Introduction to Solid-State Lighting (LEDs)

Course No: E03-025

Credit: 3 PDH

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Introduction to Solid-State Lighting (LED) Technology

A Compilation of Fact Sheets
from the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy

(http://energy.gov/eere/ssl/led-basics)

April, 2016

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Energy Efficiency of LEDs

The energy efficiency of LEDs has increased substantially since the first general illumination products came to market, with currently available lamps and luminaires having efficacies more than three times as high as the best products from 2005. This fact sheet discusses current and projected benchmarks for the efficacy of LED packages and complete luminaires, as well as providing comparisons to conventional technologies.

An LED package, the building block of most LED products.

Image Credit: Philips Lumileds

Introduction

The energy efficiency of LED products is typically characterized using *efficacy*, which in basic terms is the ratio of power input to light output—or more technically, emitted flux (lumens) divided by power draw (watts).[1] For such a simple concept, however, there are several important nuances that must not be overlooked. For example, LED packages (the individual nodes that make up an LED product, as shown in Figure 1) have their own efficacy, which is different from the efficacy of an integrated LED lamp or an LED luminaire; the difference stems from driver, thermal, and optical losses. It is also necessary to understand the different procedures and conditions used for measuring conventional and LED products, as well as the difference between commercially available products and laboratory samples.

The efficacy of both LED packages and complete products depends on many factors, which range from electrical efficiency to internal quantum efficiency to spectral efficiency. Projecting varying levels of improvement across these aspects, DOE has established a target LED package efficacy of 266 lm/W, with LED luminaire efficacy exceeding 200 lm/W.[2] Upon reaching such levels, LEDs would far surpass the efficacy of current linear fluorescent, compact fluorescent, high intensity discharge (HID), and incandescent sources, all of which are generally considered mature technologies with less opportunity for improved performance. Although this fact sheet primarily discusses best-in-class products, it is critical to remember that not all products of a given source type perform equally. This is especially true for currently available LED products.

Package Efficacy

Baseline, package-level efficacy has many variables, but three that may be noticeable to specifiers and consumers are the method of generating white light, color quality attributes, and drive current. As discussed in the fact sheet *LED Color Characteristics*, there are two primary methods for generating white light with LEDs: phosphor conversion (PC) and color mixing.[3] Currently, PC-LEDs are the most energy efficient option, providing package efficacy greater than 130 lm/W. They are also by far the most common type currently available. However, due to additional inefficiencies related to phosphor conversion, PC-LED packages are thought to have a lower potential maximum efficacy than color-mixed systems, as shown in Figure 2. Conversely, currently available color-mixed LED systems have lower package-level efficacies due to the low efficiency of green and amber LEDs. To reach DOE projections, innovative color-mixing or hybrid systems will likely be essential. Some new products are already taking this approach.

All other things held constant, a second important consideration that is likely to affect LED package efficacy is color quality. For example, achieving a specific color temperature requires changing the spectral content of a light source. If the spectral content is changed, the luminous efficacy of radiation—one of the efficiency factors determining overall efficacy—is also altered, not to mention the different LED packages that must be used. As a result, LED packages having different values for correlated color temperatures (CCT) or color rendering index (CRI) are likely to have different efficacies. Higher CRI requirements are more restrictive of spectral content, and in general require a broader

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[1] As it is most commonly used, the term efficacy refers to lumens output per watt input; however, luminous efficacy of radiation (LER) is also used in scientific applications to refer to lumens output per watt of optical radiation output. Another important distinction is that lumens are defined by the luminous efficiency function, V(λ), which corresponds to photopic vision rather than mesopic or scotopic vision.

[2] For more information, see the Solid-State Lighting Research and Development: Multi Year Program Plan, which is available at: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_mypp2012_web.pdf

[3] Hybrid approaches, where more than one spectral LED is combined with a phosphor emission (e.g., blue, red, and phosphor), are gaining momentum and promise increased efficacy with favorable color quality attributes.

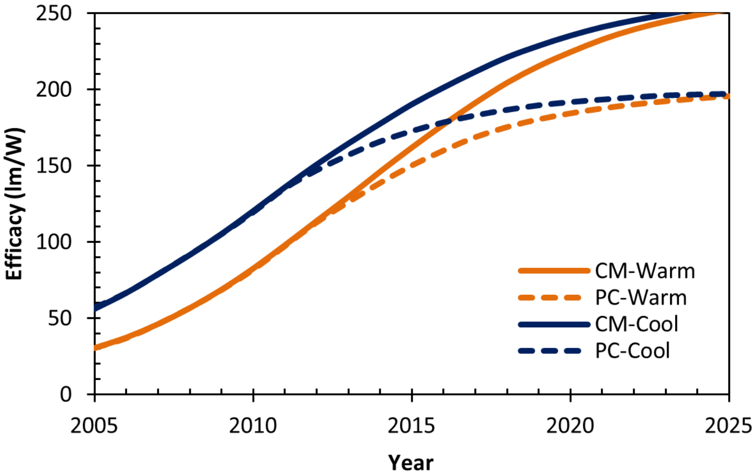

Figure 2. Actual and projected increases in the efficacy of color-mixed (CM) and phosphor-coated (PC) LED packages. CM-LED packages are predicted to have a higher maximum efficacy in the future, and the difference between warm white (CCT 2580 K to 3710 K, CRI 80–90) and cool white (CCT 4746 K to 7040 K, CRI 70–80) is expected to diminish. *Source: DOE 2012 Multi-Year Program Plan*

Absolute Versus Relative Photometry

Lighting systems can be measured using two different methods of photometry: absolute or relative. Relative photometry, commonly used with conventional lighting products, allows for the combination of separate measurements for a lamp and luminaire. Lamp efficacy can be multiplied by luminaire efficiency to determine luminaire efficacy. Although not without limitations, relative photometry is generally appropriate for fixtures that have interchangeable lamps with consistent characteristics and little interaction between the lamp and luminaire. In contrast, the system into which LED packages are incorporated has a material impact on performance. This necessitates measurement using absolute photometry, which considers the complete product.

LM-79-08, *Electrical and Photometric Measurements of Solid-State Lighting Products*, describes approved methods for measuring several attributes of LED products, including total flux, electrical power, efficacy, luminous intensity distribution, and color characteristics. LM-79 applies to LED products containing control electronics and heat sinks, but not products requiring external hardware or luminaires designed for LEDs but sold without the light source. LM-79 prescribes absolute photometry and stipulates the ambient air temperature (25 °C), mounting, airflow, power supply characteristics, seasoning and stabilization, testing orientation, electrical settings, and instrumentation for both integrating sphere and goniophotometer measurements.

As the solid-state lighting industry advances, different product configurations, such as LED light engines, may prompt a return to relative photometry in certain situations. At a minimum, the advent of LED lighting has led to a reevaluation of photometric testing procedures and increased awareness about the source of performance data.

spectral power distribution. Therefore, within a given product family, packages with a higher CRI tend to have a lower efficacy.

In theory, having a lower CCT is not detrimental to efficacy, but due to other efficiency factors, currently available cool white LED packages (e.g., 6500 K) are approximately 20% more efficacious than warm white LED packages (e.g., 3000 K), as shown in Figure 2. Current trends indicate that this difference is decreasing, with the expectation that it will eventually become negligible.

Third, LED packages can be operated at several different currents. The typical baseline is 350 mA, but 700 mA, 1000 mA, or higher drive currents are also commonly available. Driving the LEDs harder (i.e., at a higher current), increases the lumen output, but results in a commensurate decrease in efficacy; this phenomenon is known as *efficiency droop*. The cause of the decrease has been extensively investigated, and over the next ten years, the detrimental effect of droop is expected to diminish.

In turn, the variables that affect the efficacy of LED packages also contribute to lamp and luminaire performance. However, it is important to note that LED package efficacy is typically determined using brief pulses of light (rather than continuous operation) at a fixed ambient temperature (25 °C), which does not correspond to real world operating characteristics. Further, some notable achievements from laboratory samples, such as reports of LED packages producing over 276 lm/W, are made possible by carefully selecting the very best chips. Although not relevant for characterizing currently available products, these measurements are useful in foreshadowing future performance.

Lamp and Luminaire Efficacy

Thermal effects, driver losses, and optical inefficiencies all combine to reduce the efficacy of LED luminaires compared to the included LED packages. Considered collectively, these loss mechanisms can result in a decrease in efficacy of greater than 30%. Notably, the efficacy of complete LED lamps and luminaires is most relevant to building energy use.

Figure 3 shows efficacy versus lumen output for more than 7,000 LED lamps and luminaires listed by LED Lighting Facts as of February 2013. For both integrated LED lamps and LED luminaires, the listed efficacy ranged from less than 10 lm/W to approximately 120 lm/W. A majority of products were between 40 and 80 lm/W. As expected, this is considerably less than the efficacy of currently-available LED packages because the measurements are for the full lighting system.

Thermal Effects

A major factor in determining the lumen output of an LED is junction temperature.[4] As temperature increases, the light-generation process becomes less efficient and fewer lumens are emitted. For this reason, LED lamps and luminaires generally require a thermal management system. However, even in a well-designed product, the junction temperature may rise significantly above

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[4] *Junction temperature (T_j) refers to the temperature at the p-n junction, the central point of light generation. Typical junction temperatures for LEDs in a luminaire are greater than 60 °C, with temperatures over 100 °C possible.*

laboratory conditions, ultimately resulting in up to a 15% decrease in efficacy. Unlike driver and optical losses, thermal effects are generally unique to LEDs; this is one of the key reasons why LEDs are tested using *absolute photometry* rather than *relative photometry* (see sidebar).

Driver Losses

Fluorescent and HID light sources cannot function without a ballast, which provides a starting voltage and limits electrical current to the lamp. Similarly, LEDs require a driver, which is comprised of both a power source and electronic control circuitry. Most drivers convert line voltage to low voltage and current from AC to DC, and may also include supplementary electronics for dimming and/or color correction. Currently available LED drivers are typically about 85% efficient, with some improvement projected.

Optical Losses

Regardless of source type, the use of lenses, reflectors, or other optical systems to shape a product's distribution ultimately reduces the total amount of emitted light. For LEDs, this is another contributing factor in the difference between package efficacy and lamp or luminaire efficacy. However, the magnitude of the effect is difficult to state given the large diversity of fixtures in the marketplace.

For conventional products measured using relative photometry, luminaire efficiency is reported as the percentage of rated lamp lumens emitted by the luminaire. This quantity cannot be derived using absolute photometry, but the less-than-perfect efficiency of optical systems is still a key loss factor for LED lamps and luminaires.

Other Considerations

Application Efficacy

Lamp and luminaire efficacy are important indicators of energy efficiency, but they may not tell the whole story. Application efficacy, defined as the power draw necessary to achieve specified illuminance criteria, may provide valuable data when comparing products for a specific application. If a luminaire directs a greater percentage of light to the target area—a roadway, for example—it may have a higher application efficacy despite having a lower luminaire efficacy. Importantly, it is not possible to quantify application efficacy for all uses of a given product, nor should application efficacy be compared for different situations. There is no generic value that can be reported as a product characteristic, so application efficacy must be calculated on a case-by-case basis.

The different emission attributes of various light sources may have an effect on application efficacy. Due to the directional nature of their emission, LEDs have the potential to provide greater application efficacy than other light sources in certain situations. Most CFLs, incandescent "light bulbs," and HID lamps emit light in all directions, meaning an optical system must redirect a substantial proportion of the emitted light if a directional distribution is needed. Optical systems are never perfectly efficient, and they may not be able to redirect all the emitted light to the correct area. This is especially true for large area sources, such as CFLs, for which optical control is more difficult than for point sources. In short, matching the right product with the right application is another important consideration for energy efficiency, and it may have an effect equal to or greater than the choice of light source technology.

