FAQs on Market-Available LEDs

DOE's solid-state lighting (SSL) R&D program focuses on ensuring the development of *energy-efficient* SSL technologies, an emphasis that, without DOE leadership, might be lost on the path to commercialization. DOE has a responsibility to ensure that SSL reaches its full energy savings potential, significantly reducing building energy use and costs, and contributing to our nation's energy security.

This page answers some frequently asked questions about the status of light emitting diode (LED) and SSL technologies available on the market today.

- Why are we hearing so much about LEDs today?
- How long will it take before we see energy-efficient, cost-competitive, white-light SSL products on the market?
- There already appear to be a lot of white-light LED products available now… what should I look for?
- Do LEDs really last 50,000 hours? 100,000 hours?
- Why is there such variation among available SSL products, in terms of efficacy and light output?
- How is DOE coordinating its R&D activities with the market?
- Are there ENERGY STAR SSL products on the market?

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Why are we hearing so much about LEDs today?

LEDs have been around since the 1960s, but they are just now reaching the levels of luminous output and power that open the door to more applications. For example, today's commercially available LEDs offer energy efficiency, maintenance savings, impact resistance, durability, and other benefits for traffic signals, exit signs, and other specialty applications. White LEDs are approaching performance levels that make them attractive for use in automobiles, aircraft, and elevators. For most general illumination applications, however, current LEDs cannot yet compete with traditional sources on the basis of performance or cost. More research is needed to increase the efficiency and decrease the cost of LED technologies.

How long will it take before we see energy-efficient, cost-competitive, white-

light products on the market?
DOE's SSL R&D plan spans 20 years (2000-2020), and includes three components: Core Technology Research, Product Development, and Commercialization Support activities. The good news is that tremendous progress is being made, faster than originally anticipated. Researchers have already improved the efficacy of white LEDs to approximately 50 lumens per watt, almost four times more efficient than incandescent sources. Costs are still high, but continue to drop significantly, from approximately $250/kilo-lumen in 2004 to around $50/kilo-lumen in 2006 (based on manufacturer estimates for volume purchase). For comparison, conventional light sources (incandescent, fluorescent) cost around $1/kilo-lumen.

There already appear to be a lot of white-light LED products available now… what should I look for?
Some of the LED products available today are marketed as "energy-efficient," but actually have very low light output compared to typical light sources. The combination of high price and low light output may actually make them a poor replacement for current technology. It is important to compare new LED products to the most efficient conventional technology (such as fluorescent, incandescent, or metal halide) that could be used in your specific application. The following checklist will help you determine if an LED product is right for your application:

- ✔ **Ask how many watts the product consumes and how many lumens of light it produces.** Lumens per watt (lpw) is the commonly used measure of how efficiently a light source is converting electricity into useable light. For comparison, incandescent lamps typically produce 12-15 lumens per watt of electric power. Compact fluorescent lamps (CFLs) produce at least 50 lumens per watt. Currently available high-brightness LEDs can produce about 30-35 lumens per watt.

  In task lighting applications, LEDs may be able to provide enough light on the task, even though the total lumens are less than comparable incandescent or fluorescent sources. This is because LEDs emit light in a less diffuse pattern than conventional light sources. In contrast, standard incandescent bulbs and fluorescent lamps emit light in all directions, and much of the light output is absorbed inside the fixture or escapes in an unintended direction.

- ✔ **Evaluate the cost.** For comparison, a 75-watt incandescent light bulb typically produces about 1,000 lumens and costs less than $1. The problem is, it only lasts about 1,000 hours and only converts about 5% of the electricity it consumes into light (the rest is wasted as heat). A comparable CFL is 5 times more efficient, lasts 10,000 hours, and costs less than $5. So the conventional light sources cost around $1 per thousand lumens. Today's white LED products cost more than $50 per thousand lumens. But that's only part of the story. If you have lights that are on most of the time, or in a hard-to-reach area, LEDs could save significant maintenance and energy costs.

- ✔ **Assess the need for unique LED features**. In some applications, the extra durability that LEDs can provide is worth a higher purchase price. Outdoor pathway and step lighting is an example of a sensible application for today's white LEDs. They provide a small amount of light right where it's needed, and can be powered by solar cells, eliminating the need for running wire outdoors. They are also good for applications where vibration typically leads to early failure of conventional light sources. Being a solid-state device, LEDs are highly resistant to damage caused by vibration.

- **Check the color of white LEDs.** If you've ever tried to match white paint, you know there are actually many shades of white. There is a similar issue with lighting. White light varies from “warm” or more yellow/gold in appearance, to “cool” or more blue. Today's white LEDs are typically “cooler” and bluer, even compared to fluorescent sources. Further, there is a trade-off between efficiency and color. The “warmer” colored white LEDs provide less light per watt of electricity consumed, compared to the “cooler” white LEDs.

- **Get a sample of the product if possible, so you can evaluate it yourself.** Because of the current lack of standardized testing procedures and product specifications among LED product manufacturers, there is not yet a reliable way to compare product performance based on information provided by the manufacturer. The best way to assess a product you are considering is to ask for a sample.

Do LEDs really last 50,000 hours? 100,000 hours?
There is no simple answer to this question. Considering that 100,000 hours is more than 11 years of 24/7 operation, it's difficult to do life testing on these products! However, SSL researchers have developed ways to estimate LED life, based on shorter test periods. Unlike other light sources, LEDs don't typically “burn out;” they simply get dimmer over time. Although there is not yet an official industry standard defining “life” of an LED, the leading manufacturers report it as the point at which light output has reached 70% of initial light output. Using that definition, the best white LEDs have been found to have a useful life of around 35,000 hours (that's four years of continuous operation). LED lifetime is strongly dependent on appropriate electrical and thermal design of the fixture or system. While LEDs do not emit heat in the form of infrared radiation (IR), they do generate conductive heat that must be managed in order for the LED to maintain expected light output. Reputable LED manufacturers provide detailed electrical and thermal design specifications. When considering an LED-based fixture or system, it may be worthwhile to ask about the type of LEDs used and what provisions the product manufacturer has made for heat management.

Why is there such variation among available SSL products, in terms of efficacy and light output?
There is currently a lack of consensus test procedures and performance standards for LEDs. The performance of traditional light sources (incandescent, fluorescent, HID) is determined by accepted test procedures that are followed industry wide. This allows comparison of products made by different manufacturers because they all have to test their products and report results in the same way. In many cases, test procedures will need to be revised to account for technical differences in the way LEDs operate, relative to traditional light sources. DOE is working with the National Electrical Manufacturers Association (NEMA), the Next Generation Lighting Industry Alliance, and other industry and research organizations to begin developing the needed metrics, codes, and standards for SSL products.

