

Comparing White Light LEDs to Conventional Light Sources

As white light LED products become more widely available, additional factors enter into light source selection. How do current LED products compare to conventional lighting on the basics: energy efficiency, life, lumen depreciation, light output/distribution, and color quality?

Energy Efficiency

Evaluating the energy efficiency of lighting systems starts with the efficacy of the light source, but does not end there. Other factors, such as ballast or driver efficiency, luminaire optical losses, and luminaire thermal factors will also determine the final energy efficiency of any lighting system.

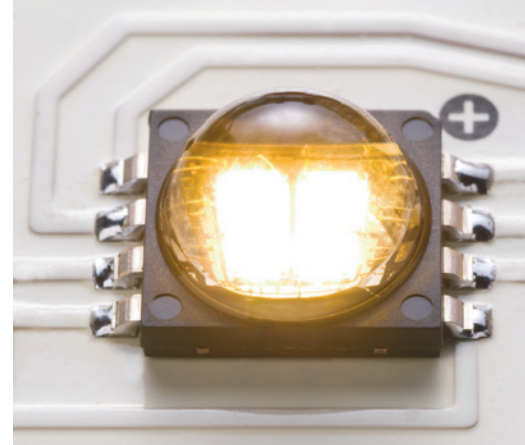
Source Efficacy

For traditional lamp types, *source efficacy* (expressed in lumens per watt, lm/W) is measured under steady-state conditions at a 25°C ambient temperature. Source efficacy cannot be measured for LEDs as it is for traditional lamps. LEDs gain heat when operated continuously, which can significantly decrease their light output and efficacy. For this reason, LEDs are attached to heat sinks to conduct heat away from the device; however, no “standard” or “reference” heat sinks exist for LEDs, complicating their performance measurements and comparison with other light sources.

Light output and efficacy data presented in LED data sheets are typically very short-term (25 milliseconds or less) measurements taken at a calculated junction temperature (T_j) of 25°C, generated using a very short pulse of current. The short current pulse prevents significant heating of the LED and, therefore, results in higher measured light output and efficacy than for continuous operation.

To better estimate actual performance, some LED manufacturers provide additional data to adjust light output values at $T_j = 25^\circ\text{C}$ for anticipated operating temperatures. These data indicate LED light output at $T_j = 75^\circ\text{C}$ is approximately 10%-15% less than rated light output at $T_j = 25^\circ\text{C}$.¹ This estimation should be used only as a general indication, and not a substitute for detailed evaluation of individual LED products.

¹Based on a survey of graphical relative flux-versus-temperature data for phosphor-converted LEDs, including Cree XLamp®, Philips Lumileds LUXEON® Rebel and K2, and Nichia POWER LED products.



Cree XLamp MC-E LED. Photo credit: Cree

Terms

Source efficacy – the luminous flux emitted by a light source divided by the nominal light source wattage (not including driver); expressed in lumens per watt (lm/W).

Junction temperature (T_j) – temperature within the LED. Direct measurement of T_j is impractical but can be calculated based on a known case or board temperature and the materials’ thermal resistance.

Luminaire efficacy – total lumens provided by the luminaire divided by the total wattage drawn by the power supply/driver, expressed in lumens per watt (lm/W).

Target D_{uv} – for a source’s measured chromaticity coordinates (as plotted on the CIE 1976 (u' , v') diagram), the maximum allowable distance from the Planckian (blackbody) locus. This distance is specified for each nominal CCT defined in ANSI C78.377-2008, and relates to the relative “whiteness” of a light source’s appearance.



Luminaire Efficacy

A more accurate way to compare LED performance with traditional sources is to measure the performance of luminaires designed for and lamped with each type of source. The metric used for comparison is called *luminaire efficacy*, expressed in lumens per watt (lm/W). Figure 1 presents a sampling of luminaire efficacy data for recessed downlights, based on DOE CALiPER product testing.

Luminaire efficacy is typically lower than source efficacy due to optical losses and, in some cases, thermal factors affecting source performance (e.g., for LEDs and fluorescent lamps). As illustrated in Figure 1, luminaire efficacy can vary between products—even when using the same type of light source—due to variations in optical components, ballast or driver efficiency, and thermal management.

The photometric test procedure developed for LED luminaires (IESNA LM-79-08) can also be used to test LED replacement lamps, which have integrated drivers and thermal management. Remember, however, that the performance of LED replacement lamps (like other temperature-sensitive sources, e.g., CFLs) will be affected by thermal conditions in the luminaire in which they are installed.