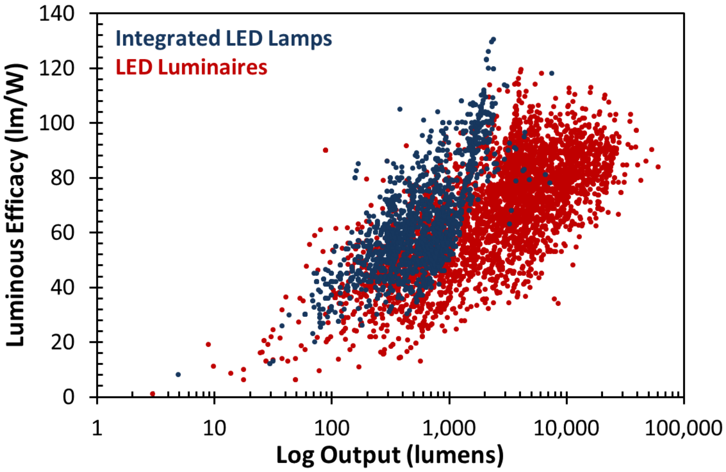

Figure 3. Efficacy versus output for integrated LED lamps and LED luminaires listed by LED Lighting Facts as of February 2013. The range in efficacy is similar for both types of product, but the potential for larger form factors in dedicated LED luminaires allows for more lumen output.

Initial and Maintained Efficacy

The lumen output of almost all lighting products depreciates over time, while—at least in theory—input power remains constant. Thus, the luminous efficacy at the beginning of life is greater than the luminous efficacy when the end of rated life is approaching. Importantly, the rate of lumen depreciation and the overall amount of decline are different for different source types, or even for different products using the same source type. For example, the lumen output of a high quality T8 fluorescent lamp may be 95% of initial at the end of rated life, whereas the output of an LED product may be 70% of the initial value. Thus, the source that is more efficacious may change over the life of the products.

Although maintained efficacy is typically not reported by manufacturers, it will likely come into play if lighting calculations are performed and lighting power density is evaluated. Because standard-practice calculations are based on future performance, a source with a lower maintained efficacy may lead to greater energy use at the time of installation and a higher rated power density. However, this "hidden" performance may be overlooked if only initial efficacy is used to compare two products.

Along with many other ideas, LEDs have brought to the mainstream the concept of increasing power draw to reduce or eliminate lumen depreciation. Although this process is used infrequently today, its prevalence may increase in the future. Such luminaires may reduce overlighting and allow for a smaller connected load initially, but the efficacy will decrease over time and energy use will increase. This approach may or may not lead to less energy use over the lifetime of the system, and it can make product comparisons more challenging.

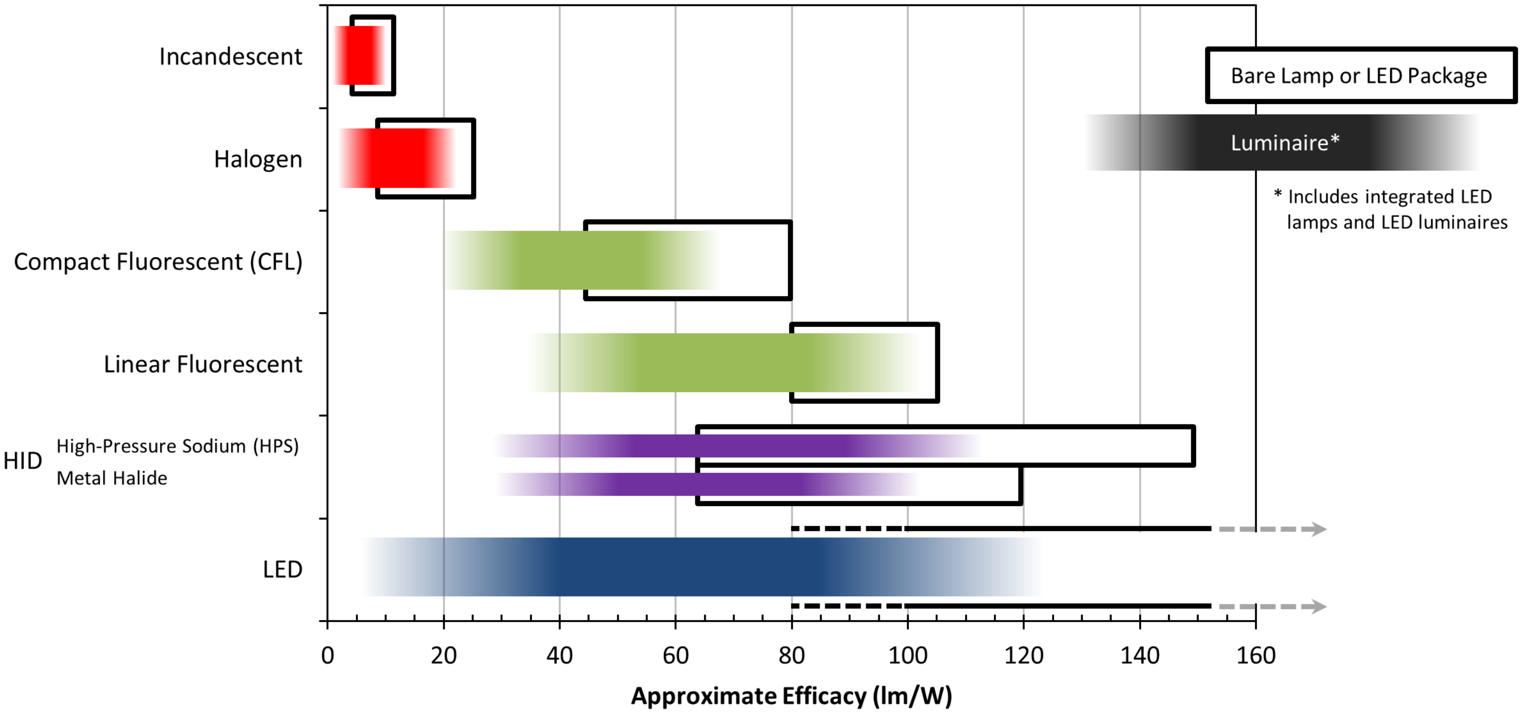

Figure 4. Approximate range of efficacy for various common light sources, as of January 2013. The black boxes show the efficacy of bare conventional lamps or LED packages, which can vary based on construction, materials, wattage, or other factors. The shaded regions show luminaire efficacy, which considers the entire system, including driver, thermal, and optical losses. Of the light source technologies listed, only LED is expected to make substantial increases in efficacy in the near future.

Efficacy Versus Energy Use

Efficacy is related to energy efficiency, but it cannot be used to establish energy use. Energy use is the power draw over time, and is typically reported in units of kilowatt-hours (kWh). A less efficacious product may in fact use less energy if it is operated for fewer hours. Control systems can be an important tool for realizing energy savings.

Making Comparisons

When comparing efficacy for LED and conventional products, it is important to consider the entire system. Even though relative photometry focuses on lamp properties and the efficiency of the luminaire, calculating total luminaire efficacy is the best way to compare conventional products to LED products, or anything measured with absolute photometry. Still, there may be differences in performance that are not captured by relative photometry.

A basic comparison of the efficacy for several major lamp technologies is provided in Figure 4, with raw lamp or package efficacy shown with black boxes and typical luminaire efficacy shown with shaded areas. The variability is substantial—partially because all luminaire types are grouped together—but in general, the efficacy of current LED products is similar to fluorescent and HID products. Figure 4 also illustrates that although the efficacy of currently available LED packages is very high, many integrated LED lamps and LED luminaires do not propagate the performance advantage. Importantly, LED is the only type of source shown for which efficacy is expected to substantially improve in the near future.

Conclusion

The efficacy of LED products has steadily improved since their introduction as a source for general illumination. This trend is expected to continue, thanks to new materials, better manufacturing processes, and new configurations. Currently, the efficacy of LED packages compares very favorably to conventional light sources, and many integrated LED lamps and LED luminaires have efficacies that are comparable to their traditional counterparts. However, the variability in LED products is greater than for the more mature technologies and the products are changing rapidly. Importantly, efficacy should not be the only factor when comparing products. Other performance characteristics, such as color quality, luminous intensity distribution, and dimmability must be included in a holistic decision. Although high efficacy is an important attribute for energy savings, it is imperceivable to the users of a space.

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PNNL-SA-94206 • March 2013

Printed with a renewable-source ink on paper containing at least
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Building Technologies Program
SOLID-STATE LIGHTING TECHNOLOGY FACT SHEET

Using LEDs to their Best Advantage

Light-emitting diodes (LEDs) are often touted for their energy efficiency and long life. Although these are important considerations, selecting a light source should involve many other factors. This fact sheet explores some of the unique attributes of LEDs, which may make them the best choice for a given application.

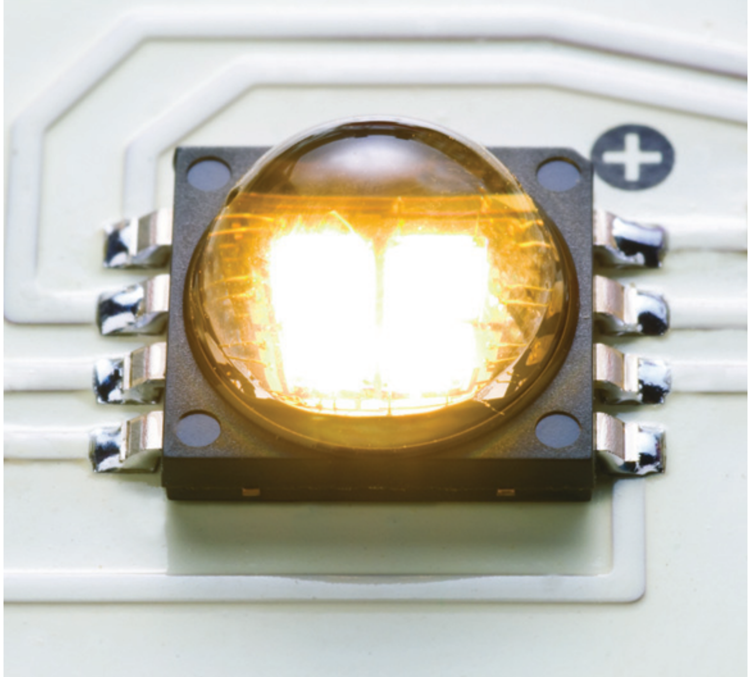

Image Credit: Cree

Introduction

Financial considerations—namely, purchase price and operating costs—always figure in the selection of lighting products, but many other aspects also come into play, varying in importance depending on the application. LEDs have several unique attributes, and it is critical to understand how they can be used advantageously. Some considerations are dependent on product design, but others amount to using LEDs in appropriate situations. Some of the potentially favorable characteristics of LED sources compared to traditional lamps include:

- Directional light emission
- Size and form factor
- Resistance to mechanical failure (i.e., breaking)
- Instant on at full output
- Rapid on-off cycling capability without detrimental effects
- Improved performance at cold temperatures
- Dimming and control capability
- Opportunity for color tuning
- Minimal nonvisible radiation [e.g., ultraviolet (UV), infrared (IR)]
- Extended lifetime

LEDs are semiconductor devices that emit light through electroluminescence.[1] This basic fact is the foundation for many of the advantages of LEDs, since it is different from traditional light sources. For example, incandescent lamps rely on a heated filament to emit light, fluorescent lamps create light using a gas discharge to excite phosphors, and high-intensity discharge (HID) lamps utilize an electric arc discharge. All of these traditional technologies require a glass bulb to contain essential gases and/or coatings.