How is DOE coordinating its R&D activities with the market?
The SSL Partnership between DOE and the Next Generation Lighting Industry Alliance is designed to enhance the manufacturing and commercialization focus of the DOE SSL R&D program. The Alliance is administered by NEMA, and its membership includes 3M, Acuity Brands Lighting, Air Products & Chemicals Inc., CAO Group Inc., Color Kinetics Inc., Corning Inc., Cree Inc., Dow Corning Corporation, Eastman Kodak Company, GELcore LLC, General Electric Company, Lumileds Lighting LLC, OSRAM Opto Semiconductors Inc., OSRAM Sylvania Inc., and Philips Electronics North America Corporation. Learn more about the SSL Partnership and Next Generation Lighting Industry Alliance activities. In addition, DOE has developed a commercialization support strategy to ensure that its R&D investments lead to SSL technology commercialization. Working with the SSL Partnership and other industry and energy organizations, DOE is planning a full range of activities, including:

- ENERGY STAR® designation for SSL technologies and products
- Design competitions for lighting fixtures and systems using SSL
- Coordination with utility promotions and regional energy efficiency programs
- Technology procurement programs that encourage manufacturers to bring high-quality, energy-efficient SSL products to the market, and that link these products to volume buyers
- Consumer and business awareness programs
- Information resources for lighting design professionals and students

At the 2006 DOE SSL Workshop, DOE provided an update on initial activities under way, including progress in the development of ENERGY STAR criteria for SSL products, and the announcement of a new SSL category in the 2006 Lighting for Tomorrow design competition. For more information, see the 2006 SSL Workshop Highlights or download specific workshop presentations and materials.

Are there ENERGY STAR SSL products on the market?
Not yet, although DOE's commercialization support strategy does include the development of an ENERGY STAR designation for SSL technologies and products. DOE will coordinate the timing of this process with SSL technology advances, to ensure optimal alignment of technology readiness and market readiness.

LED Application Series:

Recessed Downlights

Recessed downlights are very common in both residential and commercial buildings. Is this a good application for LEDs? This fact sheet explores issues unique to this type of luminaire, and the potential for use of LEDs in downlights.

Recessed downlights are the most common installed luminaire type in residential new construction. Downlights are used for general ambient lighting in kitchens, hallways, bathrooms, and other areas of the home. Downlights with small apertures and more directional lensing and baffling are also used for wall-washing and accent lighting. In commercial settings, a wide variety of downlight types, sizes, and finishes are used in lobbies, perimeter areas, hallways, and restrooms.

The light output of a recessed downlight is a function of the lumens produced by the lamp and the luminaire efficiency. Reflector-style lamps are specially shaped and coated to emit light in a defined cone, while "A" style incandescent lamps and CFLs emit light in all directions, leading to significant light loss within the luminaire. Downlights using non-reflector lamps are typically only 50% efficient, meaning about half the light produced by the lamp is wasted inside the fixture. LEDs are more directional, but can they provide enough light? For comparison, the table below shows typical light output and efficiency of residential-style fluorescent and incandescent recessed downlights and an LED downlight.

Examples of Recessed Downlight Performance Using Different Light Sources

		Fluorescent*		Incandescent*		LED**
		26W pin-based CFL	15W R-30 CFL Edison base	65W R-30	100W A-19	LED 15W Downlight
LAMP	Rated lamp lumens	1800	750	755	1700	unknown
	Lamp wattage (nominal W)	26	15	65	100	9 × 1W LEDs
	Lamp efficacy (lm/W)	**70**	**50**	**12**	**17**	**45**
LUMINAIRE	Luminaire efficiency	50%	90%	90%	50%	unknown
	Delivered light output (lumens), initial	900	675	680	850	300
	Luminaire wattage (nominal W)	27	15	65	100	15
	Luminaire efficacy (lm/W)	**33**	**45**	**10**	**9**	**20**

*Based on photometric data for commonly available products. Actual product performance depends on reflectors, trims, lamp positioning, and other factors. Assumptions available from PNNL.

**Based on one commercially-available product tested. Other LED-based downlights may differ. Lamp efficacy for the LED product refers to the manufacturer listed "typical luminous flux" of the LEDs used. Luminous flux of the 9-LED array is not known.

Even though the 26W CFL is the most efficacious light source listed, the 15W reflector CFL provides higher luminaire efficacy, i.e., total lumens out of the fixture per watt consumed. The 15W LED downlight provides less than half the delivered light output of the 15W reflector CFL. As LED technology matures, this performance is expected to improve.


Source: PNNL

Terms

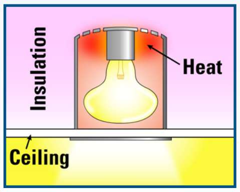
Luminaire – a complete lighting unit including lamp(s), ballast(s) (when applicable), and the parts designed to distribute the light, position and protect the lamps, and connect to the power supply.

Luminaire (fixture) efficiency – the ratio of luminous flux (lumens) emitted by a luminaire to that emitted by the lamp or lamps used therein; expressed as a percentage.

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

ICAT – stands for "insulated ceiling (or "insulation contact"), air tight" and refers to ratings on recessed downlight luminaires used in residential construction.

Downlights installed on the top floor of a house are immersed in insulation, creating a high-temperature operating environment that is difficult for CFLs and potentially similarly challenging for LEDs. Further, energy codes in most states require downlights installed in the building shell to be rated "air tight" to minimize loss of heating and cooling energy.



Potential for use of LEDs in downlights

Given the prevalence of downlights in both residential and commercial buildings, potential energy savings from high-performing, energy-efficient downlights would be significant. The high-temperature environment described above has plagued attempts to use CFLs in downlights, although recent developments in reflector CFLs are promising (see **www.pnl.gov/rlamps**). Would LEDs do better?

The inherent directionality of LEDs is a potential advantage for their use in downlighting applications. If designed effectively, LED downlights could essentially eliminate luminaire light losses. LEDs also work with standard wall-mounted dimmers, unlike CFLs.

However, to approach the light output typically expected for downlights requires multiple LEDs to be grouped together. Clustering LEDs in the relatively small downlight package generates considerable heat. Actual light output depends on good thermal management in the fixture. If the heat is not adequately managed, LED device temperature will rise, light output will fall, and the useful life of the fixture will be disappointingly short. This concern is particularly important in residential insulated ceiling applications.

LED downlights available to date provide about half the delivered light output of downlights using 65W R incandescent or 15W reflector CFLs. However, as LED technology and product designs mature, LEDs are expected to compete favorably with traditional light sources in downlighting applications.

Comparison of Recessed Downlight Lamping Options

	Advantages	Disadvantages
Incandescent Reflector	• Dimmable • High color quality • Low lamp cost	• High wattage • Short life (2000 hrs) • Heat increases cooling load
CFL Reflector	• High efficacy • Long life (6000-8000 hrs)	• Few dimmable products • More expensive than incand.
CFL Pin-based	• High efficacy • Long life (10000 hrs)	• Few dimmable products • More expensive than incand. • Replacement lamps can be difficult to find
LED Downlight	• Dimmable • Potentially long life • Lower wattage than incand. • Directional light source	• Relatively low light output* • Expensive to purchase* • Very sensitive to high-temperature environment* • Replacement lamps not available

*Listed disadvantages reflect current status of LED technology (Nov 2006). Expected technology improvements in coming years will mitigate and possibly eliminate these disadvantages.

