cost of the PV-powered lighting system is only half the cost of the grid-powered system. The lower light level requirement makes the PV system a much more viable option. Increasing the electricity cost to $0.15 per kWh only increases the LCC of the grid-powered system by $2, a negligible effect on the LCC.

Scenario 3: Five indicator luminaires

In some residential or rural pathway applications, an 11-watt CFL or a 1-watt LED will produce more light than needed. In addition, it will be difficult to distribute the light uniformly along a pathway. In these environments, it is sometimes only necessary to use indicator lights to outline the path's edge. For this purpose, it may be preferable to use a series of luminaires with 0.2-watt LEDs as the light sources. In this case, the power requirement drops to 1.6 watt-hours per day per luminaire. Although these luminaires provide significantly less light than the 11-watt CFL or the 1-watt LED, the light is not being used to provide illumination, but rather to provide sufficient luminance to mark the edge of the path.

	PV-powered lighting	Grid-powered lighting
Component	**Present worth ($)**	**Present worth ($)**
Luminaire hardware	100	25
Electricity cost	-	3
Grid line extension (50 ft)	-	800
TOTAL	**$100**	**$828**

In this case, the solar LED garden lights provide a much less expensive solution. Because the pathway lighting only needs to provide enough light to define the profile of the path, a series of 0.2-watt LEDs provide enough light for this purpose. For more information see "What are the most suitable applications for photovoltaic lighting?"

Scenario 4: Parking lot luminaire and post-top luminaires located one mile from the grid

The differences in cost between PV-powered and grid-powered systems becomes far more significant when the utility grid connection is far from the lighting system. The tables below show comparisons for systems located one mile away from the grid connection. The grid extension cost is $30,000 per mile (EERE 2005):

For one 10-lux illuminator: parking lot luminaire

	PV-powered lighting	Grid-powered lighting
Component	**Present worth ($)**	**Present worth ($)**
PV panel	300	-
Electronics	100	-
Battery 0 yr.	100	-
Battery 5 yr.	95	-
Luminaire hardware	200	200
Lamp 0 yr.	10	10
Lamp 3 yr.	10	10
Lamp 6 yr.	9	9
Maintenance	479	192
Electricity	-	36
Grid line extension (1 mi.)	-	30,000
TOTAL	**$1303**	**$30,457**

For one 0.5 lux illuminator: post-top luminaire:

	PV-powered lighting	Grid-powered lighting
Component	**Present worth ($)**	**Present worth ($)**
PV panel	30	-
Electronics	10	-
Battery 0 yr.	20	-
Battery 5 yr.	19	-
Luminaire hardware	80	80
Lamp 0 yr.	15	15
Lamp 3 yr.	-	-
Lamp 6 yr.	-	-
Maintenance	239	96
Electricity	-	4
Grid line extension (1 mi.)	-	30,000
TOTAL	**$414**	**$30,195**

There are large cost savings from using the PV lighting system because the installation is located far from the utility grid. One may argue that the LCCs of $30,457 and $30,195 for the grid-powered lighting are exaggerated, because the cost for extending the utility grid may be shared with a number of other power users or prorated over multiple luminaires.

Re-calculating this case for ten, 10-lux illuminators/parking lot luminaires:

	PV-powered lighting	Grid-powered lighting
Component	**Present worth ($)**	**Present worth ($)**
PV panel	3000	-
Electronics	1000	-
Battery 0 yr.	1000	-
Battery 5 yr.	953	-
Luminaire hardware	2000	2000
Lamp 0 yr.	100	100
Lamp 3 yr.	97	97
Lamp 6 yr.	94	94
Maintenance	4789	1916
Electricity	-	364
Grid line extension (1 mi.)	-	30,000
TOTAL	**$13,033**	**$34,571**

Recalculating this case for ten, 0.5-lux illuminators/post top luminaires:

	PV-powered lighting	Grid-powered lighting
Component	**Present worth ($)**	**Present worth ($)**
PV panel	300	-
Electronics	100	-
Battery 0 yr.	200	-
Battery 5 yr.	190	-
Luminaire hardware	800	800
Lamp 0 yr.	150	150
Lamp 3 yr.	-	-
Lamp 6 yr.	-	-
Maintenance	2395	958
Electricity	-	42
Grid line extension (1 mi.)	-	30,000
TOTAL	**$4135**	**$31,950**

As these calculations show, PV-powered lighting systems still have cost saving advantages compared to grid-powered systems, even if the utility grid extension cost is shared among 10 luminaires.

Lesson learned

In certain applications, such as remote areas located far from the utility grid, and/or where the power requirement is low, PV-powered lighting systems have a cost-saving advantage compared to grid-powered systems.