In contrast to the large form factors of traditional lamps, LED lighting starts with a tiny chip (also called a die; most commonly about 1 mm^2) comprised of layers of semiconducting material—the exact material determines the wavelength (color) of radiation that is emitted. At the next level are LED packages, which may contain one or more chips mounted on heat-conducting material and usually enclosed in a lens or encapsulant. The resulting device, typically less than 1 cm^2, can then be used individually or in an array. Finally, LEDs are mounted on a circuit board and incorporated into a lighting fixture, attached to an architectural structure, or made to fit the form factor of a traditional lamp (or as it is colloquially known, a light bulb).

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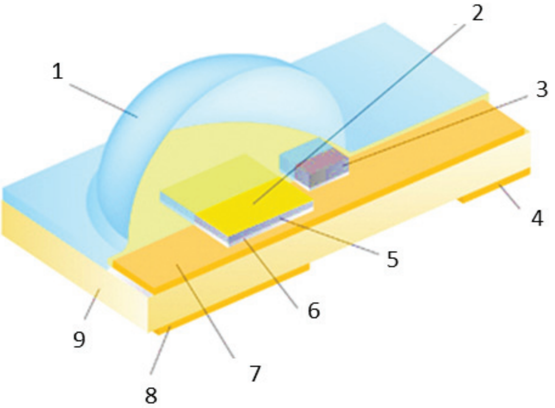
[1] LEDs rely on injection luminescence, a specific type of electroluminescence. In this case, light is generated directly when electrons recombine with holes, in the process emitting photons. For more on the physics of LED light generation, see the *IES Lighting Handbook* or other reference sources.

LED Package Design

Although not all LED packages are built the same way, the basic components are often similar. Besides the chip that is responsible for emitting light, the various components are needed for thermal regulation, producing the desired spectrum, regulating electrical characteristics, or creating the appropriate distribution of light. All these components must work in harmony to produce a high-performance product. Many of the advantages of LEDs are derived from their unique physical attributes.



1. Silicone Lens
2. Phosphor Plate
3. Transient Voltage Suppressor
4. Cathode
5. LED Chip
6. Bond Layer
7. Metal Interconnect Layer
8. Thermal Bed
9. Ceramic Substrate

Image Credit: Philips Lumileds

Directional Light Emission

Traditional light sources emit radiant energy in all directions. As such, an optical system—a lamp housing or a luminaire, with elements such as a reflector or lens—is typically necessary to direct output in the desired direction. Because no optical system is perfectly efficient, losses in efficacy result. Further, if the optical system is not well designed (or is not present), light can be wasted, going in undesired directions.

Due to their physical characteristics and because they are mounted on a flat surface, LEDs emit light hemispherically, rather than spherically. For task lighting and other applications requiring directional lighting, this may increase the application efficacy[2] of the source. In contrast, with LEDs it is more difficult to obtain an omnidirectional distribution when it is desired, although innovative system designs now provide this capability.

Size and Form Factor

The small size, scalability of arrays, and directional light emission of LEDs offer the potential for innovative, low profile, or compact lighting products. This advantage can be aesthetic, but may also be functional. For example, reducing the depth of a luminaire may allow more room for ducts, conduit, or other building systems in a ceiling cavity. It is even possible that the size of the ceiling plenum could be reduced. In contrast, the unique form factor of LEDs can be a disadvantage when competing with high-wattage HID sources. To match the lumen output, a very large array of LEDs is necessary.

Source Type:
LED
Dimensions:
6.1” deep
17.5” square
Input Watts:
133
Lumen Output:
10,575

Source Type:
Metal Halide
Dimensions:
11.5” deep
15” round
Input Watts:
175
Lumen Output:
10,400

The physical characteristics of LEDs allow for the design of luminaires that are different shapes and sizes compared to those made for conventional lamps. In this example, the depth of the LED parking garage luminaire is significantly less than a more traditional luminaire with a metal halide lamp.

Achieving small form factors requires careful design, specifically with regard to thermal management. Although LEDs used for general lighting do not emit infrared radiation (i.e., heat), they do generate thermal energy that must be moved away from the chip by a mass of material, which is called a heat sink. In order to produce more light output, LEDs are often grouped into arrays, which dictate the use of additional heat-sinking material. Thus, although LED packages are small, matching the performance of small traditional lamps, such as MR16s, can be challenging.

Breakage Resistance

LEDs are largely impervious to vibration because they do not have filaments or glass enclosures. The life of standard incandescent and discharge lamps may be reduced by vibration when operated in vehicular or industrial applications, although specialized vibration-resistant lamps can help alleviate this problem. The inherent vibration resistance of LEDs may be beneficial in applications such as transportation lighting (planes, trains, or automobiles), lighting on and near industrial equipment, or exterior area and roadway lighting.

In addition to benefits during operation, LEDs offer increased resistance to breaking during transport, storage, handling, and installation. LED devices mounted on a circuit board are connected with soldered leads that may be vulnerable to direct impact, but no more so than cell phones and other electronic devices. Because they do not contain any glass, LED fixtures may be especially appropriate in applications with a high likelihood of lamp breakage, such as sports facilities or vandalism-prone areas, although they are not indestructible. LED durability may also be beneficial in applications where broken lamps present a hazard to occupants, such as children’s rooms, assisted living facilities, or food preparation areas.

Instant On

Most fluorescent lamps do not provide full brightness immediately after being turned on. This is particularly relevant to amalgam compact fluorescent lamps (CFLs), which can take three minutes or more to reach full light output. HID lamps have even longer warm up times, ranging from several minutes for metal halide to ten minutes or more for high-pressure sodium (HPS). HID lamps also have a restrike time delay; if turned off, they must be allowed to cool before turning on again, usually for 2 to 20 minutes, depending on the ballast. In contrast to traditional technologies, LEDs turn on at full brightness almost instantly, with no restrike delay. This advantage can be simply aesthetic or a user preference, but can also be beneficial for emergency egress or high-security situations. It is also especially important for vehicle brake lights—LED versions illuminate 170 to 200 milliseconds faster than standard incandescent lamps, providing an estimated 19 feet of additional stopping distance at highway speeds (65 mph).[3]

Rapid Cycling

LEDs are impervious to the deleterious effects of on-off cycling. In fact, one method for dimming LEDs is to switch them on and

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[2] Application efficacy is defined as the lumens delivered to the target plane divided by the input watts to the lamp (or the ballast or driver, if applicable).

[3] See *Energy Savings Estimates of Light Emitting Diodes in Niche Lighting Applications* at *http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/niche_final_report.pdf.*

off at a frequency that is undetectable by the human eye. For fluorescent lamps, the high starting voltage erodes the emitter material coating the electrodes. Thus, lifetime is reduced when the rate of on-off cycles is increased. Due to the long warm up and restrike times, rapid cycling is not an option for HID lamps. Because of their operating characteristics, LEDs have an advantage when used in conjunction with occupancy sensors or daylight sensors that rely on on-off operation. Whereas the lifetime of fluorescent sources would diminish, there is no negative effect on LED lifetime.

Cold Temperature Operation

Cold temperatures present a challenge for fluorescent lamps.[4] In contrast, LED light output (and efficacy) increases as operating temperatures drop. This makes LEDs a natural fit for refrigerated and freezer cases, cold storage facilities, and many outdoor applications. In fact, CALiPER testing of an LED refrigerated case light measured 5% higher efficacy at -5 °C compared to operation at 25 °C.[5] Conversely, operation of LEDs in hot environments or use of products with poor thermal management characteristics can lead to undesirable performance attributes ranging from reduced lumen output to premature failure.

Dimming Performance

Dimming is often a desirable operating characteristic, but most energy-efficient technologies have challenges that must be overcome or mitigated. Many (but not all) LED products can be dimmed, although great care must be taken to ensure compatibility between the different hardware devices (e.g., the driver and dimmer). Incompatible lamp and dimmer combinations may result in flicker, color shift, audible noise, premature lamp failure, very limited or no range of dimming, or failure to light. These problems may manifest themselves at full output and/or when dimmed. Furthermore, they are typically dependent on the number of lamps connected to the dimmer. The best performing LEDs, when matched with a compatible dimmer, have better dimming performance than CFLs (limited range) or HID lighting (limited, if any, dimmability). However, there is a substantial performance differential among LED products and for various LED-dimmer combinations.

Tunability

One of the most significant advantages of LEDs is the ability to mix chips of multiple types in a single product. For example, red, green, and blue (RGB) chips can be combined to make white light (and any color within their gamut), or two shades of white LEDs can be combined and adjusted independently to create light with varying color temperatures (i.e., warmer or cooler in appearance). Combining multiple fluorescent lamps also provides this capability, but in practice, it is seldom utilized. Although the idea of tunable light sources is not prevalent today, it is a tool that can be used to increase occupant satisfaction in a variety of settings, such as offices, hotels, restaurants, and homes. Thus, as LEDs become more widely used, the concept may see increased recognition and application.

Image Credit: GE Lighting Solutions

In addition to color customization, the output of LEDs can also be altered over the course of their lifetime. In this manner, it is possible to prevent color shift and/or greatly reduce lumen depreciation. Eliminating lumen depreciation is particularly advantageous because it would allow for the removal of lamp lumen depreciation from design calculations, reducing initial over-lighting. This technology is not currently in widespread use, but as the equipment becomes less expensive, the potential advantage may be realized.

No Infrared or Ultraviolet Emissions

Ultraviolet and infrared radiation bookend the spectrum of visible light, but do not contribute to humans' ability to see. Ultraviolet radiation can damage artwork, artifacts, and fabrics, as well as causing skin and eye burns. Similarly, excessive infrared radiation from lighting presents a burn hazard to people and materials. With traditional sources, ultraviolet and infrared emissions are either necessary to generate visible light (e.g., fluorescent lamps) or simply an unavoidable component. The consequences of these undesirable emissions include reduced efficacy and/or the necessity of providing additional safeguards. For example, the infrared radiation generated by incandescent lamps accounts for more than 90% of the power they draw. Metal halide lamps require an ultraviolet-blocking outer bulb (or to be operated in an enclosed

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[4] At low temperatures, a higher voltage is required to start fluorescent lamps and luminous flux is decreased. A non-amalgam CFL, for example, will drop to 50% of full light output at 0°C. The use of amalgam (an alloy of mercury and other metals that is used to stabilize and control mercury pressure in the lamp) largely addresses this problem, allowing CFLs to maintain light output over a wide temperature range (-17 °C to 65 °C). The trade-off is that amalgam lamps take a noticeably longer time to reach full brightness.

[5] The summary report for CALiPER Round 2 can be found at *http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/cptp_round_2_summary_final_draft_8-15-2007.pdf*.

APPLICATION: MUSEUM LIGHTING

Museums often display artwork that is highly sensitive to both ultraviolet and visible radiation. The ability to carefully tune the spectrum of LED products (and essentially eliminate ultraviolet radiation) give them a unique advantage in this application.

LEDs are used to illuminate the Rose Gallery at the Smithsonian American Art Museum. Lighting and photography by Scott Rosenfeld.

fixture) due to the significant level of ultraviolet radiation emitted from the inner arc tube.

Based on how they generate radiant energy, LEDs chosen for general lighting applications do not emit much (if any) ultraviolet or infrared radiation. This helps boost efficacy and reduces the potential for undesirable consequences.

Extended Lifetime

The rated lifetime of LED products is at least comparable to other high-efficacy lighting products, if not better, and for many specific product types, LEDs have the highest rated lifetime. This attribute can be especially important where access is difficult or where maintenance costs are high. In fact, several U.S. Department of Energy GATEWAY demonstrations have revealed that maintenance savings, as opposed to energy savings, are the primary factor in determining the payback period for an LED product.