In conclusion, recessed downlighting is potentially a good application for LEDs, when the technology matures. As new LED downlights are introduced on the market, they should be evaluated carefully, keeping the following considerations in mind:

- The light output of current LED downlights may be 25% to 50% lower than standard incandescent and CFL downlights. The overall room lighting design will need to account for this.
- Ask the LED downlight manufacturer about measured performance of the luminaire in insulated ceilings. Does the luminaire design adequately manage the heat? If such performance information is not available, it may be best to avoid LED use in insulated ceiling, airtight (ICAT) conditions.

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http://www.buildings.gov
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Click on 'Commercial Product Testing Program' in the left menu for further information on performance of commercially-available LED products.

For Information on the Next Generation Lighting Industry Alliance:

www.nglia.org

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Thermal Management of White LEDs

LEDs won't burn your hand like some light sources, but they do produce heat. In fact, thermal management is arguably the most important aspect of successful LED system design. This fact sheet reviews the role of heat in LED performance and methods for managing it.

All light sources convert electric power into radiant energy and heat in various proportions. Incandescent lamps emit primarily infrared (IR), with a small amount of visible light. Fluorescent and metal halide sources convert a higher proportion of the energy into visible light, but also emit IR, ultraviolet (UV), and heat. LEDs generate little or no IR or UV, but convert only 15%-25% of the power into visible light; the remainder is converted to heat that must be conducted from the LED die to the underlying circuit board and heat sinks, housings, or luminaire frame elements. The table below shows the proportions in which each watt of input power is converted to heat and radiant energy (including visible light) for various white light sources.

Power Conversion for "White" Light Sources

	Incandescent† (60W)	Fluorescent† (Typical linear CW)	Metal Halide‡	LED*
Visible Light	7.5%	21%	27%	15-25%
IR	73.3%	37%	17%	~ 0%
UV	0%	0%	19%	0%
Total Radiant Energy	80.8%	58%	63%	10-15%
Heat (Conduction + Convection)	19.2%	42%	37%	75-85%
Total	100%	100%	100%	100%

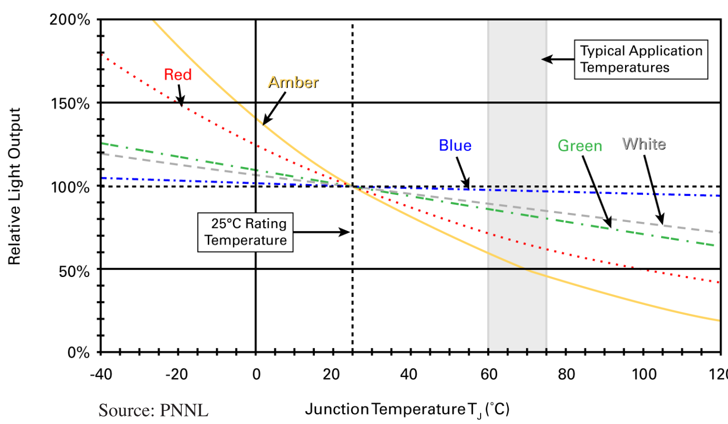
† IESNA Handbook ‡ Osram Sylvania

* Varies depending on LED efficacy. This range represents best currently available technology in color termperatures from warm to cool. DOE's SSL Multi-Year Program Plan (Mar 2006) calls for increasing extraction efficiency to more than 50% by 2012.

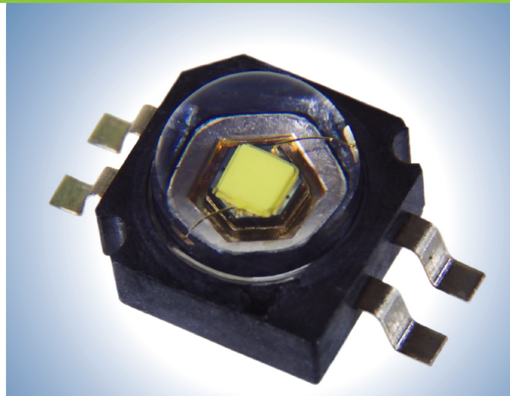
Why does thermal management matter?

Excess heat directly affects both short-term and long-term LED performance. The short-term (reversible) effects are color shift and reduced light output while the long-term effect is accelerated lumen depreciation and thus shortened useful life.

The light output of different colored LEDs responds differently to temperature changes, with amber and red the most sensitive, and blue the least. (See graph at right.) These unique temperature response rates can result in noticeable color shifts in RGB-based white light systems if operating T_j differs from the design parameters. LED manufacturers test and sort (or "bin") their products for luminous flux and color based on a 15-20 millisecond power pulse, at a fixed T_j of 25°C (77°F). Under constant current operation at room temperatures and with engineered heat mitigation mechanisms, T_j is typically 60°C or greater. Therefore white LEDs will provide at least 10% less light than the manufacturer's rating, and the reduction in light output for products with inadequate thermal design can be significantly higher.



Source: PNNL



Philips Lumileds Luxeon K2

Terms

Conduction – transfer of heat through matter by communication of kinetic energy from particle to particle. An example is the use of a conductive metal such as copper to transfer heat.

Convection – heat transfer through the circulatory motion in a fluid (liquid or gas) at a non-uniform temperature. Liquid or gas surrounding a heat source provides cooling by convection, such as air flow over a car radiator.

Radiation – energy transmitted through electromagnetic waves. Examples are the heat radiated by the sun and by incandescent lamps.

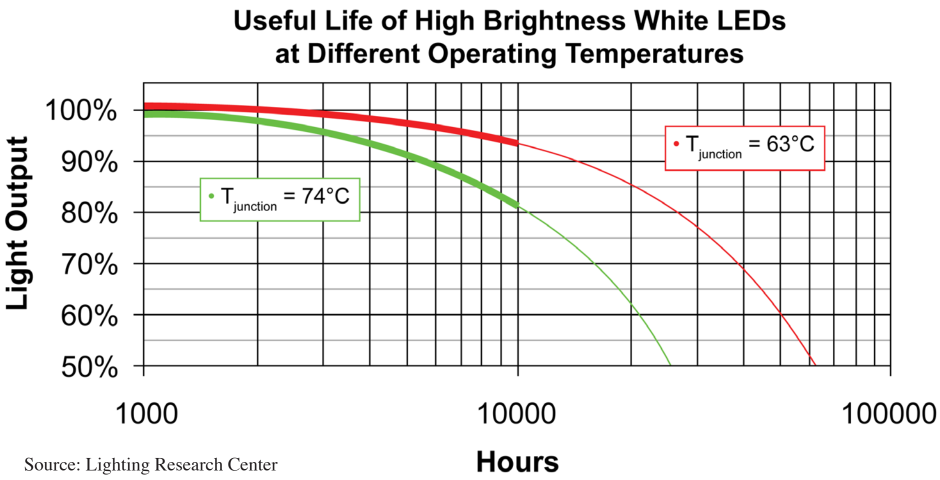
Junction temperature (T_j) – temperature within the LED device. Direct measurement of T_j is impractical but can be calculated based on a known case or board temperature and the materials' thermal resistance.