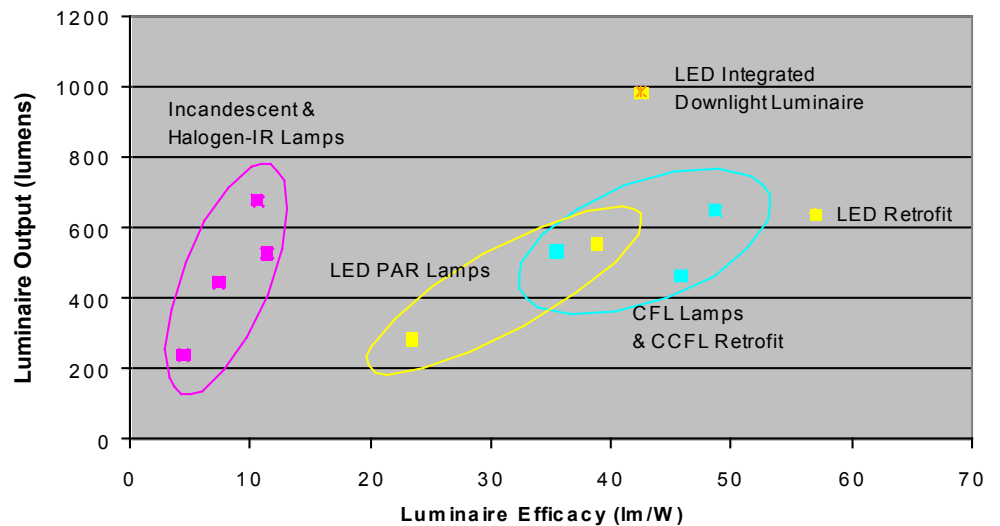


Figure 1. Comparison of Luminaire Efficacies for Recessed Downlights with LED, Compact Fluorescent (CFL), Cold-Cathode Fluorescent (CCFL), Halogen-IR and Incandescent Sources (includes ballast, driver and thermal losses, where applicable). Lamps and retrofit products were tested in the same downlight fixture housing. Source: CALiPER

Lumen Depreciation

All light sources diminish in output over their operating life. Consequently, most lighting installations are designed around the average (i.e., mean or design mean) lumen output of the lamp or, in critical applications, on output at the end of life. By extension, when comparing the energy efficiency of different types of light sources and luminaires, it is important to consider mean or end-of-life efficacy, and not initial efficacy.

Lifetime for traditional light sources is based on lamp failure, with mean lumen output measured at a percentage of rated lamp life, typically 40% for fluorescent and metal halide lamps. LEDs can continue to operate long after their light output has dropped below useful levels, so their design life is instead based on a percentage of initial lumens. In the LED industry, these lifetime specifications are known as L_{50} and L_{70} , which represent estimated operating hours to 50% and 70% of initial light output, respectively.

Currently, high-performance linear fluorescent lamps offer mean lumen outputs that are as high as 95% to 97% of their initial values. Lumen depreciation for LEDs is not yet as well understood; with useful life defined as L_{70} , a linear depreciation curve would imply mean lumen values of about 85% of initial output. To achieve comparable mean luminaire efficacy in this case, LED luminaires must have a higher initial efficacy than their fluorescent or other counterparts. Table 1 illustrates how a hypothetical LED luminaire with initial luminaire efficacy equal to a high-performance T8 fluorescent luminaire

will yield a lower mean efficacy, decreasing net energy savings by approximately 12% (Case 1). To achieve the same mean efficacy, the LED system would require an initial efficacy approximately 14% higher than the fluorescent system (Case 2).

Remember that mean lumen output for a fluorescent or metal halide lamp is measured at 40% of rated life. For high-performance T8 fluorescent lamps, rated lamp life can range from 30,000 to 46,000 hours, which means that mean lumen output (and mean luminaire efficacy) would occur after approximately 12,000 to 18,000 hours. Major LED manufacturers generally claim design life (L_{70}) values in excess of 50,000 hours; the actual operating time to reach mean luminaire efficacy will vary with the LED device and luminaire design, and actual operating conditions. Note also that useful design life in some applications may be less than a manufacturer's L_{70} value, necessitating a careful evaluation of available lumen depreciation data to estimate mean luminaire efficacy.

	T8 Fluorescent	LED Case 1	LED Case 2
Lamp Initial Lumens	2,850		
No. of Lamps	2		
Total Lamp Initial Lumens	5,700		
Ballast Factor	0.88		
System Initial Lumens	5,016		
System Input Power (W)	52		
System Initial Efficacy (lm/W)	96		
Luminaire Efficiency (%)	85.6		
Luminaire Initial Efficacy (lm/W)	83	83	94
Lamp Mean Lumens (% of initial)	97	85	85
Luminaire Mean Efficacy (lm/W)	80	71	80

Light Output and Distribution

LED light output and efficacy depend on effective thermal management. However, the required heat sink surface area can limit the installed density, input power, and lumen output of LEDs—particularly in small luminaires and replacement lamps. A LED-based MR16 replacement lamp, for example, can neither aggregate enough LEDs nor provide sufficient heat sinking to match the light output and luminous intensity of a typical 50-watt tungsten-halogen MR16 today. In contrast, multiple arrays of high-flux LEDs can be assembled in larger outdoor area and roadway luminaires with integrated heat sinking, providing an energy-efficient alternative to high-pressure sodium and metal halide lamps.