Conclusion

The LED product market continues to grow rapidly. In many applications, today's high-quality LEDs can outperform traditional technologies when evaluated with conventional metrics including efficacy, color quality, and operating cost. However, LED products have significant variation in performance from one product to the next. Thus, generalized comparisons are often misrepresentative. When purchasing or specifying LED products, it is essential to evaluate appropriate data and, if necessary, conduct a physical evaluation of a mock-up.

The attributes discussed in this fact sheet are predominantly a result of the physical characteristics of LEDs, and may not show up in a catalog or on a specification sheet. It is critical to understand the specific needs of a given application in order to select the most appropriate technology. Considered holistically, the best option may not always be the most efficacious. No matter how much energy can be saved, a product that does not meet the performance requirements is not a good choice.

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LED Frequently Asked Questions

LED technology continues to develop rapidly as a general light source. As more LED lighting products are introduced on the market, what do retailers, energy efficiency advocates, and consumers need to know to make informed buying decisions?

Are LEDs ready for general lighting?

The number of white-light LED products available on the market continues to grow, including a wide range of replacement lamps, as well as integrated light fixtures, such as portable desk/task lights, under-cabinet lights, recessed downlights, track heads, and outdoor fixtures for street and area lighting. Some of these products perform very well, but the quality and energy efficiency of LED products still varies widely, for several reasons:

1. LED technology continues to evolve very quickly. Performance and pricing of LED packages/devices are dynamic but both are steadily improving.
2. Lighting manufacturers face a learning curve in applying LEDs. Because they are sensitive to thermal and electrical conditions, LEDs must be carefully integrated into lighting products. Manufacturers vary in their ability to do this effectively.
3. Price pressures can affect the quality of components used in LED products, particularly replacement lamps targeted to the general consumer.

Terms

SSL – solid-state lighting; umbrella term for semiconductors used to convert electricity into light.

LED – light-emitting diode.

CCT – correlated color temperature; a measure of the color appearance of a white light source. CCT is measured on the Kelvin absolute temperature scale. White lighting products are most commonly available from 2700K (warm white) to 5000K (cool white).

CRI – color rendering index; a measure of how a light source renders colors of objects, compared to a "perfect" reference light source. CRI is given as a number from 0 to 100, with 100 being equivalent to the reference source.

Lumen Maintenance – the percentage of initial light output produced by a light source at some percentage of rated useful life (usually 100% for LED and 40% for source types characterized by sudden failure).

LED light sources used in a residential application.

Courtesy of Osram Opto Semiconductor.

Are LEDs energy-efficient?

The best white LED products meet or exceed the efficiency of fluorescent and high-intensity discharge (HID) light sources. However, many LED products currently available in consumer market channels are only marginally more efficient than incandescent lamps, and many suffer from very low light output relative to incandescent lamps and CFLs.

For several categories of luminaires (complete lighting fixtures), LED products are now widely available and meet or exceed the performance of conventional light sources. For example, nearly 500 LED recessed downlights are now listed by DOE's Lighting Facts program (*www.lightingfacts.com*), which requires verification of each product's light output, efficacy, and color characteristics. More than half of those downlights exceed the initial output and efficacy requirements of the ENERGY STAR® program, indicating they may perform at least as well as fluorescent downlights.

An LED package used in lighting products

Courtesy of Philips Lumileds

How long do LEDs last?

Unlike other light sources, LEDs usually don't suddenly "burn out;" instead, they gradually fade in brightness over time. LED useful life is generally based on the number of operating hours until the LED is emitting 70% of its initial light output. Good quality white LEDs in well-designed fixtures are expected to have a rated useful life on the order of 30,000 to 50,000 hours. A typical incandescent lamp lasts about 1,000 hours; a comparable CFL lasts 8,000 to 10,000 hours, and some linear fluorescent lamp-ballast system can last more than 40,000 hours. LED light output and useful life are strongly affected by temperature. LEDs must be "heat sinked" (placed in direct contact with materials that can conduct heat away from the LED) and driven at an appropriate input current.

Courtesy of CREE.

LED downlight showing heat sink.

Do LEDs provide high quality lighting?

Color appearance and color rendering are important aspects of lighting quality. Until recently, most white LEDs had very high CCTs, often above 5000 Kelvin. High CCT light sources appear "cool" or bluish-white. While very high CCT LEDs are still common, products with neutral and warm-white LEDs are now readily available. They are less efficient than cool white LEDs, but have improved significantly, and the efficacy gap between cool and warm LEDs is narrowing. Whereas warm-white (2700 to 3000K) is appropriate for most indoor residential applications, neutral-white (3500 to 4000K) is more common in commercial settings.

The CRI measures the ability of light sources to render colors, compared to incandescent and daylight reference sources. The CRI has been found to be an unreliable predictor of color preference of LED lighting products. A new metric called the Color Quality Scale (CQS) is under development, but in the meantime, color rendering of LED products should be evaluated in person and in the intended application if possible.

Are LEDs cost-effective?

Costs of LED lighting products vary widely. Good quality LED products currently carry a significant cost premium compared to standard lighting technologies. However, costs are declining rapidly. Recent industry roadmapping indicates prices for warm white LED packages have declined by half, from $36 to $18 per thousand lumens (kilolumens, klm) from 2009 to 2010. Prices are expected to continue to decline significantly to approximately $2/klm by 2015. It is important to compare total lamp replacement, electricity, and maintenance costs over the expected life of the LED product.

What other LED features might be important?

Depending on the application, other unique LED characteristics may merit consideration:

- Directional light
- Low profile / compact size
- Breakage and vibration resistance
- Improved performance in cold temperatures
- Life unaffected by rapid cycling
- Instant on / no warm up time
- No IR or UV emissions

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Building Technologies Program
SOLID-STATE LIGHTING TECHNOLOGY FACT SHEET

Establishing LED Equivalency

An LED product package states "energy-saving 60-watt equivalent," implying a direct one-for-one replacement for the common 60 W incandescent light bulb. Will it really produce the same quantity and quality of light?

The checklist below summarizes key performance characteristics that should be considered when comparing LED products and evaluating their equivalency to conventional lighting technologies. No two products are identical in every respect, and tradeoffs are often necessary due to inherent differences in technologies. In fact, it may be possible to improve performance in one category, such as color rendition, while achieving equivalency in others. For any given application, a number of additional characteristics should be considered during product selection. Notable examples include sensitivity to heat in enclosed spaces, dimming capability and behavior, flicker, and power factor.

Characteristic	Description
☑ **Light Output**	**Will the product appear equally bright?** Equivalent products should produce the same light output, as measured in lumens. Wattage (input power) cannot be used to compare light output, even between two LED products.
☑ **Spatial Distribution of Light**	**Will the product direct or focus light in the same manner?** Equivalent products should emit similar amounts of light in any given direction. That is, they should have a comparable luminous intensity distribution. It may also be important to consider the pattern created by the light, such as the sharpness of beam edges.
☑ **Color Quality and Appearance**	**What color light does the product emit? How do objects look under the light?** An equivalent LED product should emit light that appears the same color (e.g., warm-white or cool-white) as the conventional light source, and any given object should appear the same color when illuminated by the light sources being compared. These attributes are typically characterized using the correlated color temperature (CCT) and color rendering index (CRI) metrics, respectively.
☑ **Form Factor**	**Is the product the same shape and size?** A replacement lamp is of little use if it does not fit into an existing luminaire. Equivalent products should be within dimensional tolerances established by the American National Standards Institute (ANSI) for a variety of lamp types.
☑ **Compatibility**	**Will the new product work with my existing system?** Different lighting technologies often require different accessory components. It is important to know if the product will perform as desired given the type of transformer, type of dimmer, and the connected load. Manufacturers should provide compatibility charts for their products.
☑ **Useful Lifetime**	**How long will the product last?** Comparisons of rated useful lifetime are difficult because of the different rating methods used for LEDs and other light sources. Longer lifetime claims should be accompanied by longer warranty periods, and the product should continue to perform for the duration of the rated life.
☑ **Cost**	**Is the product worth the extra money?** It is important to consider lifetime costs, not just the initial cost, because energy and maintenance savings can yield an attractive return on investment. LED products are typically more expensive on a first-cost basis, but prices continue to fall as performance improves.

In a highly competitive and rapidly changing lighting marketplace, establishing equivalency is the first step toward making an informed buying decision. Although no attribute is universally more important, quantity and distribution of light are perhaps the two basic attributes most directly related to equivalency claims.

Wattage and Lumens

A prevalent claim in marketing literature is that an energy saving LED product is equivalent to a higher wattage incandescent lamp. Such claims are often ambiguous, these claims, could be taken to imply equivalent light output. CALiPER[1] testing has demonstrated that such claims are often overstated, with products marketed as replacements for particular lamps (e.g., 50 W MR16) often providing light output comparable to much lower wattage versions (e.g., 20 W MR16).

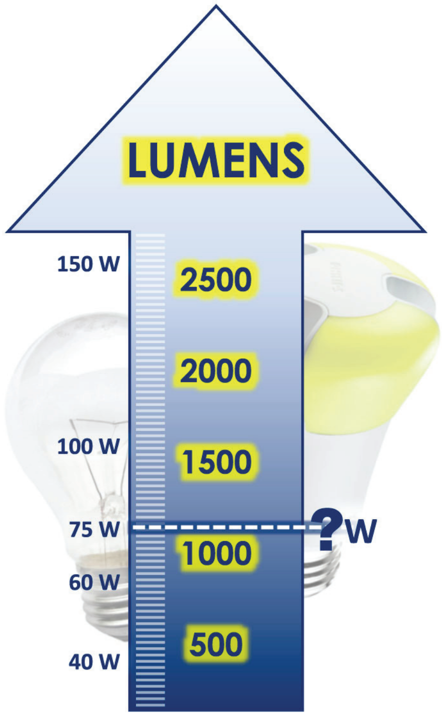

Figure 1. Lumen equivalency

Figure 1 provides rough benchmarks for the lumen output of incandescent lamps with different wattages. Because LED efficacy is continually improving and varies between products, it is necessary to compare lumens rather than watts. Typical lumen values for a variety of product types can be found in the DOE Lighting Facts performance scales for residential and commercial products.[2]

Spatial Distribution of Light

Equivalent products should have similar light distributions to ensure the lumens produced are directed where they are needed. An IES LM-79 photometric report, which should include lumen output and a polar plot of the luminous intensity distribution,[3] can be an important aid in the comparison process. For example, Figure 2 shows the intensity distributions for a 60 W incandescent lamp (black line) and two different LED replacement lamps (red and blue lines). The total lumen output of both LED lamps is comparable to the 60 W incandescent, but only one of them (blue) produces a similar omnidirectional distribution. Although a directional "beam" may be of benefit in some applications, it is important to be aware of these differences.

When replacing incandescent PAR lamps and other directional light sources, intensity distribution metrics such as the beam angle—which determines the basic "spot" and "flood" classifications—should be used in combination with lumen output and center beam candlepower (CBCP) to ensure proper focusing of the light.