Heat sink – thermally conductive material attached to the printed circuit board on which the LED is mounted. Myriad heat sink designs are possible; often a "finned" design is used to increase the surface area available for heat transfer. For general illumination applications, heat sinks are often incorporated into the functional and aesthetic design of the luminaire, effectively using the luminaire chassis as a heat management device.

Source: Enlux

Continuous operation at elevated temperature dramatically accelerates lumen depreciation resulting in shortened useful life. The chart below shows the light output over time (experimental data to 10,000 hours and extrapolation beyond) for two identical LEDs driven at the same current but with an 11°C difference in T_j. Estimated useful life (defined as 70% of initial lumen output) decreased from ~37,000 hours to ~16,000 hours, a 57% reduction, with the 11°C temperature increase.

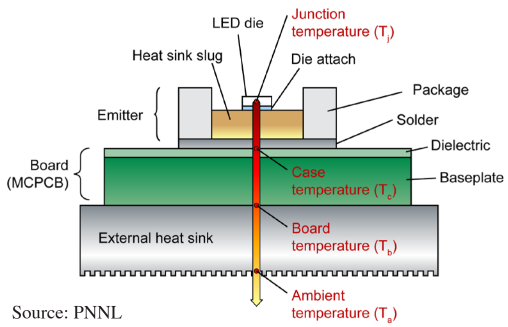
However, the industry continues to improve the durability of LEDs at higher operating temperatures. The Luxeon K2 shown on page 1, for example, claims 70% lumen maintenance for 50,000 hours at drive currents up to 1000 mA and T_j at or below 120°C.[1]



Source: Lighting Research Center

What determines junction temperature?

Three things affect the junction temperature of an LED: drive current, thermal path, and ambient temperature. In general, the higher the drive current, the greater the heat generated at the die. Heat must be moved away from the die in order to maintain expected light output, life, and color. The amount of heat that can be removed depends upon the ambient temperature and the design of the thermal path from the die to the surroundings.



Source: PNNL

The typical high-flux LED system is comprised of an emitter, metal-core printed circuit board (MCPCB), and some form of external heat sink. The emitter houses the die, optics, encapsulant, and heat sink slug (used to draw heat away from the die) and is soldered to the MCPCB. The MCPCB is a special form of circuit board with a dielectric layer (non-conductor of current) bonded to a metal substrate (usually aluminum). The MCPCB is then mechanically attached to an external heat sink which can be a dedicated device integrated into the design of the luminaire or, in some cases, the chassis of the luminaire itself. The size of the heat sink is dependent upon the amount of heat to be dissipated and the material's thermal properties.

Heat management and an awareness of the operating environment are critical considerations to the design and application of LED luminaires for general illumination. Successful products will use superior heat sink designs to dissipate heat, and minimize T_j. Keeping the T_j as low as possible and within manufacturer specifications is necessary in order to maximize the performance potential of LEDs.

[1] Luxeon K2 Emitter Datasheet DS51 (5/06)

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For Information on the Next Generation Lighting Industry Alliance:

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Lifetime of White LEDs

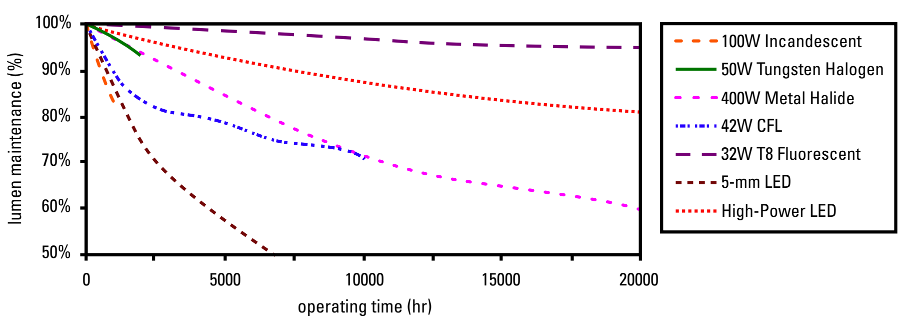
One of the main "selling points" of LEDs is their potentially very long life. Do they really last 50,000 hours or even 100,000 hours? This fact sheet discusses lumen depreciation, measurement of LED useful life, and the features to look for in evaluating LED products.

Lumen Depreciation

All electric light sources experience a decrease in the amount of light they emit over time, a process known as lumen depreciation. Incandescent filaments evaporate over time and the tungsten particles collect on the bulb wall. This typically results in 10-15% depreciation compared to initial lumen output over the 1,000 hour life of an incandescent lamp.

In fluorescent lamps, photochemical degradation of the phosphor coating and accumulation of light-absorbing deposits cause lumen depreciation. Compact fluorescent lamps (CFLs) generally lose no more than 20% of initial lumens over their 10,000 hour life. High-quality linear fluorescent lamps (T8 and T5) using rare earth phosphors will lose only about 5% of initial lumens at 20,000 hours of operation.

Typical Lumen Maintenance Values for Various Light Sources



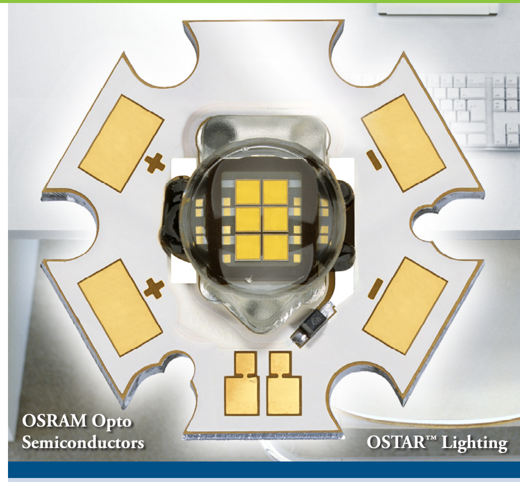
Source: Adapted from Bullough, JD. 2003. *Lighting Answers: LED Lighting Systems.* Troy, NY. National Lighting Product Information Program, Lighting Research Center, Rensselaer Polytechnic Institute.

