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Abstract. Although lighting systems powered by photovoltaic (PV) cells have existed for many years, they are not widely used, especially in lighting for buildings, due to their high initial cost and low conversion efficiency. One of the technical challenges facing PV-powered lighting systems has been how to use the dc power generated by the PV module to energize common light sources that are designed to operate efficiently under ac power. Usually, the efficacy of dc light sources is very poor compared to ac light sources. Rapid developments in LED lighting systems have made this technology a potential candidate for PV-powered lighting systems. This study analyzed the efficiency of each component of PV-powered lighting systems to identify optimum system configurations for different applications. © 2005 Society of Photo-Optical Instrumentation Engineers. [DOI: 10.1117/1.2130109]

Subject terms: photovoltaic; PV; lighting; LED; light-emitting diode; efficacy.

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1 Introduction

Photovoltaic (PV) cells convert sunlight into electricity and produce direct current (dc), which can be used for energizing various devices. Lighting is one way to use this solar-generated electricity. Some examples of PV-powered lighting systems are decorative pathway markers and residential garden lights, portable highway signs, and off-grid, rural-area light fixtures. However, PV-powered lighting systems are not widely used, due to their high initial cost, low system efficiency, and poor reliability. One reason for the low system efficiency is that the dc produced by the PV cells has to be converted to ac using an inverter in order to power the light source. Although there are light sources that can be operated off dc, they generally have very poor efficacy.

Light-emitting diode (LED) technology has been advancing rapidly over the past several years.¹ Some of the white LEDs in the marketplace have efficacies exceeding 25 lm/W including the driver losses, which is twice the efficacy of the residential incandescent lamp and may be up to five times greater than that of a dc-powered incandescent light source.² Therefore, white LED technology is a candidate for creating efficient PV-powered lighting systems.

The goal of the study described in this manuscript was to analyze the different components of PV-powered lighting systems, to estimate the whole-system efficiency, to understand what affects system efficiencies, and to identify optimum system configurations for various applications. The light sources considered were halogen lamps, compact fluorescent lamps (CFLs), linear fluorescent lamps (LFLs), and LED lamps. The information required for this analysis was gathered from literature and laboratory measurements. An

experiment was conducted to evaluate the efficiency of a hybrid power-conditioning unit used in PV-powered lighting systems.

A literature survey was conducted to understand what types of lighting system configurations exist for PV operation, the performance of each of these configurations, and how efficient each of the components is. Components typically used in a PV-powered lighting system may include a PV cell array (or PV panel), battery, electricity grid, power-conditioning unit (to provide dc output), ac load center (to provide ac output), dc-to-ac converter, ac-to-dc converter (LED ac driver), dc current regulator, and light source, as well as the luminaire. Depending on the light source and the different application requirements, the system configuration may include only some of these components.

Three major types of system configuration exist for PV-powered lighting systems. These include the standalone system, the utility-connected (intertie) system, and the hybrid system.^{3,4} *Standalone systems* are mostly seen in residential pathway markers, parking lot luminaires, and off-grid facility lighting systems. They normally require batteries, which introduce high storage-retrieval losses and high maintenance costs.⁵ *Utility-connected systems* do not require batteries; instead they are connected to an electrical grid and draw power from the grid when the solar power collected from the PV panels is not sufficient for the intended application. Depending on the type of load (i.e., dc or ac), a power-conditioning unit or an ac load center is needed in utility-connected systems to mix the input power from PV panels and the input power from the utility grid. Optionally, some utility-connected systems can feed power back to the grid when the PV panels generate more energy than needed. *Hybrid systems* combine a number of electricity production and storage elements to meet the energy demand—for example, a utility-connected system with a

battery backup. These systems are complicated and expensive but are more reliable, especially when connected to a utility grid.