Despite their comparatively low light output, LEDs are inherently directional sources and offer better optical control than traditional energy-efficient sources like fluorescent and metal halide lamps. This allows properly-designed LED luminaires to direct light where it is needed, efficiently achieving desired illumination levels and uniformity. With fewer total lumens, LED luminaires can produce high light levels on nearby surfaces (e.g., indoor applications using recessed downlights or task lighting), or low light levels on more distant surfaces (e.g., outdoor nighttime applications using pole-mounted area or roadway luminaires). As an example, Figure 1 illustrates how LED luminaires can achieve higher efficacies in directed light applications (e.g., downlights) than traditional sources. To maximize energy efficiency and lighting quality, it is important to evaluate each luminaire against the specific light level and uniformity requirements of each application.

Color Quality

To produce white light, most currently available LED luminaires employ phosphor-coated blue LEDs or, less commonly, various combinations of red, green and blue (RGB) LEDs. White light LEDs are available in a wide range of correlated color temperatures (CCT), allowing LED luminaires to integrate with or replace many traditional light sources. For example, ANSI C78.377-2008 establishes eight acceptable CCTs for LED products, ranging from 2700K (similar to incandescent) to 6500K (similar to daylight fluorescent). The ANSI standard also establishes D_{uv} chromaticity targets and tolerances to prescribe the relative “whiteness” for each nominal CCT.² As shown in Figure 2, a number of CALiPER-tested LED replacement lamps with acceptable CCT values had D_{uv} values that exceeded ANSI tolerances and were off-white (e.g., greenish, bluish, etc.) in appearance.

Phosphor-converted LEDs generally offer a color rendering index (CRI) higher than that for RGB LED systems and comparable to or higher than traditional light sources. However, the existing CRI metric has been found to be a poor predictor of user acceptance for RGB LED systems, which can provide good subjective color rendering despite having low CRI values.

Phosphor-converted LEDs with higher CCTs tend to have higher efficacies than LEDs with lower CCTs, and some manufacturers emphasize the performance of their high CCT LEDs in their advertising. When evaluating LED luminaires and

replacement lamps, verify that the performance data correspond with the correct CCT for your application. Remember also that products with similar CCT and CRI can deliver noticeably different color quality, and that luminaire color appearance and rendering should be evaluated in person if practicable.

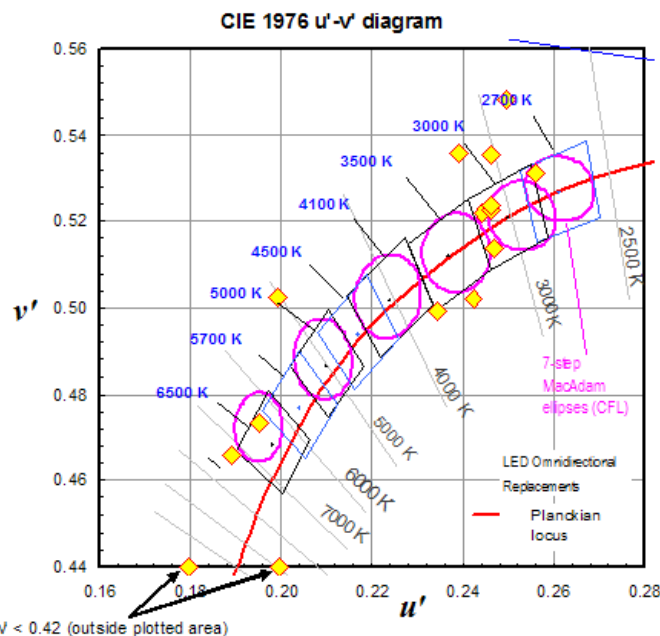


Figure 2. Chromaticity of LED Omnidirectional Replacement Lamps (shown as diamonds) plotted against ANSI Chromaticity Specifications (chromaticity diagram from ANSI C78.377-2008). Data source: CALiPER

²LED products meeting white light CCT specifications but falling outside D_{uv} tolerances may appear colored (e.g., green, yellow, purple).

A Strong Energy Portfolio for a Strong America

Energy efficiency and clean, renewable energy will mean a stronger economy, a cleaner environment, and greater energy independence for America. Working with a wide array of state, community, industry, and university partners, the U.S. Department of Energy’s Office of Energy Efficiency and Renewable Energy invests in a diverse portfolio of energy technologies.

For more information contact:

EERE Information Center
1-877-EERE-INF
(1-877-337-3463)
www.eere.energy.gov

Acknowledgement:

U.S. DOE acknowledges the major contribution of Victor Roberts in the writing of this document.

For Program Information on the Web:

www.ssl.energy.gov
DOE sponsors a comprehensive program of SSL research, development, and commercialization.

For Program Information:

Kelly Gordon
Pacific Northwest National Laboratory
Phone: (503) 417-7558
E-mail: kelly.gordon@pnl.gov

PNNL-SA-63254
October 2008

Printed on 30% post-consumer recycled paper.