The primary cause of LED lumen depreciation is heat generated at the LED junction. LEDs do not emit heat as infrared radiation (IR), so the heat must be removed from the device by conduction or convection. Without adequate heat sinking or ventilation, the device temperature will rise, resulting in lower light output. While the effects of short-term exposure to high temperatures can be reversed, continuous high temperature operation will cause permanent reduction in light output. LEDs continue to operate even after their light output has decreased to very low levels. This becomes the important factor in determining the effective useful life of the LED.

Defining LED Useful Life

To provide an appropriate measure of useful life of an LED, a level of acceptable lumen depreciation must be chosen. At what point is the light level no longer meeting the needs of the application? The answer may differ depending on the application of the product. For a common application such as general lighting in an office environment, research has shown that the majority of occupants in a space will accept light level reductions of up to 30% with little notice, particularly if the reduction is gradual.[1] Therefore a level of 70% of initial light level could be considered an appropriate threshold of useful life for general lighting. Based on this research, the Alliance for Solid State Illumination Systems and Technologies (ASSIST), a group led by the Lighting Research Center (LRC),

[1]Rea MS (ed.). 2000. IESNA Lighting Handbook: Reference and Application, 9th ed. New York: Illuminating Engineering Society of North America.
Knau H. 2000. Thresholds for detecting slowly changing Ganzfeld luminances. J Opt Soc Am A 17(8): 1382-1387.



Terms

Lumen depreciation - the decrease in lumen output that occurs as a lamp is operated.

Rated lamp life – the life value assigned to a particular type lamp. This is commonly a statistically determined estimate of average or median operational life. For certain lamp types other criteria than failure to light can be used; for example, the life can be based on the average time until the lamp type produces a given fraction of initial luminous flux.

Life performance curve – a curve that presents the variation of a particular characteristic of a light source (such as luminous flux, intensity, etc.) throughout the life of the source. Also called lumen maintenance curve.

Source: Rea 2000.

Checklist

What features should you look for in evaluating the projected lifetime of LED products?

- ☑ Does the LED manufacturer publish thermal design guidance?
- ☑ Does the lamp design have any special features for heat sinking/ thermal management?
- ☑ Does the fixture manufacturer have test data supporting life claims?
- ☑ What life rating methodology was used?
- ☑ What warranty is offered by the manufacturer?

recommends defining useful life as the point at which light output has declined to 70% of initial lumens (abbreviated as L_{70}) for general lighting and 50% (L_{50}) for LEDs used for decorative purposes. For some applications, a level higher than 70% may be required.

Measuring Light Source Life

The lifetimes of traditional light sources are rated through established test procedures. For example, CFLs are tested according to LM-65, published by the Illuminating Engineering Society of North America (IESNA). A statistically valid sample of lamps is tested at an ambient temperature of 25° Celsius using an operating cycle of 3 hours ON and 20 minutes OFF. The point at which half the lamps in the sample have failed is the rated average life for that lamp. For 10,000 hour lamps, this process takes about 15 months.

Full life testing for LEDs is impractical due to the long expected lifetimes. Switching is not a determining factor in LED life, so there is no need for the on-off cycling used with other light sources. But even with 24/7 operation, testing an LED for 50,000 hours would take 5.7 years. Because the technology continues to develop and evolve so quickly, products would be obsolete by the time they finished life testing.

The IESNA is currently developing a life testing procedure for LED products, based in part on the *ASSIST recommends* approach. The proposed method involves operating the LED component or system at rated current and voltage for 1,000 hours as a "seasoning period." This is necessary because the light output actually increases during the first 1,000 hours of operation, for most LEDs. Then the LED is operated for another 5,000 hours. The radiant output of the device is measured at 1,000 hours of operation; this is normalized to 100%. Measurements taken between 1,000 and 6,000 hours are compared to the initial (1,000 hour) level. If the L_{70} and L_{50} levels have not been reached during the 6,000 hours, the data are used to extrapolate those points.

LED Lifetime Characteristics

How do the lifetime projections for today's white LEDs compare to traditional light sources?

Light Source	Range of Typical Rated Life (hours)* (varies by specific lamp type)	Estimated Useful Life (L_{70})
Incandescent	750-2,000	
Halogen incandescent	3,000-4,000	
Compact fluorescent (CFL)	8,000-10,000	
Metal halide	7,500-20,000	
Linear fluorescent	20,000-30,000	
High-Power White LED		35,000-50,000

*Source: lamp manufacturer data.

Electrical and thermal design of the LED system or fixture determine how long LEDs will last and how much light they will provide. Driving the LED at higher than rated current will increase relative light output but decrease useful life. Operating the LED at higher than design temperature will also decrease useful life significantly.

Most manufacturers of high-power white LEDs estimate a lifetime of around 30,000 hours to the 70% lumen maintenance level, assuming operation at 350 milliamps (mA) constant current and maintaining junction temperature at no higher than 90°C. However, LED durability continues to improve, allowing for higher drive currents and higher operating temperatures. Specific manufacturer data should be consulted because some LEDs available today are rated for 50,000 hours at 1000 mA with junction temperature up to 120°C.[2]

[2]Philips Lumileds Lighting. LUXEON K2 Emitter Datasheet DS51 (5/06)

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Energy Efficiency of White LEDs

The energy efficiency of light-emitting diodes (LEDs) is expected to rival the most efficient white light sources by 2010. But how energy efficient are LEDs right now? This fact sheet discusses various aspects of lighting energy efficiency and the rapidly evolving status of white LEDs.

Luminous Efficacy

Energy efficiency of light sources is typically measured in lumens per watt (lm/W), meaning the amount of light produced for each watt of electricity consumed. This is known as luminous efficacy. DOE's long-term research and development goal calls for white-light LEDs producing 160 lm/W in cost-effective, market-ready systems by 2025. In the meantime, how does the luminous efficacy of today's white LEDs compare to traditional light sources? Currently, the best white LEDs approach the efficacy of compact fluorescent lamps (CFLs). However, there are several important caveats, as explained below.

Color Quality

To date, LED luminous efficacy similar to that of CFLs has been achievable only with higher color temperature products, which produce a "cool" or bluish-toned light and relatively low color rendering index (CRI) in the 70s. LEDs with warmer color appearance and higher CRI are only marginally more efficacious than incandescent sources. However, this is changing rapidly, with new performance improvements being announced regularly by the industry. For more detail, see DOE fact sheet "Color Quality of White LEDs."

Driver Losses

Fluorescent and high-intensity discharge (HID) light sources cannot function without a ballast, which provides a starting voltage and limits electrical current to the lamp. LEDs also require supplementary electronics, usually called drivers. The driver converts line power to the appropriate voltage (typically between 2 and 4 volts DC for high-brightness LEDs) and current (generally 200-1000 milliamps or mA), and may also include dimming and/or color correction controls.

Currently available LED drivers are typically about 85% efficient. So LED efficacy should be discounted by 15% to account for the driver. For a rough comparison, the range of luminous efficacies for traditional and LED sources, including ballast and driver losses as applicable, are shown below.