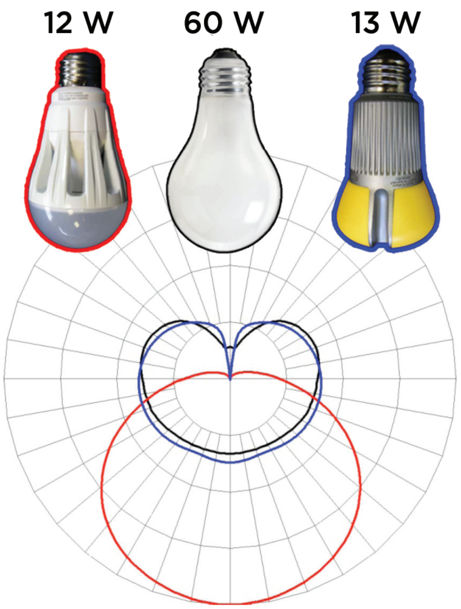

Figure 2. Distribution equivalency

Additional Considerations

In addition to lumen output and spatial distribution of light, consideration should be given to the other aspects described in this fact sheet before evaluating energy savings. Detailed information and objective guidance can be found in other DOE Solid-State Lighting (SSL) fact sheets,[4] on the Lighting Facts website,[5] and in CALiPER reports.

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[1] www.ssl.energy.gov/caliper.html

[2] www.lightingfacts.com/Downloads/Performance_Scale.pdf and www.lightingfacts.com/downloads/performance_scale_commercial.pdf

[3] Polar plots provide a graphical representation of the intensity distribution of a lamp. Figure 2 traces luminous intensity in a vertical plane passing through the light source. Note that whereas the black-traced and blue-traced products direct some light upward, the red-traced product directs nearly all light downward.

[4] www.ssl.energy.gov/factsheets.html

[5] www.lightingfacts.com

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Lifetime and Reliability

Long life has been billed as a key advantage of LEDs, but understanding and communicating how LED products fail and how long they last can be challenging. While LED-based products hold the potential to achieve lifetimes that meet or exceed their traditional counterparts, manufacturer claims can be misconstrued by users who do not fully understand LED product failure mechanisms or the difference between lifetime and reliability.

Concerns about lifetime and maintenance have been around for a long time. *Credit: Ford Motor Company*

Introduction

All lighting products fail at some point; that is, they reach the end of their useful life. Under normal use and conditions, product failure results from design flaws, manufacturing defects, or wear-out mechanisms. The familiar bathtub curve (Figure 1) shows how failure rate typically changes over the life of a product.

For conventional, lamp-based lighting systems (e.g., incandescent, fluorescent, and high-intensity discharge), failure most commonly results when a lamp "burns out"—otherwise referred to as catastrophic failure. In almost all cases, other system components (e.g., the ballast or luminaire housing) last longer than the lamp, and have lifetimes that are not dependent on the lamp. Further, lamp replacement is easy and relatively inexpensive. As a result, it has been sufficient to consider only the lifetime of the lamp itself. Typically, manufacturers assign a lifetime rating to a lamp based on the time at which 50% of a large sample is expected to have stopped working, using measurements and predictive models. Historically, the use of this median time, denoted B_{50}, to represent the useful life of a product has worked acceptably well for completing economic analyses and calculating associated design parameters.

Unlike conventional lighting systems, LED systems are not necessarily lamp based; commercially available LED products include fully integrated luminaires, integral-driver lamps (with conventional bases), lamps with external drivers, and modules (with newly developed interfaces to other components), among others. Regardless of product type, LED system performance is typically affected by interactions between system components; for example, LED package lifetime is highly dependent on thermal management, and LED lamp performance can be dependent on the luminaire in which it is installed. Establishing a rated lifetime for a complete LED system is further complicated by the cost and impracticality of traditional life testing, especially because the continued development and advancement of LED technology can render results obsolete before testing is finished. Consequently, the typical approach to characterizing lifetime is no longer viable for LED systems.

LED Product Failure

The failure of any LED system component—not just the array of LED packages, but also the electronics, thermal management, optics, wires, connectors, seals, or other weatherproofing, for example—can directly or indirectly lead to product failure. Further, while some LED products will fail in a familiar catastrophic way, others may exhibit parametric failure—meaning they stop producing an acceptable quantity or quality of light. A complete characterization of the useful life of an LED product must consider the possibility of catastrophic or parametric failure for each system component, operating together as a system. At this time, however, there is no standard or well-accepted method for performing such a characterization. Consequently, understanding the intricacies of failure, lifetime, and reliability is very important for evaluating LED products.

Some of the issues surrounding the lifetime of LED products are not completely unique. For example, fluorescent lamps also require a ballast and other system components that can fail, and lamp lifetime is somewhat dependent on ballast type. However, lamp designs and construction have changed slowly, allowing for the development of robust models for predicting lamp life and mature, reliable ballasts. As a result, the traditional focus on lamp rated life has been sufficient for deploying and managing fluorescent systems. When source life regularly meets or exceeds the lifetime of other components in a lighting system, however, lifetime management becomes more complicated. This is the case for a vast majority of LED products, as well as some new extra-long-life fluorescent lamps.

Failure of LED Packages

There are many components in an LED lighting system that can fail, but to date LED packages have been the focal point. LED packages rarely fail catastrophically, necessitating consideration

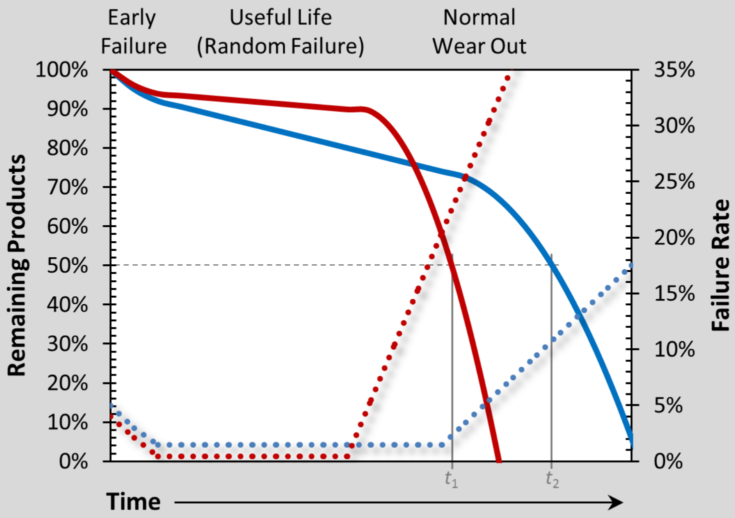

Figure 1. Failure rate (dotted lines) and percent remaining (solid lines) versus time for two hypothetical products. Reliability is the rate of random failure during the useful life phase, which is slightly lower (better) for the product shown in red. Using a 50% remaining metric for determining lifetime, the blue product has a longer rated life. Lifetime and reliability are not synonymous.

The plots of failure rate illustrate the bathtub curve, which typically arises from some combination of design flaws, material and manufacturing defects, and normal wear out. For LED products, design flaws may include insufficient thermal management, poor driver design, or incompatible materials, among others. Material and manufacturing defects are the primary contributors to early failure, otherwise known as infant mortality, as well as failure during the useful life period. Some manufacturers attempt to reduce or eliminate early failures by utilizing a "burn-in" period prior to shipment. Products that are well designed and well made should reach "normal" end of life, an event that can be caused by one or more failure mechanisms.

A desirable product has a short early failure period (with failures that can be identified during infant mortality testing), a long useful life with a low rate of random failure (i.e., is highly reliable), and a short wear out period (consistent with steeper slopes in the bathtub curve), allowing for more predictable end-of-life planning.

of parametric failures such as degradation or shifts in luminous flux, luminous intensity distribution, color temperature, color rendering, or efficacy. Of these, lumen depreciation has received the most attention, although there is little long-term data to confirm that it is the primary failure mechanism for LED products. Nonetheless, lumen maintenance is often used as a proxy for LED lamp or luminaire lifetime ratings, in large part due to the availability of standardized methods for measuring and projecting LED package lumen depreciation.

A lumen maintenance failure criterion is typically specified as a relative percentage of initial output, most often the point when output has dropped to 70% of the original value, denoted L_{70}. Because failures among a set of installed lamps or luminaires do not all occur simultaneously, lumen maintenance ratings are usually established based on the time at which 50% of a sample of products are expected to reach L_{70}, denoted L_{70}-B_{50}.

Other ways of conveying lumen maintenance performance have also been introduced. One notable method, offered as a reporting option for LED Lighting Facts,[1] is to identify the expected lumen maintenance at a fixed time interval (e.g., 25,000 hours). This may allow for more effective comparisons between products, especially when the calculated L_{70} value exceeds the intended product use cycle or the anticipated lifetime of another component in the system.

While lumen maintenance is important, other forms of parametric failure for LED packages must not be overlooked. For example, color shift may be more detrimental than lumen depreciation for some applications. It is, however, more difficult to predict, and is generally considered an aesthetic issue rather than a safety issue. For these reasons, it has received less attention than lumen depreciation. Substantial changes in luminous intensity distribution are also a potential cause of failure, but they are most often associated with changes in lumen output. For example, if half of the LEDs in a luminaire stop working, both the distribution and lumen output may be altered.

Failure of Other Components

Aside from the LED package itself, many other system components, like the driver, can cause an LED product to fail. Like any electronic device, a driver has a useful life that is related to the lifetime of its internal components, such as electrolytic capacitors, and that is strongly dependent on operating temperature. Ideally, the expected lifetime for the LED package(s) and the driver used in a product would be similar; however, given the long lifetimes of today's LED packages, the driver is the weak link for some currently available LED products, as illustrated in Figure 2. Market pressures to minimize cost or comply with specific form factors pose challenges for the longevity of LED drivers, particularly for lamp products.

Other components in an LED system may similarly struggle to outlive the LED packages. Thermal management components may become less efficient as they accumulate dirt and debris, and optical materials have been known to discolor or otherwise degrade over time, especially in high temperature environments. Gaskets and other materials may age prematurely due to compatibility issues with adjoining components. Oftentimes, the failure of auxiliary components is difficult to predict, and may only be exposed by real-world installations that have been operating for some time. Thankfully, as the body of knowledge surrounding the construction and materials of LED lighting systems has grown, it has become easier to recognize and avoid potential problems.

Standards

The measurement of lumen (and color) maintenance for LED packages is prescribed by IES LM-80-08 (*Measuring Lumen Maintenance of LED Light Sources*), while the projection of lumen maintenance beyond the duration of available LM-80 data is prescribed by IES TM-21-11 (*Projecting Long Term Lumen Maintenance of LED Light Sources*). TM-21 lumen maintenance projections can be applied to luminaires (and possibly lamps), through the proper use of in-situ temperature measurement; however, even if this extrapolation is done correctly, it can only be used to estimate the onset of one failure mode: lumen depreciation. Two new documents are slated to define standards for measuring the lumen and color maintenance of lamps and luminaires (IES LM-84), and projecting the lumen maintenance of lamps (IES TM-28); the lumen maintenance projection for luminaires is likely to be addressed in a future revision of TM-28 or a separate standard.

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[1] *http://www.lightingfacts.com/Downloads/Lumen_Maintenance_FAQ.pdf*

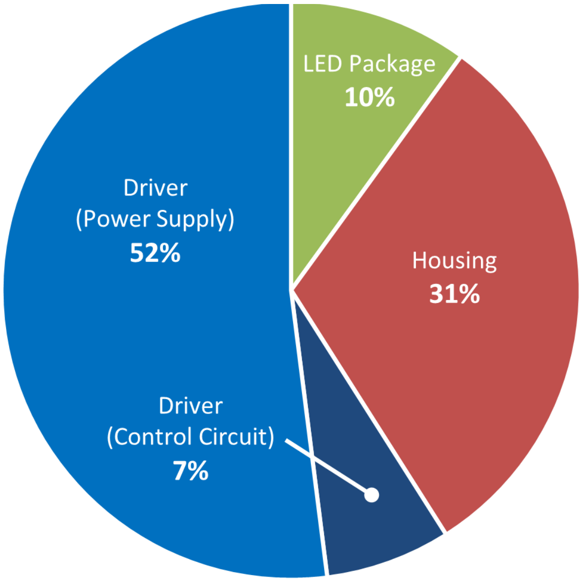

Figure 2. The distribution of failures over 34 million operating hours for one manufacturer's family of outdoor luminaires. A total of 29 fixtures failed out of more than 5,400 (0.56%). *Source: Appalachian Lighting Systems, Inc.*

Lifetime and Reliability

The rated lifetime assigned by a manufacturer is a statistical estimate of how long a product is expected to perform its intended functions under a specific set of environmental, electrical, and mechanical conditions. It is specifically related to normal wear out and end of life behavior. Typically, a single number is given as an estimate of a more complex distribution of failures; some products will fail before the rated lifetime, and some will fail afterwards. The rated lifetime of a product may be affected by its design, materials, component selection, manufacturing process, and use environment, among other factors. Importantly, the rated lifetime for a complete system cannot be longer than the in-situ lifetime for any of its components. The useful life of a product corresponds to the middle portion of the bathtub curve, where failures result from unexpected random events, and the failure rate is ideally constant.