The literature indicates that the conversion efficiency of a state-of-the-art GaInP/GaAs/Ge PV cell can be up to 35%.⁶ However, a typical conversion efficiency for a commercially available PV module is 15%.⁷ Typically, the battery efficiency is 80%,⁸ the LED ac driver (ac-dc converter) efficiency is 80%,⁹ the LED current regulator efficiency is 85%,^{10,11} and the dc-ac inverter efficiency is 80%.¹² The luminaire efficiency is typically 85% for an LED luminaire,¹³ 80% for a halogen luminaire,¹⁴ 60% for a CFL luminaire in a directional lighting application,¹⁵ and 70% for an LFL luminaire in a directional lighting application.^{16,17} In directional lighting applications, CFLs and LFLs have lower luminaire efficiencies because the large sizes of these light sources cause difficulty in optical control. In general lighting applications, CFLs and LFLs have higher luminaire efficiencies. It is estimated that the luminaire efficiency in a general lighting application is typically 70% for a CFL luminaire and 80% for a LFL luminaire. The efficiency of an ac load center is estimated to be 90%.

2 Experiment

The efficiency of a grid-connected hybrid power-conditioning unit, which outputs dc power with both ac (grid) and dc (PV) input powers, was evaluated through an experiment. The power-conditioning unit draws power from the ac grid when the amount of dc power collected from the PV panels is not sufficient to meet the needs of the lighting system.¹⁸

During the day, the solar energy reaching the PV panels changes significantly, and as a result, the dc power generated by the PV panels also changes. When the power is not sufficient to meet the needs of the lighting system, additional power is drawn from the electrical grid of the building to maintain constant light output. When the amount of dc input power varies, the efficiency of the power-conditioning unit may also change. The efficiency is defined as the ratio of the output power to the input power:

$$\eta_{\text{cond}} = \frac{\text{output power}}{\text{input power}}$$

The power-conditioning unit used in this study has a capacity of 720-W input and 660-W output. The requirements for the input power are 208 V ac and at least 28 V for the dc; for the output power, the requirement is 26.6 V. In this laboratory study, a dc power supply was used to mimic the PV power source.

2.1 Experimental Setup

The system configuration used in this experiment (see Fig. 1) includes the following components: the power-conditioning unit, 208 V ac power from a grid, a dc power supply (simulating the power collected from PV panels), a dc current regulator, and an LED lighting system with high-flux white LEDs. This setup simulates a utility-connected PV-powered LED lighting system in buildings (see Fig. 2).

Since the power-conditioning unit's output power capacity is relatively high, a series resistor was added to the LED

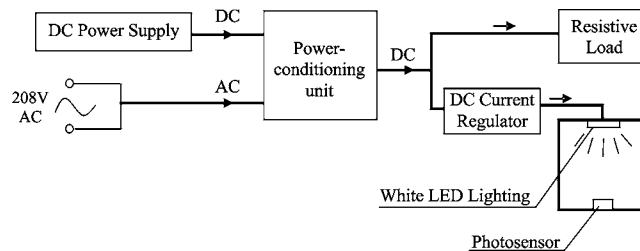


Fig. 1 Schematic of the experimental setup.

lighting system to get to about 80% of its capacity. The power dissipated by the LED lighting system is approximately 20 W, and in the resistor is about 520 W. Please note that this resistive load is not necessary in a full-scale installation. The input power from the dc power supply, the input power from the 208-V ac grid, the output power for the LED lighting and the resistive load, and the relative light output of the LED lighting system were monitored and recorded. A photosensor was used to record the relative light output of the LED lighting system.

The different dc input power levels were achieved by setting different output current levels while maintaining a constant voltage from the dc power supply. The input power from the dc power supply, the input power from the 208-V ac grid, and the total output power were measured. The efficiency of the power-conditioning unit under different dc input power levels was calculated by taking the ratio of the total output power to the total input power. The relative light output of the white LED lighting was monitored by a photosensor under varied dc input power levels.

3 Results

Figure 3 shows the input power from the dc power supply, the 208-V ac grid power, and the output power for the different current settings of the power supply. As seen, when the input dc power decreases, the ac power drawn from the grid increases. The output power remained constant for various dc input power levels, with a maximum-to-minimum difference of 2.6%. The total input power (sum of dc and ac) also remained fairly stable, with a maximum-to-minimum difference of 5.3%.