Light Source	Typical Luminous Efficacy Range in lm/W (varies depending on wattage and lamp type)
Incandescent	10-18
Halogen incandescent	15-20
Compact fluorescent (CFL)	35-60
Linear fluorescent	50-100
Metal halide	50-90
Cool white LED 5000K	45-59*
Warm white LED 3300K	22-37*

*Current as of October 2006.

Thermal Effects

The luminous flux figures cited by LED manufacturers are based on an LED junction temperature (T_j) of 25°Celsius. LEDs are tested during manufacturing under conditions that differ from actual operation in a fixture or system. In general, luminous flux is measured under instantaneous operation (perhaps a 20 millisecond pulse) in open air. T_j will always be higher when operated under constant current in a fixture or system. LEDs in a well-designed luminaire with adequate heat sinking will produce 10%-15% less light than indicated by the "typical luminous flux" rating.

Cree Inc.

Terms

Lumen – the SI unit of luminous flux. The total amount of light emitted by a light source, without regard to directionality, is given in lumens.

Luminous efficacy – the total luminous flux emitted by the light source divided by the lamp wattage; expressed in lumens per watt (lm/W).

Luminaire efficacy – the total luminous flux emitted by the luminaire divided by the total power input to the luminaire, expressed in lm/W.

Application efficiency – While there is no standard definition of application efficiency, we use the term here to denote an important design consideration: that the desired illuminance level and lighting quality for a given application should be acheived with the lowest practicable energy input. Light source directionality and intensity may result in higher application efficiency even though luminous efficacy is lower relative to other light sources.

Efficiency or efficacy? – The term "efficacy" normally is used where the input and output units differ. For example in lighting, we are concerned with the amount of light (in lumens) produced by a certain amount of electricity (in watts). The term "efficiency" usually is dimensionless. For example, lighting fixture efficiency is the ratio of the total lumens exiting the fixture to the total lumens produced by the light source. "Efficiency" is also used to discuss the broader concept of using resources efficiently.

Comparing LEDs to Traditional Light Sources

Energy efficiency proponents are accustomed to comparing light sources on the basis of luminous efficacy. To compare LED sources to CFLs, for example, the most basic analysis should compare lamp-ballast efficacy to LED+driver efficacy in lumens per watt. Data sheets for white LEDs from the leading manufacturers will generally provide “typical” luminous flux in lumens, test current (mA), forward voltage (V), and junction temperature (T_j), usually 25 degrees Celsius. To calculate lm/W, divide lumens by current times voltage. As an example, assume a device with typical flux of 45 lumens, operated at 350 mA and voltage of 3.42 V. The luminous efficacy of the LED source would be:

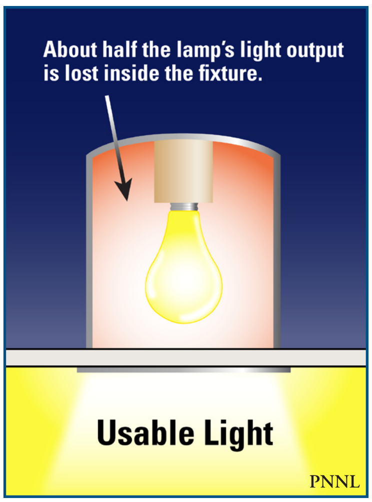
$$45 \text{ lumens}/(.35 \text{ amps} \times 3.42 \text{ volts}) = 38 \text{ lm/W}$$

To include typical driver losses, multiply this figure by 85%, resulting in 32 lm/W. Because LED light output is sensitive to temperature, some manufacturers recommend de-rating luminous flux by 10% to account for thermal effects. In this example, accounting for this thermal factor would result in a system efficacy of approximately 29 lm/W. However, actual thermal performance depends on heat sink and fixture design, so this is only a very rough approximation. Accurate measurement can only be accomplished at the luminaire level.

Application Efficiency

Luminous efficacy is an important indicator of energy efficiency, but it doesn’t tell the whole story, particularly with regard to directional light sources.

Due to the directional nature of their light emission, LEDs potentially have higher application efficiency than other light sources in certain lighting applications. Fluorescent and standard “bulb” shaped incandescent lamps emit light in all directions. Much of the light produced by the lamp is lost within the fixture, reabsorbed by the lamp, or escapes from the fixture in a direction that is not useful for the intended application. For many fixture types, including recessed downlights, troffers, and under-cabinet fixtures, it is not uncommon for 40-50% of the total light output of the lamp(s) to be lost before it exits the fixture.



*Cut-away view of recessed downlight installed in ceiling

LEDs emit light in a specific direction, reducing the need for reflectors and diffusers that can trap light, so well-designed fixtures and systems using LEDs can potentially deliver light more efficiently to the intended location.

For example, several manufacturers have introduced LED systems for lighting refrigerated display cases in grocery stores. These products are currently based on white LEDs with lower luminous efficacy than the fluorescent lamps they are designed to replace. But because the system design takes advantage of the directional nature of LEDs and their especially good performance under low temperatures, they are demonstrating energy savings of 50% or more compared to standard fluorescent case lights.

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Energy-Efficient Lighting and Light-Emitting Diodes

Light-emitting diode (LED) technology is developing rapidly as a general light source. This fact sheet discusses some of the key challenges facing the technology and the important questions to ask when evaluating new LED products.

What is solid-state lighting?

Solid-state lighting (SSL) uses semi-conducting materials to convert electricity into light. It is the first truly new lighting technology to emerge for many years. SSL is an umbrella term encompassing different types of technologies including light-emitting diodes (LEDs) and organic light-emitting diodes (OLEDs). While both technologies are evolving rapidly, LEDs are the more mature technology, particularly for white-light general illumination applications.

Are LEDs available for general lighting?

A variety of white LED products are available on the market including desk and under-cabinet lights, flashlights, head lamps, outdoor pathway lights, and decorative string lights. For most illumination applications, however, white LEDs cannot yet compete with traditional light sources on the basis of performance or cost. Colored LEDs are often cost-effective and offer energy efficiency and durability for traffic signals, exit signs, commercial signage, and other indicator applications.

Are white LEDs energy-efficient?

The best white LEDs are similar in efficiency to CFLs, but most of the white LEDs currently available in consumer products are only marginally more efficient than incandescent lamps. Lumens per watt (lpw) is the measure of how efficiently the light source is converting electricity into usable light. The best white LEDs available today can produce about 45-50 lpw. For comparison, incandescent lamps typically produce 12-15 lpw; CFLs produce at least 50 lpw. Many LED products use only a small amount of energy, and therefore may appear energy efficient, but they often have very low light output. True energy efficiency means using the most efficient light source or system that is capable of providing the amount and quality of light needed. On-going research and development efforts are making steady progress in improving the performance of white LEDs to levels suitable for general lighting applications.