Reliability is a different statistical measure of performance that, in principal, describes the ability of a product to perform its intended functions under a specific set of conditions and for a specific period of time. Reliability estimates are typically made for some portion of a product's useful life phase, prior to the point at which normal wear out starts to generate mass failures in a population of products. No matter how well engineered a product is, some samples will inevitably fail early; reliability is essentially a measure of the probability of these unanticipated failures, which are typically random. In relation to the bathtub curve, reliability estimates are made for the useful life (i.e., middle) portion of the curve, and are often reported as the mean time between failures (MTBF). Note that while both lifetime and MTBF are typically reported in hours or years, the latter is actually an average failure rate metric, rendering direct comparison between the two ratings meaningless and cause for misguided conclusions. For example, while a lifetime of 100,000 hours might be considered excellent, a ballast or driver MTBF of 100,000 hours means that over a 10-year (continuous) useful life period, 87.6% of the units will likely fail and need to be replaced.[2] Reliability metrics are useful for approximating the average maintenance interval of serviceable systems, but since MTBF only describes an average failure rate, the accuracy of such estimates is reduced for systems that do not have a constant failure rate during their useful life.

Serviceability

A serviceable product has components that are replaceable or repairable by regular maintenance personnel. Whereas lamp-based luminaires are almost all easily serviced in the field, some LED luminaires are not serviceable at all, or must be returned to the manufacturer for repair. Even for serviceable LED luminaires, the lack of standardized components—a situation that is improving—leads to several questions that must be answered on a product-by-product basis. For example, what components are replaceable and what are their rated lifetimes and reliabilities? Will replacement components be available in the future? Will next-generation components be backwards compatible?

Serviceability should factor into any purchasing decision where long or unproven system lifetime is expected, or where component lifetimes are not well known or well matched. While making a product serviceable typically adds some cost, concerns about the reliability of specific components over very long lifetimes can be alleviated if the components are replaceable or repairable. For some applications, a serviceable product with short-lived or less reliable components may be less costly to operate over its useful life than a more expensive product with well-matched component lifetimes.

Important Terms

Failure – The end of useful life; may occur either catastrophically (i.e., "burn out") or parametrically, where a product does not perform as intended (e.g., emits less than 70% of the initial output).

Lifetime – A statistical measure (or estimate) of how long a product is expected to perform its intended functions under a specific set of environmental, electrical and mechanical conditions. Lifetime specifications can only describe the behavior of a population; any single product may fail before or after the rated lifetime.

Mean Time Between Failures (MTBF) – The average time between failures during useful life for repairable or redundant systems.

Mean Time To Failure (MTTF) – The average time to failure during useful life for components or non-repairable systems.

Reliability – A statistical measure (or estimate) of the ability of a product to perform its intended functions under a specific set of environmental, electrical, and mechanical conditions, for a specific period of time. Reliability estimates for the entire useful life phase of a product are commonly reported using MTBF or MTTF.

Serviceability – The ability of a product to be repaired by regular maintenance personnel, typically through replacement of a subsystem or one or more associated components.

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[2] *Percent failures is equal to the period of use divided by the MTBF. In this case, 87,600 hours/100,000 hours × 100% = 87.6%.*

Discussion

The accurate portrayal of LED product lifetime and reliability is important for consumers, manufacturers, and the lighting industry as a whole. It was not long ago that the default lifetime claim for an LED product was 100,000 hours, often with little or no supporting evidence. Such unsubstantiated claims can lead to significant user frustration that hinders the adoption of LED technology. Similarly, portraying the lumen maintenance of LED packages as the lifetime of a complete LED lamp or luminaire may misrepresent the actual performance of some products.

While standards groups are making steady progress characterizing the lumen maintenance of LED lamps and luminaires, more work is needed to project lifetime considering all possible failure modes. Testing a statistically significant sample of complete luminaires while addressing all possible permutations of features is an arduous task, but an approach that uses statistical methods for combining test results from multiple components can significantly reduce the testing burden; Figure 3 shows an example of such an approach, with the cumulative probability of failure plotted for a theoretical product, considering only the LED packages and driver. Accelerated (overstress) testing methods may also help reduce required testing time and improve reliability through the identification of design flaws and manufacturing defects. Continued work to standardize testing procedures, projection methods, and reporting practices is necessary and ongoing.

Consumers and specifiers can find a wide range of lifetime ratings for LED products, from less than 10,000 hours to more than 100,000 hours, depending on the type and quality of the product. However, these ratings are usually based exclusively on the expected lumen depreciation of the LED package, and little other data is readily available. Therefore, it may be difficult for consumers and specifiers to identify a truly long-life, reliable LED product. Even if consistent reporting of system-level lifetime and reliability data becomes commonplace, LED product variability may necessitate weighing various tradeoffs and asking additional questions. A well-designed product may take many forms, some of which may be more or less acceptable to a given user:

- Failure results from a single, well known, and easily understood wear-out mechanism.
- Failure results from multiple sources or mechanisms, but the product is designed such that the lifetime of each component is similar. For example, the lifetime of the LED driver matches the lifetime of the LED package(s).
- Failure results from multiple sources or mechanisms, but components with a shorter lifetime or lower reliability are easily serviced or replaced, thereby enabling an acceptable maintained system lifetime (and cost).

Users are advised to give thought to what balance between lifetime, reliability, serviceability, warranty, sustainability, and cost is necessary or ideal for their lighting application. Typically, the design and manufacture of products that last longer comes at a cost, yet the advantages of longer life may not be realized if the expected use cycle is less than the lifetime. For example, a building scheduled to be renovated in the next 10 to 15 years may not benefit from lighting products with a 30-year lifetime. Instead, it may be better to use a less expensive product with a shorter useful life, but higher reliability. On the other hand, shorter-lived products generate more waste and compromise sustainability goals or requirements. Minimizing the net amount of disposed material ideally results in the lowest user cost and environmental impact.

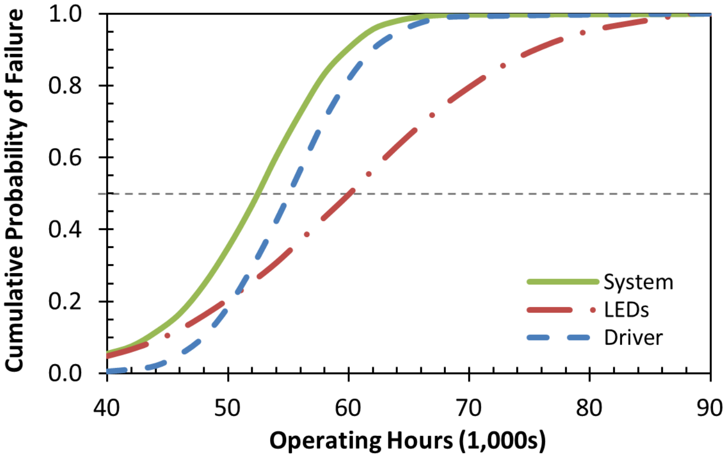

Figure 3. In this theoretical example, the rated life of the LED system is a function of both the LEDs and the driver. The rated life of the combined system is approximately 52,000 hours, which is less than for either component individually.

Lumen maintenance projections can help sophisticated users compare products, as long as their limitations are properly understood. Evaluating lifetime projections for other system components should also be considered, since the lifetime of a lamp or luminaire cannot be longer than the lifetime of any of its components. If payback period is critical, it may also be advisable to give extra consideration to the terms and credibility of the manufacturer's warranty.

Conclusion

As LED technology matures, some of the current issues surrounding the measurement and reporting of lifetime and reliability may abate. However, it is likely that products will continue to fail both catastrophically and parametrically, through various mechanisms. The dependence of LED package performance on other components will continue to require that discussions about lifetime be focused at the luminaire, and not component or even lamp level, as lamp performance in different luminaires can vary. Innovative luminaire designs and control strategies—such as variable drive products that maintain lumen output—will further complicate the measurement and reporting of lifetime. As with many performance attributes, LEDs have the potential to best other technologies in terms of longevity, but choosing the right product requires some understanding of expected failure mechanisms, lifetime, reliability, and serviceability, as well as asking the right application-specific questions.

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PNNL-SA-97534 • August 2013

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General Service LED Lamps

Performance gains and dropping prices have made LED products increasingly viable for general illumination. How do they stack up against the familiar incandescent light bulb?

The winner of the L Prize 60 W replacement competition features remote phosphors that appear yellow when in the off state. (www.lightingprize.org)

Incandescent lamps were introduced more than a century ago, and they remain in widespread use today. In fact, the installed base of incandescent A lamps (Figure 1) is currently greater than that of any other lamp type. Incandescent lamps are particularly popular in residential applications due to familiarity with the technology, the low initial cost and ease of replacement, and the quality of light emitted. However, there is tremendous potential for energy savings by replacing incandescent lamps with more efficient halogen, CFL, or LED alternatives. For example, if the entire nationwide installed base of incandescent A lamps was converted instantaneously to LED, an estimated 84.1 TWh per year would be saved—equating to the total annual electricity consumption of nearly seven million residential households.[1]

This fact sheet addresses direct replacements for general service incandescent lamps—including most A lamps and some other formats—as defined in the Energy Independence and Security Act of 2007 (EISA 2007).[2] Products affected by this legislation include standard incandescent or halogen lamps that are intended for general service applications, have a medium screw base, emit between 310 and 2,600 lumens, and are capable of being operated at a voltage range at least partially within 110 and 130 V. Products in this category emit light in all directions (i.e., are omnidirectional), are generally more functional than decorative in application, and are fully integrated (i.e., all components are integral to the lamp). With some basic guidance, prospective buyers can find cost-effective alternatives which save energy without compromising the quality or quantity of illumination.

Figure 1. *A lamps (left) are the most common type of general service incandescent lamp, but others (such as some G- or BT-shaped lamps) are also included in the definition.*

Lower Wattage, Equal Lumens

When evaluating energy-saving alternatives to conventional lamps, emphasis should be placed on lumen output rather than input power (watts). This is because luminous efficacy—the quotient of lumen output and input power—can differ greatly between product types. For example, the integrated LED lamp that won the L Prize competition (www.lightingprize.org) produces as many lumens as a 60 W incandescent A lamp while drawing just 10 W of power. By comparison, equivalent CFLs typically draw 13 to 15 W.

EISA 2007 established new performance requirements for general service incandescent lamps. The affected incandescent and halogen lamps were classified based on lumen output, with input power restricted for each output class—this resulted in minimum efficacy criteria as shown in Table 1. Traditional incandescent A lamps do not satisfy these requirements, but some newer halogen lamps comply. Integrated LED lamps and CFLs are excluded from the legislation but most feature efficacies well above these values.