Figure 4 shows the efficiency of the power-conditioning unit as a function of dc input current. We see that the sys-

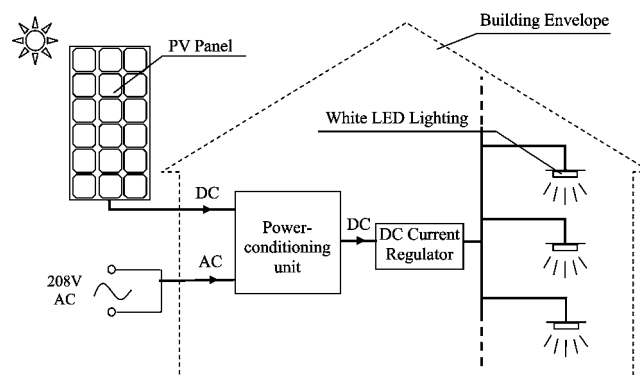


Fig. 2 Simulation of PV-powered lighting systems in buildings.

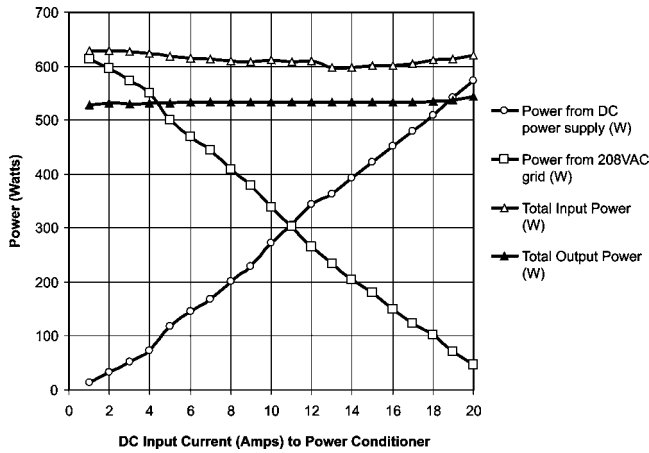


Fig. 3 Hybrid power-conditioning system: input and output power analysis.

tem efficiency is slightly higher when the dc input power is high, the maximum-to-minimum difference being 6.1%. The average system efficiency across different dc input power levels is 87.1%. For convenience, an efficiency value of 87% is used for this power-conditioning unit in the latter part of this paper.

Figure 5 shows the relative light output of the white LED lighting system as a function of dc input power. The photosensor was placed 1 ft (30 cm) away from the light source. As seen, the relative light output of the white LED lighting system drops slightly with increased dc power, and the maximum-to-minimum difference is 7.7%. This means the light output of an LED lighting system could change up to 7.7% in a real-life system. In most lighting applications, this amount of change will be hardly perceivable.¹⁹

3.1 Estimating Overall System Efficacy

The formula below was used to estimate the overall system efficacy for PV-powered lighting systems:

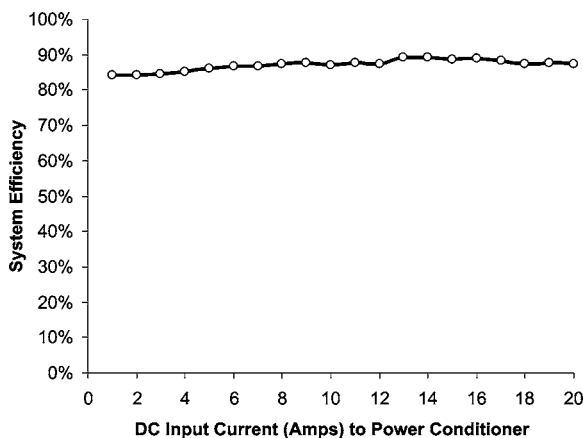


Fig. 4 Hybrid power-conditioning system: efficiency at different current levels.