What is DOE doing to help develop this technology?

The U.S. Department of Energy has formed a partnership with the Next Generation Lighting Industry Alliance to support research and development leading to enhanced performance and energy efficiency of LED lighting. The Alliance is made up of major manufacturers including 3M, Acuity Brands Lighting, Air Products, CAO Group, Color Kinetics, Corning Inc., Cree Inc., Dow Corning, GELcore LLC, General Electric Company, Eastman Kodak Company, LPI LLC, Lumileds Lighting LLC, Osram Opto Semiconductors Inc., Osram Sylvania, and Philips Electronics North America. Working with these partners, DOE is planning a full range of activities including:

- ENERGY STAR® criteria for SSL technologies and products
- Design competitions for lighting fixtures and systems using SSL
- Coordination with utility promotions and regional energy efficiency programs
- Technology procurement programs that encourage manufacturers to bring high-quality, energy-efficient SSL products to the market, and that link these products to volume buyers
- Consumer and business awareness programs

Cree, Inc.

What are light-emitting diodes (LEDs)?

An LED is a very small (dot-sized) electrical device that produces light through the semi-conducting properties of its metal alloys. LEDs have been around since the 1960s, but were used mainly as simple indicator lamps in electronics and equipment. White LEDs are now approaching performance levels that make them attractive for use in automobiles, aircraft, elevators, and some task light applications.

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What should I look for?

You must be an educated consumer to receive the most benefit from LED lighting. The following questions will help you determine if an LED product is right for your application.

How much light is produced?

To approach the total light output of a typical incandescent or CFL, a number of LEDs must be grouped together. Even the "high-brightness" white LEDs typically come in just 1-watt to 3-watt sizes. However, for some applications, LEDs can provide enough light on the task, even though the total light output is lower than comparable incandescent or fluorescent sources. This is because the light emitted from an LED is directional in nature, and in some applications, less light is lost in the fixture than with traditional light sources. Still, it is helpful to know how much total light the LED product provides and compare it to competing products using traditional light sources.

How long do LED lights last?

Unlike other light sources, LEDs don't "burn out;" they simply get dimmer over time. Although there is not yet an official industry standard defining "life" of an LED, the leading manufacturers define it as the point at which light output has decreased to 70% of initial light output. Using that definition, the best white LEDs have been found to have a useful life of around 35,000 hours (that's four years of continuous operation). For comparison, a 75-watt incandescent light bulb lasts about 1,000 hours; a comparable CFL lasts 8,000 to 10,000 hours.

LED lifetime depends greatly on operating temperature. An increase in operating temperature of 10 °C can cut the useful life of an LED in half. When evaluating LED product life claims, ask about the assumed operating temperature and any measures to mitigate heat in the device.

What do LED lights cost?

White-light LEDs currently cost significantly more than traditional light sources. The combination of high price and low light output may make them a poor replacement for current technology in most general illumination applications. However, for applications with long running hours, difficult access, or other specific requirements, LEDs may make sense. Today's white LEDs cost more than $50 per thousand lumens; a typical 75-watt incandescent light bulb, providing 1,000 lumens costs about $1.00; a comparable CFL costs less than $5.00.

Does LED lighting have the features I need?

In some applications, the extra durability that LEDs can provide is worth a higher purchase price. Outdoor pathway and step lighting is an example of a sensible application for today's white LEDs. They provide a small amount of light right where it's needed, avoid frequent bulb changes in fixtures that are difficult to access, and can be powered by solar cells, eliminating the need for running wire outdoors. LEDs are also good for applications where vibration often leads to early failure of conventional light sources. Being a solid-state device, LEDs are highly resistant to damage caused by vibration.

How can I compare LED lighting to other sources?

Because of the current lack of standardized reporting practices among LED product manufacturers, consumers have no reliable way to compare product performance based on information provided by the manufacturer. The best way to assess a product you are considering is to ask for a sample from the vendor.

Lumileds Lighting

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Color Quality of White LEDs

Color quality is one of the key challenges facing light-emitting diodes (LEDs) as a general light source. This fact sheet reviews the basics regarding light and color and summarizes the most important color issues related to white light LEDs.

Unlike incandescent and fluorescent lamps, LEDs are not inherently white light sources. Instead, LEDs emit light in a very narrow range of wavelengths in the visible spectrum, resulting in nearly monochromatic light. This is why LEDs are so efficient for colored light applications such as traffic lights and exit signs. However, to be used as a general light source, white light is needed. The potential of LED technology to produce high-quality white light with unprecedented energy efficiency is the impetus for the intense level of research and development currently being supported by the U.S. Department of Energy.

White Light from LEDs

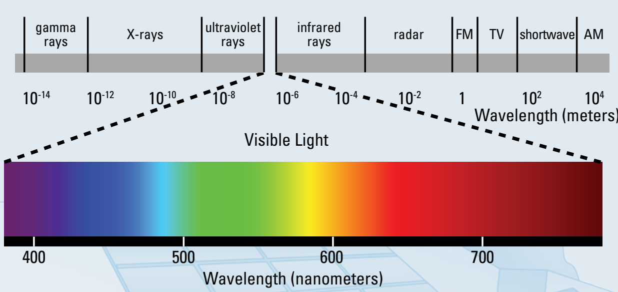
White light can be achieved with LEDs in two main ways: 1) phosphor conversion, in which a blue or ultraviolet (UV) chip is coated with phosphor(s) to emit white light; and 2) RGB systems, in which light from multiple monochromatic LEDs (red, green, and blue) is mixed, resulting in white light.

The phosphor conversion approach is most commonly based on a blue LED. When combined with a yellow phosphor (usually cerium-doped yttrium aluminum garnet or YAG:Ce), the light will appear white to the human eye. A more recently developed approach uses an LED emitting in the near-UV region of the spectrum to excite multi-chromatic phosphors to generate white light.

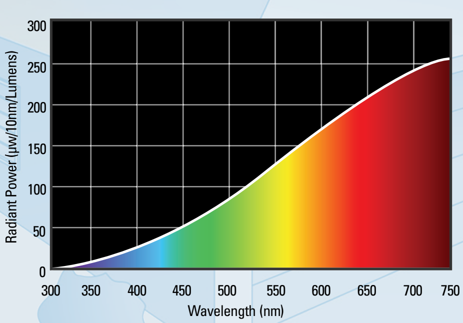
The RGB approach produces white light by mixing the three primary colors red, green, and blue. Color quality of the resulting light can be enhanced by the addition of amber to "fill in" the yellow region of the spectrum. Status, benefits and trade-offs of each approach are explored on page 2.

What is White Light?

We are accustomed to lamps that emit white light. But what does that really mean? What appears to our eyes as "white" is actually a mix of different wavelengths in the visible portion of the electromagnetic spectrum. Electromagnetic radiation in wavelengths from about 380 to 770 nanometers is visible to the human eye.