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[1] From the DOE report, "Energy Savings Estimates of Light Emitting Diodes in Niche Lighting Applications" (January 2011), provided at www.ssl.energy.gov/tech_reports.html.

[2] An overview of EISA 2007, including a discussion of excluded lamp types, is provided at www.energysavers.gov/lighting.

Table 1. *EISA 2007 requirements for general service incandescent lamps.*

Rated Output (lm)	Maximum Input Power (W)	Minimum Efficacy (lm/W)	Inc. A Lamp Affected (W)	Effective Date
1490–2600	72	20.7	100	Jan. 2012
1050–1489	53	19.8	75	Jan. 2013
750–1049	43	17.4	60	Jan. 2014
310–749	29	10.7	40	Jan. 2014

A Wide Range of Performance

Many currently available integrated LED lamps meet or exceed the performance of general service incandescent lamps, but performance varies widely and is not always accurately portrayed by manufacturers. Several market-based programs have been established by the U.S. Department of Energy (DOE) to help prospective buyers make informed decisions. One such program, LED Lighting Facts, publishes performance data from manufacturer-supplied LM-79 test reports,[3] and allows partner manufacturers to use the voluntary LED Lighting Facts label on products.[4] This information facilitates accurate comparison of products. Another DOE program, CALiPER, goes one step further by anonymously acquiring and testing LED and benchmark products, thereby helping to ensure rated performance accurately characterizes products available on store shelves and through other distribution channels.[5]

Figure 2 summarizes lumen output and efficacy data from LED Lighting Facts and CALiPER. Efficacies of LED products vary substantially but are consistently higher than the incandescent and halogen benchmarks, and in some cases surpass typical CFLs. In recent years, there have been notable improvements in both efficacy and lumen output of LED products. For example, CALiPER testing showed that the average efficacy of LED A lamps acquired from retail stores in 2010 and 2011 improved from 40 to 58 lm/W during that period. A majority of the products tested by CALiPER or listed by LED Lighting Facts already exceed the 2020 backstop requirement of 45 lm/W established by EISA 2007. Many also meet the more stringent ENERGY STAR® (Integral LED Lamps version 1.4) efficacy requirement of 50 lm/W (< 10 W) or 55 lm/W (≥ 10 W).

Beyond Lumens and Watts

Although early CFLs could emit equal lumen output while drawing less power than incandescent lamps, many left consumers dissatisfied with the quality of light. This underscores the need to consider more than just lumens and watts when comparing

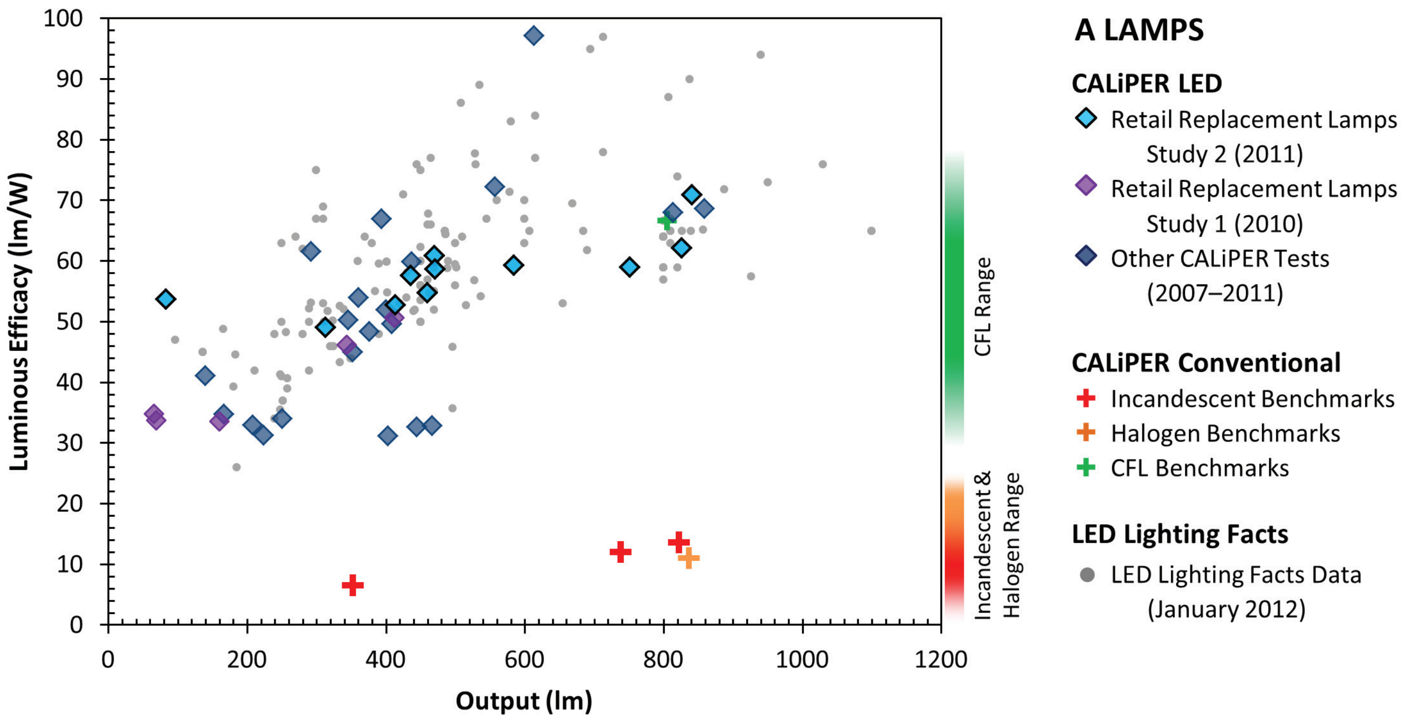

Figure 2. *Luminous efficacy (lm/W) versus output (lm) for LED A lamps compared to conventional benchmarks. Generally, the efficacy of LED A lamps is equal to or better than typical CFL A lamps. Some lamps have lumen output equivalent to a 60 W incandescent lamp, and a few are beginning to reach higher equivalency levels.*

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[3] *See the DOE fact sheet, "Understanding LM-79 Reports" (www.ssl.energy.gov/factsheets.html).*

[4] *For more information on LED Lighting Facts, please visit www.lightingfacts.com. Note that a separate Lighting Facts program has been developed by the Federal Trade Commission (FTC), which mandates labels on medium screw-base lamps.*

[5] *The CALiPER and LED Lighting Facts programs require that testing laboratories be independent and have LM-79 accreditation which includes proficiency testing, such as that available through the National Voluntary Laboratory Accreditation Program (NVLAP). For details, please visit www.ssl.energy.gov/test_labs.html.*

products.[6] Among others, key equivalency criteria to consider include color attributes, spatial distribution of light, electrical and mechanical compatibility, rated lifetime, warranty, and cost. In some situations differing performance may be welcomed as an improvement, but it is generally safer to assume that an integrated LED lamp must be equivalent to the product it replaces.

Color Attributes

Two basic metrics of color quality are correlated color temperature (CCT) and the color rendering index (CRI).[7] A nominal CCT of 2700 to 3000 K is generally appropriate if the intent is to match the appearance of an incandescent lamp. The highest nominal CCT allowed by ENERGY STAR for integrated LED lamps is 4000 K, although higher CCTs may be preferred by some users.

ENERGY STAR also requires a minimum CRI of 80 to ensure that the apparent color of objects will not differ greatly whether illuminated by the LED product or by a standard reference source. This criterion is met by many LED products, but not all. Consumers should be diligent in reviewing manufacturer-listed values to ensure expectations are met.

Spatial Distribution of Light

Omnidirectional lamps are generally most effective when installed in pendants and other luminaires designed to emit light in all directions (see Figure 3). By contrast, a directional lamp (e.g., PAR or R) would be better suited for use in recessed downlights since a smaller proportion of the output would be trapped in the luminaire. Some LED products are designed to resemble incandescent A lamps in physical appearance—and are indeed marketed as suitable replacements—but actually behave more like directional lamps. Polar plots of luminous intensity offer one method of identifying such products. For example, it is clear from Figure 4 that CALiPER 10-55 more closely replicated the omnidirectional distribution of the benchmark incandescent A lamp than did CALiPER 11-03.

For omnidirectional lamps to achieve ENERGY STAR qualification, the luminous intensity at any angle up to 135° from the center-beam axis cannot differ by more than 20% from the mean intensity for this region, and at least 5% of the total lumen output must be emitted in the 135°–180° region. These criteria were both satisfied by CALiPER 10-55, but neither was met by CALiPER 11-03.

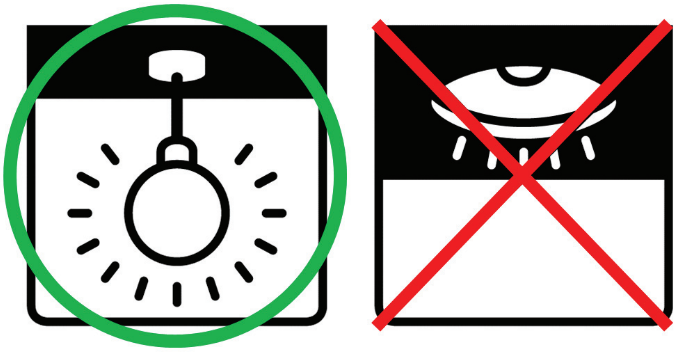

__Figure 3.__ Omnidirectional lamps tend to be more compatible with pendant-type luminaires or table lamps than with recessed downlights. (Image credit: ENERGY STAR)

Electrical and Mechanical Compatibility

Beyond performance equivalency, basic electrical and mechanical compatibility are important to consider when choosing a lamp, especially if an integrated LED lamp is replacing a conventional lamp:

- If the physical profile of the LED product differs substantially from the lamp for which the luminaire was designed, performance may be compromised due to optical misalignment or blocked light. In the worst case, the replacement lamp may not fit at all. Such problems may be revealed by side-by-side visual comparisons and trial installations.
- The lamp must feature a base that matches the socket into which it will be installed. By definition, general service incandescent lamps have an E26 (medium) screw base, but some alternatives have other base types (e.g., GU-24).[8]
- Many integrated LED lamps are labeled as dimmable, but actual dimming performance might vary depending on the combination of devices being used. If the lamp will be controlled by a dimmer, then it should be rated to be compatible

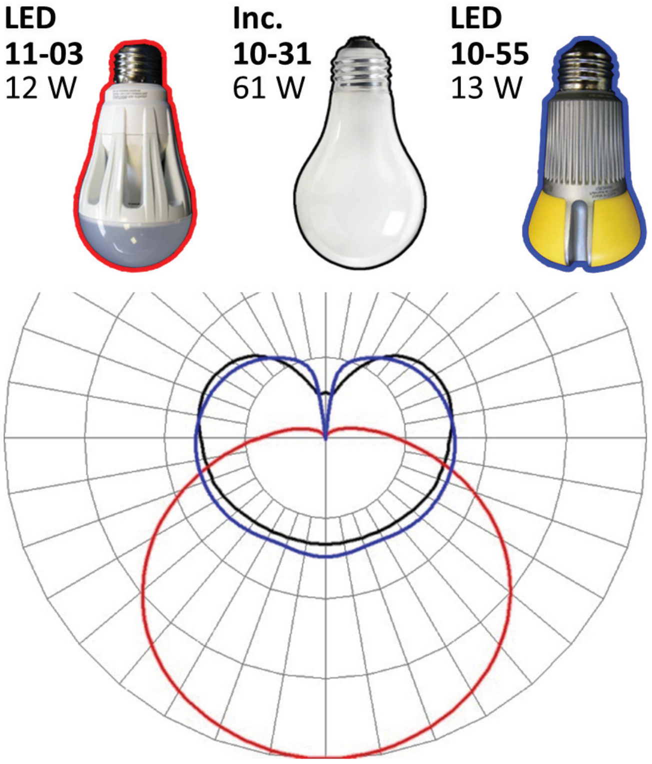

__Figure 4.__ Polar plots of luminous intensity distribution for three different A lamps tested by CALiPER. CALiPER 10-55 more accuratly replicated the distribution of a 60 W incandescent lamp than did CALiPER 11-03.