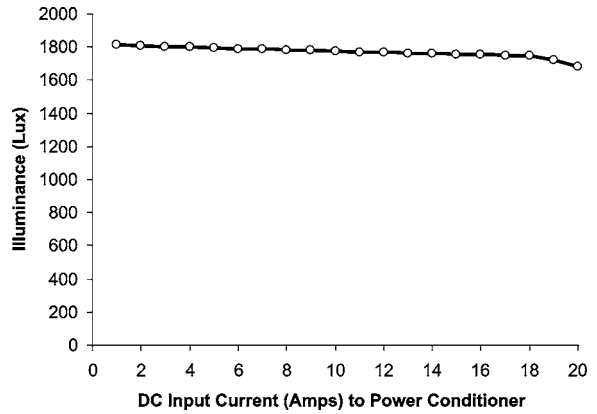


Fig. 5 Relative light output of the white LED lighting system in this experiment.

$$E = \eta_{PV} \eta_{bat} \eta_{cond} \eta_{ac} \eta_{inv} \eta_{reg} E_{src} \eta_{lum},$$

where

- η_{PV} =PV panel efficiency; assume $\eta_{PV}=15\%$
- η_{bat} =battery efficiency; assume $\eta_{bat}=80\%$ ($\eta_{bat}=100\%$ if not including batteries in system)
- η_{cond} =power-conditioning unit efficiency; based on our experiment, $\eta_{cond}=87\%$ ($\eta_{cond}=100\%$ if not including a power-conditioning unit in system)
- η_{ac} =ac load center efficiency; assume $\eta_{ac}=90\%$ ($\eta_{ac}=100\%$ if not including an ac load center in system)
- η_{inv} =dc-ac inverter efficiency ($\eta_{inv}=100\%$ if light source is LED or incandescent/halogen)
- η_{reg} =dc current regulator efficiency ($\eta_{reg}=100\%$ if light source is not LED)
- E_{src} =efficacy of light source (lm/W)
- η_{lum} =Luminaire efficiency = ratio of total output lumens from the luminaire to total lumens from the lamps.

Table 1 contains the assumptions used to estimate system efficacies for different system configurations. Note in this table that CFL and LFL luminaire efficiencies are higher in general lighting applications than in directional lighting applications.

Examples are given below for calculating overall system efficacies of PV-powered lighting systems. For example, assume we have a utility-connected PV-powered lighting system that uses white LEDs as the light source, and a hybrid power-conditioning unit that is the same as the one previously tested to connect to the electricity grid. The system efficacy for such a lighting system in directional lighting applications, expressed as lumens per watt of solar energy that arrives at the PV panels, can be calculated as

$$\begin{aligned} E_{utility-connected LED} &= \eta_{PV} \eta_{bat} \eta_{cond} \eta_{ac} \eta_{inv} \eta_{reg} E_{src} \eta_{lum} \\ &= 15\% \times 100\% \times 87\% \times 100\% \\ &\quad \times 100\% \times 85\% \times (25 \text{ lm/W}) \\ &\quad \times 85\% \\ &= 2.4 \text{ lm/W}. \end{aligned}$$

For comparison, if the lighting system uses a CFL as the light source, it does not need a dc current regulator, but it

Table 1 Assumptions on the efficiency of components of PV-powered lighting systems.

White LED		Halogen		CFL		LFL	
LED dc current regulator efficiency	85%	No inverter or regulator necessary		Dc-to-ac inverter efficiency	80%	Dc-to-ac inverter efficiency	80%
LED ac driver efficiency	80%						
Lamp efficacy with dc power	25 lm/W	Lamp efficacy with ac or dc power	20 lm/W	Lamp and ballast efficacy with ac power	65 lm/W	Lamp and ballast efficacy with ac power	85 lm/W
Luminaire efficiency (directional lighting)	85%	Luminaire efficiency (directional lighting)	80%	Luminaire efficiency (directional lighting)	60%	Luminaire efficiency (directional lighting)	70%
Luminaire efficiency (general lighting)	85%	Luminaire efficiency (general lighting)	80%	Luminaire efficiency (general lighting)	70%	Luminaire efficiency (general lighting)	80%