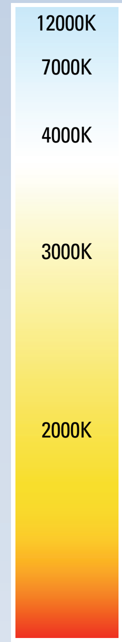
Incandescent, fluorescent, and high-intensity discharge (HID) lamps radiate across the visible spectrum, but with varying intensity in the different wavelengths. The spectral power distribution (SPD) for a given light source shows the relative radiant power emitted by the light source at each wavelength. Incandescent sources have a continuous SPD, but relative power is low in the blue and green regions. The typically "warm" color appearance of incandescent lamps is due to the relatively high emissions in the orange and red regions of the spectrum.



◄ *Example of a Typical Incandescent Spectral Power Distribution*

Correlated Color Temperature (CCT)

CCT describes the relative color appearance of a white light source, indicating whether it appears more yellow/gold or more blue, in terms of the range of available shades of white.



CCT is given in kelvins (the unit of absolute temperature) and refers to the appearance of a theoretical black body (visualize a chunk of metal) heated to high temperatures. As the black body gets hotter, it turns red, orange, yellow, white, and finally blue. The CCT of a light source is the temperature (in K) at which the heated theoretical black body matches the color of the light source in question. Incongruously, light sources with a higher CCT are said to be "cool" in appearance, while those with lower CCT are characterized as "warm."

Color Rendering Index (CRI)

CRI indicates how well a light source renders colors, on a scale of 0 – 100, compared to a reference light source. The test procedure established by the International Commission on Illumination (CIE) involves measuring the extent to which a series of eight standardized color samples differ in appearance when illuminated under a given light source, relative to the reference source. The average "shift" in those eight color samples is reported as R_a or CRI.

In addition to the eight color samples used by convention, some lighting manufacturers report an "R_9" score, which indicates how well the light source renders a saturated deep red color.

Comparison of White Light LED Technologies

Each approach to producing white light with LEDs (described above) has certain advantages and disadvantages. The key trade-offs are among color quality, light output, luminous efficacy, and cost. The technology is changing rapidly due to intensive private and publicly funded research and development efforts in the U.S., Europe, and Asia. The primary pros and cons of each approach at the current level of technology development are outlined below.

	Advantages	Disadvantages
Blue LED + phosphor	• Most mature technology • High-volume manufacturing processes • Relatively high luminous flux • Relatively high efficacy • Comparatively lower cost	• High CCT (cool/blue appearance) • Low CRI (typically in the 70s) • Color variability in beam
Near-UV LED + phosphor	• Higher color rendering • Warmer color temperatures possible • Color appearance less affected by chip variations	• Less mature technology • Relatively low efficacy • Relatively low light output
RGB	• Color flexibility, both in multi-color displays and different shades of white • Potentially very high color rendering	• Individual colored LEDs respond differently to drive current, operating temperature, dimming, and operating time • Controls needed for color consistency add expense

Most currently available white LED products are based on the blue LED + phosphor approach. Phosphor-converted chips are produced in large volumes and in various packages (light engines, arrays, etc.) that are integrated into lighting fixtures. RGB systems are more often custom designed for use in architectural settings.

Typical Luminous Efficacy and Color Characteristics of Current White LEDs

How do currently available white LEDs compare to traditional light sources in terms of color characteristics and luminous efficacy? Standard incandescent A-lamps provide about 15 lumens per watt (lpw), with CCT of around 2700 K and CRI close to 100. ENERGY STAR qualified compact fluorescent lamps (CFLs) produce about 50 lpw at 2700-3000 K and CRI at least 80. Typical efficacies of currently available LEDs from the leading chip manufacturers are shown below. Improvements are announced by the industry regularly.

CCT ▾ / CRI ▸	70-79	80-89	90+
2600-3500 K	23-43 lpw		16 lpw
3500-5000 K	33-47 lpw	27 lpw	
> 5000 K	33-56 lpw	38 lpw	

Sources: Manufacturer datasheets for Cree XLamp 7090 XR, Lumileds Luxeon K2 Emitter, Luxeon Warm White Emitter, and Osram Opto OSTAR-Lighting. April 2006. Efficacy figures do not include driver losses.

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April 2006

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Standards Development for Solid-State Lighting

Solid-state lighting differs fundamentally from traditional lighting technologies in terms of materials, drivers, system architecture, controls, and photometric properties. A host of new test procedures and industry standards is needed to accommodate these technical differences. To accelerate the development of needed standards for SSL products, DOE facilitates ongoing dialogue and collaboration with key standards setting organizations, and offers technical assistance in the development of new standards.

In March 2006, DOE hosted an LED Standards Industry Workshop to provide a forum for greater cooperation and coordination among standards organizations, including the Illuminating Engineering Society of North America (IESNA), National Institute of Standards and Technology (NIST), National Electrical Manufacturers Association (NEMA), American National Standards Institute (ANSI), Underwriters Laboratories (UL), International Electrotechnical Commission (IEC), International Commission on Illumination (CIE), and Canadian Standards Association (CSA).

DOE continues to work with these organizations to align their individual priorities and schedules, and maintain a master roadmap of development activities. With DOE support and leadership, the group will continue to coordinate, update progress, and accelerate the development process.

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DOE ENERGY STAR® Program for Solid-State Lighting

The ENERGY STAR label is a highly valued and widely recognized mark of energy efficiency that helps guide the American public to select cost-effective, energy-efficient products. As part of DOE's national strategy to accelerate market introduction of high efficiency SSL products, the Department is leading ENERGY STAR management, specification development, and partner relations for SSL devices used for general illumination, including:

- Residential, commercial, industrial, and outdoor lighting SSL applications of all types
- Innovative SSL systems applications of all types (includes "free-form" SSL systems, and those incorporated into furniture, buildings, and equipment)

The DOE ENERGY STAR strategy for SSL general illumination products establishes near-term and long-term requirements. The near-term transitional criteria apply to niche application products that are at least as efficient as fluorescent light sources. The long-term criteria are for future products that are far more efficient. The rapid pace of SSL performance improvements will require DOE to periodically review and amend the criteria to parallel technological advances and ensure the criteria remain up-to-date.

DOE Releases Draft ENERGY STAR Requirements for SSL Luminaires

The Department has released draft ENERGY STAR Requirements for Solid-State Lighting Luminaires intended for general illumination. The draft requirements are posted below for public review and comment. All comments should be forwarded by January 19, 2007, to Richard Karney, DOE ENERGY STAR Product Manager, at richard.karney@ee.doe.gov or via facsimile at 202-586-4617.

A Stakeholder Workshop to discuss the criteria and comments will be held in the coming weeks. More information on this workshop will be posted as it becomes available.

Draft ENERGY STAR Requirements for SSL Luminaires (PDF - 369 KB)

Stakeholder Workshop (details to come)

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