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Glossary

Sources of term definitions: National Lighting Product Information Program (NLPIP), Lighting Research Center's Lighting Education Online, the IEEE Standard Dictionary of Electrical and Electronics Terms (IEEE Std 100-1996).

Application	The use to which a lighting system will be put; for example, a lamp may be intended for indoor residential applications.
Ballast	A device required by electric-discharge light sources such as fluorescent or HID lamps to regulate voltage and current supplied to the lamp during start and throughout operation.
Color rendering index (CRI)	A measure of the degree of color shift that objects undergo when illuminated by a lamp, compared with those same objects when illuminated by a reference source of comparable correlated color temperature (CCT). A CRI of 100 represents the maximum value. A lower CRI value indicates that some colors may appear unnatural when illuminated by the lamp. Incandescent lamps have a CRI above 95. The cool white fluorescent lamp has a CRI of 62; fluorescent lamps containing rare-earth phosphors are available with CRI values of 80 and above.
Compact fluorescent lamp (CFL)	A family of single-ended fluorescent-discharge light sources with small-diameter [16-millimeter (5/8-inch) or less] tubes.
Correlated color temperature (CCT)	A specification of the apparent color of a light source relative to the color appearance of an ideal incandescent source held at a particular temperature and measured on the Kelvin (K) scale. The CCT rating for a lamp is a general indication of the warmth or coolness of its appearance. As CCT increases, the appearance of the source shifts from reddish white toward bluish white; therefore, the higher the color temperature, the cooler the color appearance. Lamps with a CCT rating below 3200 K are usually considered warm sources, whereas those with a CCT above 4000 K usually considered cool in appearance.
Driver	For light emitting diodes, a device that regulates the voltage and current powering the source.
Efficacy	The ratio of the light output of a lamp (lumens) to its active power (watts), expressed as lumens per watt.
Fluorescent lamp	A low-pressure mercury electric-discharge lamp in which a phosphor coating on the inside of the glass tubing transforms some of the ultraviolet energy created inside the lamp into visible light.
Footcandle (fc)	A measure of illuminance in lumens per square foot. One footcandle equals 10.76 lux, although for convenience 10 lux commonly is used as the equivalent.
Glare	The sensation produced by luminances within the visual field that are sufficiently greater than the luminance to which the eyes are adapted, which causes annoyance, discomfort, or loss in visual performance and visibility.
Grid	The combination of electric power plants and transmission lines operated by an electric utility.
Halogen lamp	An incandescent lamp that uses a halogen fill gas. Halogen lamps have higher rated efficacies and longer lives than standard incandescent A-lamps.
High-intensity discharge (HID)	An electric lamp that produces light directly from an arc discharge under high pressure. Metal halide, high-pressure sodium, and mercury vapor are types of HID lamps.

Illuminance	The amount of light (luminous flux) incident on a surface area. Illuminance is measured in footcandles (lumens/square foot) or lux (lumens/square meter). One footcandle equals 10.76 lux, although for convenience 10 lux commonly is used as the equivalent.
Illumination	The process of using light to see objects at a particular location.
Inverter	Also known as "power inverter." A device used to convert direct current (dc) electricity into alternating (ac) current.
Irradiance	The density of radiant flux incident on a surface.
Lamp	A radiant light source.
Light-emitting diode (LED)	A small electronic device that emits visible light when electricity is passed through it. LEDs are energy-efficient, have long lives, and can be red, green, blue or white in color.
Lumen (lm)	A unit measurement of the rate at which a lamp produces light. A lamp's light output rating expresses the total amount of light emitted in all directions per unit time. Ratings of initial light output provided by manufacturers express the total light output after 100 hours of operation.
Lumen maintenance	The ability of a lamp to retain its lumen output over time. Greater lumen maintenance means a lamp will remain brighter longer. The opposite of lumen maintenance is lumen depreciation, which represents the reduction of lumen output over time. Lamp lumen depreciation factor (LLD) is commonly used as a multiplier to the initial lumen rating in illuminance calculations to compensate for the lumen depreciation. The LLD factor is a dimensionless value between 0 and 1.
Luminaire	A complete lighting unit consisting of a lamp or lamps and the parts designed to distribute the light, to position and protect the lamp(s), and to connect the lamp(s) to the power supply. (Also referred to as fixture.)
Luminance	The photometric quantity most closely associated with the perception of brightness, measured in units of luminous intensity (candelas) per unit area (square feet or square meter).
Lux (lx)	A measure of illuminance in lumens per square meter. One lux equals 0.093 footcandle.
Photon	A small bundle or quantum of electromagnetic energy, including light.
Photovoltaic (PV)	Photovoltaic (PV) cells produce electric current from light energy (photons). PV cells are joined to make PV panels.
PN junction	For light emitting diodes, the portion of the device where positive and negative charges combine to produce light.

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