does need a dc-to-ac inverter. Also, since a CFL uses ac power, this lighting system does not need a power-conditioning unit that provides dc power; instead it needs an ac load center to mix the ac power inverted from dc and the ac power from the grid. The system efficacy can be calculated as

$$\begin{aligned}
 E_{\text{utility-connected CFL}} &= \eta_{\text{PV}} \eta_{\text{bat}} \eta_{\text{cond}} \eta_{\text{ac}} \eta_{\text{inv}} \eta_{\text{reg}} E_{\text{src}} \eta_{\text{um}} \\
 &= 15 \% \times 100 \% \times 100 \% \times 90 \% \\
 &\quad \times 80 \% \times 100 \% \times (65 \text{ lm/W}) \\
 &\quad \times 60 \% \\
 &= 4.1 \text{ lm/W}.
 \end{aligned}$$

Note that these efficacy values were calculated for every solar watt that arrives at the PV panels. In contrast to a PV-powered lighting system, if the light source is directly and completely energized by ac grid power, the efficacy values can be calculated for every watt from the ac grid, as shown below for ac-powered white LEDs:

$$\begin{aligned}
 E_{\text{ac-powered LED}} &= (\text{LED ac driver efficiency}) \\
 &\quad \times (\text{LED lamp efficacy}) \\
 &\quad \times (\text{LED luminaire efficiency}) \\
 &= 80 \% \times (25 \text{ lm/W}) \times 85 \% \\
 &= 17.0 \text{ lm/W}.
 \end{aligned}$$

Using similar calculations, we obtained the results found in Table 2, which summarizes the system efficacy (lm/W) for different system configurations of PV-powered lighting systems in directional lighting applications (ac-powered systems are also included for reference). As we can see from the Table the system efficacy of PV-powered LED lighting systems using white LEDs as the light source is higher than those using halogen lamps, but is still not as high as those using CFL and LFL. The main reason for this difference is that the luminous efficacy of white LED lamps is still not high enough, currently at 25 lm/W. In order to compete with other light sources in PV-powered lighting

Table 2 System efficacy for different system configurations of PV-powered lighting systems for directional lighting applications.

System configuration	Efficacy (lm/W)			
	Dc light source		Ac light source	
	White LED	Halogen	CFL	LFL
Ac-powered	17.0	16.0	39.0	60.0
Standalone (PV+ battery)	2.2	1.9	3.7	5.7
Utility-connected (PV+ grid, no battery)	2.4	2.1	4.2	6.4
Hybrid (PV+ grid+ battery)	Depends on the proportion of usage between grid and battery			

Table 3 Target white LED efficacy to compete with other light sources in PV-powered lighting systems for directional lighting applications.

System configuration	Target efficacy (lm/W)		
	Halogen	CFL	LFL
Ac-powered	24	57	88
Standalone (PV+battery)	22	43	66
Utility-connected (PV+grid, no battery)	22	45	68

systems for directional lighting applications, the luminous efficacy of white LED lamps must reach the values listed in Table 3.

As shown in Table 3, for ac-powered lighting systems, the efficacy of white LED lamps needs to be at least 57 lm/W in order to compete with CFL, and 88 lm/W to compete with LFL. White LED lamps are far less competitive than fluorescent lamps in ac-powered lighting applications. In standalone PV-powered lighting systems, the efficacy of white LED lamps needs to be at least 43 lm/W in order to compete with CFL, and 66 lm/W to compete with LFL. In utility-connected PV-powered lighting systems, the efficacy of white LED lamps needs to be at least 45 lm/W in order to compete with CFL, and 68 lm/W to compete with LFL. In all the lighting systems we have discussed, using white LEDs is already more efficacious than using halogen lamps.

The preceding calculations and results assume the PV-powered lighting systems are used in directional lighting applications. If they are used in general lighting applications, the estimated overall system efficacies will be higher for CFL and LFL, because their luminaires have higher efficiencies in general lighting applications. Calculations were performed for general lighting applications, and the overall system efficacy results are shown in Table 4. In order to compete with other light sources in general lighting applications, the luminous efficacy of white LED lamps must reach the values listed in Table 5.

Table 5 Target white LED efficacy to compete with other light sources in PV-powered lighting systems for general lighting applications

System configuration	Target efficacy (lm/W)		
	Halogen	CFL	LFL
Ac-powered	24	67	100
Standalone (PV+battery)	22	50	75
Utility-connected (PV+grid, no battery)	22	52	78

The system efficacy of white LED lamps in either directional lighting applications or general applications still is not competitive enough to be used in PV-powered lighting systems for buildings. But with the rapid development of LED technology, LED light sources have the potential to become the preferred light source for PV-powered lighting systems for buildings in the near future. Recent white-LED technology has shown an efficacy of more than 40 lm/W,²⁰ very close to becoming more efficacious than CFL in PV-powered directional lighting applications.

4 Discussion

Besides the luminous efficacy of white LED lamps, the efficiency of the dc current regulator is another critical parameter that can help the white LED to be a more competitive light source in PV-powered lighting systems. Some manufacturers of current regulators have claimed conversion efficiencies greater than 90%.²¹

People may want to know the overall system efficacy of PV-powered lighting systems in terms of the amount of light produced by the light source inside the building for a certain area of PV panels located outside the building. This can be calculated from the system efficacy (lm/W) for different system configurations of PV-powered lighting systems, which were summarized in Table 2, and an assumption of certain solar radiation conditions. On a clear sunny day at noon at sea level, the solar radiation arriving at the

Table 4 System efficacy for different system configurations of PV-powered lighting systems for general lighting applications.

System configuration	Efficacy (lm/W)			
	Dc light source		Ac light source	
	White LED	Halogen	CFL	LFL
Ac-powered	17.0	16.0	45.5	68.0
Standalone (PV+battery)	2.2	1.9	4.4	6.5
Utility-connected (PV+grid, no battery)	2.4	2.1	4.9	7.3
Hybrid (PV+grid+battery)	Depends on the proportion of usage between grid and battery			

Table 6 Light outputs produced for every square meter of PV panel under the ideal solar condition for different system configurations and for directional lighting applications (numbers rounded to nearest 100 lm).

System configuration	Light output (lm)			
	Dc light source		Ac light source	
	White LED	Halogen	CFL	LFL
Stand alone (PV+battery)	2200	1900	3700	5700
Utility-connected (PV+grid, no battery)	2400	2100	4200	6400
Hybrid (PV+grid+battery)	Depends on the proportion of usage between grid and battery			

earth is approximately 1000 W/m^2 , which we call the *ideal solar condition*. Under this condition, every square meter of PV panel can supply enough energy to produce the light outputs shown in Table 6 for different system configurations of PV-powered lighting systems, using directional lighting applications as an example. For instance, 1.5 m^2 of PV panels outside the building will convert enough solar energy to produce 3600 lm (1.5×2400) inside the building if we use white LED lamps with a utility-connected PV-powered lighting system under the ideal solar condition (1000 W of solar energy per square meter). These 3600 lm of light output are about equivalent to the light output of a recessed fluorescent luminaire using two T8 lamps in each luminaire. That is, with PV-powered lighting systems, every 1.5 m^2 of PV panels coupled with white LED lamps can replace a two-lamp T8 fluorescent luminaire under the ideal solar condition. When the solar energy arriving at the PV panels is less than under the ideal solar condition, the balance of the energy needed will be drawn from the utility grid.

Even though white LED lamps are not yet the most efficacious light source for PV-powered general illumination in buildings, their advantages should not be underestimated. A PV-powered LED lighting system may have reduced maintenance costs because of the LED lamps' longer life.²² Also, LED lamps can fit into smaller, flexible lighting fixtures, making them useful for lighting tight spaces. If colored light is needed, as in store display lighting, ball-room lighting, and mood lighting, colored LED lamps will be the most efficacious light source if using PV-powered lighting systems.

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