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[6] *See the DOE fact sheet, "Establishing LED Equivalency" (www.ssl.energy.gov/factsheets.html).*

[7] *See the DOE fact sheet, "LED Color Characteristics" (www.ssl.energy.gov/factsheets.html).*

[8] *For example, California Title 24 established statewide criteria for GU-24 bases and sockets (www.energy.ca.gov/title24).*

with the specific type of dimmer used.[9] This can increase the likelihood—but does not guarantee—that the LED product will dim appropriately.

- Integrated LED lamps sold in the United States must bear a mark (i.e., label) from a Nationally Recognized Testing Laboratory (NRTL) indicating compliance with safety regulations.[10]

Rated Lifetime and Warranty

Expected lifetime can vary widely among different lamp types. ENERGY STAR qualified LED lamps are rated to remain in service for at least 25,000 hours—approximately 23 years when operated for an average of three hours per day—which is significantly longer than typical incandescent lamps (1,000 hours) or integrated CFLs (6,000–10,000 hours). ENERGY STAR qualified products must also feature a warranty, covering repair or replacement, of at least three years from the date of purchase. Some LED manufacturers claim much greater lifetimes, which often cannot be substantiated using available industry standards. Although some of these claims may prove valid, they are generally best regarded with skepticism, particularly if the warranty is not of commensurate duration or if the product is not carried by a reputable retailer.

Cost and Return on Investment

LED product price is not always a clear indicator of performance, but relatively low prices are often associated with some form of compromise. In comparing lamps that produce an equivalent quantity and quality of illumination, current prices for LED products are substantially higher than for more established technologies. Table 2 provides an example of a life-cycle cost analysis, which accounts for rated life, energy costs, and the time value of money. Although energy rebates were excluded from this analysis, such incentives can offset the purchase price of energy-efficient products such as integrated LED lamps and CFLs.

The cost analysis presented in Table 2 is a generalized example—actual pricing may vary from store to store or between regions. Prices are also changing rapidly; for example, the average price per lumen of LED lamps acquired by CALiPER from retail stores decreased by 55% between August 2010 and November 2011.[11] Some integrated LED A lamps already represent a cost-effective alternative to incandescent and halogen lamps, and if the current trend continues they will soon offer cost savings compared to integrated CFLs.

Table 2. *Life-cycle costs and savings (2012 dollars) for four different lamps. The example CFL is slightly more cost-effective than the example LED, although there is considerable variability among products.*

Technology	Inc.	Hal.	CFL	LED
Rated Input Power (W)	60	43	14	12
Rated Output (lm)	860	750	800	800
Rated Lifetime (hours)	1,000	1,000	8,000	25,000
Lamps Required	25	25	4	1
Initial Unit Cost ($)	0.37	1.50	4.50	25.00
Present Value of Replacement Unit Costs ($)	6	23	6	-1
Present Value of Energy Costs ($)	103	74	24	21
Total Life-Cycle Cost ($)	109	98	34	45
Net Savings ($)	**n/a**	**11**	**74**	**64**

Note: These calculations assume three hours of operation per day and an initial electricity rate of $0.11 per kilowatt-hour (kWh)—both of these values are the same as used for the FTC Lighting Facts label. The calculations also assume a 4.0% real discount rate (constant-dollar analysis) and end-of-year discounting, utilize NIST forecasts of future U.S. residential sector electricity rates, account for residual value, and exclude labor costs. The results are based on a 22-year analysis period.

Conclusions

Although performance varies widely among available general service LED lamps, the technology continues to improve even as the price per lumen decreases. Some LED products have already demonstrated equivalence to the ubiquitous 60 W incandescent light bulb, and higher-output alternatives to 75 W and 100 W incandescent A lamps will be tested by CALiPER and LED Lighting Facts in the near future. When chosen carefully, LED products can offer substantial energy savings without compromise to the quantity or quality of illumination, while also saving money in the long run.

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[9] *See the DOE fact sheet, "Dimming LEDs," for details (www.ssl.energy.gov/factsheets.html).*

[10] *Integrated lamps must satisfy UL 1993 and UL 8750. For a list of NRTLs, visit www.osha.gov/dts/otpca/nrtl.*

[11] *Additional information can be found in the CALiPER exploratory study, "Retail Replacement Lamps – 2011."*

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Building Technologies Office
SOLID-STATE LIGHTING TECHNOLOGY FACT SHEET

Optical Safety of LEDs

The safety of LED lighting with regard to human health has occasionally been the subject of scrutiny. One such concern is photoretinitis—photochemical damage to the retina—which can result from too much exposure to violet and blue light. This is known as *blue light hazard*. The risk of blue light hazard is sometimes associated with LEDs, even though LEDs that emit white light do not contain significantly more blue than any other source at the same color temperature. According to current international standards, no light source that emits white light and is used in general lighting applications is considered hazardous to the retina for healthy adults. That said, the optical safety of specialty lamps or colored sources must be considered on a case-by-case basis, and light sources used around susceptible populations, such as infants or adults with certain types of eye disease, require additional evaluation.

The Effects of Optical Radiation

Light is a physical (and psychological) stimulus that has many effects on the human body. Besides enabling vision, light entrains our circadian rhythms—body processes such as our sleep/wake cycle, appetite, body temperature fluctuations, and more. Visible light is just one portion of the electromagnetic spectrum. It is sandwiched between ultraviolet (UV) and infrared (IR) radiation, which have shorter and longer wavelengths, respectively (see Figure 1). Collectively, this radiant energy is referred to as optical radiation, with wavelengths ranging from 200 to 3,000 nm. The complete electromagnetic spectrum also includes radio waves, X-rays, gamma rays, and microwaves, among other types of radiant energy.

Optical radiation falls on the skin and eyes, where the energy is transformed via photochemical processes or thermal reactions. While this sensory interaction is an essential part of human perception, too much radiant energy can damage tissue. Shorter wavelengths (UV) can cause sunburn, or may even have effects at a cellular/DNA level. Longer wavelengths (IR) are perceived as heat; again, too much can lead to discomfort or injury. Among the six defined optical radiation hazards,[1] the only one that is practically applicable to LEDs is blue light hazard; by design, LEDs used for lighting do not emit UV or IR radiation. For more information on current standards, see page 2.

Regardless of the source type, the blue component cannot be removed from white light that is appropriate for interior environments. Besides being necessary for proper visual appearance and color rendering, blue light is essential for nonvisual photoreception, such as regulating our circadian rhythms.

The amount of blue light in typical architectural lighting products is not hazardous. Even when the light intensity gets uncomfortably high, the risk is mitigated by natural defense mechanisms, including aversion response (blinking, head movement, and pupil constriction) and continuous eye movement (saccades), which protect the retina from overexposure. Without these, the sun could damage our eyes.

The radiation to which our eyes and skin are exposed can cause both acute and long-term effects. The acute effect of blue light exposure (i.e., blue light hazard) is the focus of this fact sheet.

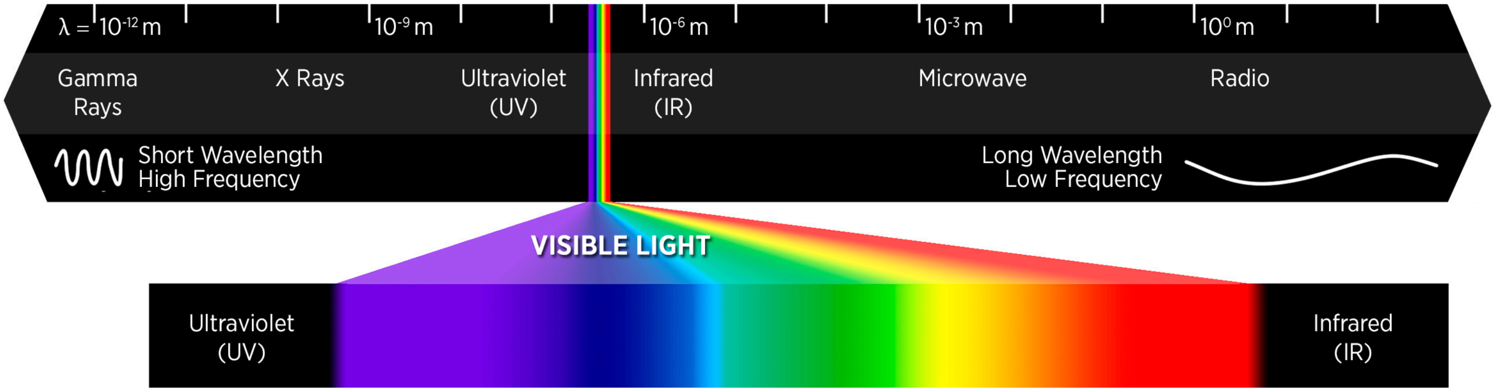

Figure 1. Illustration of the electromagnetic spectrum. The defined limits for different types of radiation can vary. This is especially true for visible light, with the low end often cited between 350 nm and 400 nm, and the high end listed between 700 nm and 830 nm. The spectrum shown is a simple approximation.

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[1] *Current standards cover six types of hazard: Actinic UV, Near UV, Retinal Thermal, Blue Light, Cornea/Lens IR, and Low Luminance Retinal IR.*

Current Standards for Photobiological Safety

Optical safety is addressed by international guidelines and standards including:

- CIE S009-2002: *Photobiological Safety of Lamps and Lamp Systems*
- ANSI/IES RP27: *Recommended Practice for Photobiological Safety for Lamps and Lamp Systems*
- IEC/EN 62471: *Photobiological Safety of Lamps and Luminaires*. Supporting guidance is provided in IEC/TR 62471-2 (2009) and IEC/TR 62778 (2012).

These three documents provide harmonized definitions of optical radiation hazards, exposure limits, proper measurement techniques, and a risk classification system. IEC 62471 was officially adopted by the European Union as EN 62471 in 2008; thus, all new products with a *Conformité Européenne* (CE) label must indicate potential optical hazards with appropriate labels, if applicable. Labeling is currently voluntary in most other countries, including the United States.

Characterizing Blue Light Hazard: Risk Groups

The primary factors affecting the blue light hazard damage potential of a light source are the quantity and spectrum of radiation incident on a given area of the retina, as well as the size of the source and duration of exposure. Given these factors, the standard documents establish exposure limit risk groups (RGs) based on recommendations from the American Conference of Governmental Industrial Hygienists (ACGIH) and the International Commission on Non-Ionizing Radiation Protection (ICNIRP). Four risk groups are used to categorize exposure based on human characteristics:

- The exempt group, RG0, is established on the principle that the lamp poses no photobiological hazard, with maximum exposure times greater than 10,000 seconds (about 2.8 hours). There are no labeling requirements.
- The RG1 classification is based on behavioral limitations to exposure—that is, humans don't typically stare at lights for long periods of time. The maximum exposure times are between 100 and 10,000 seconds. There are no labeling requirements.
- The RG2 classification is for maximum exposure times between 0.25 seconds and 100 seconds. Optical radiation at this level is not dangerous due to humans' natural aversion response. Nonetheless, to meet relevant standards, products in this group must include a label that states, "CAUTION. Do not stare at exposed lamp in operation. May be harmful to the eyes."
- Lamps classified as RG3 may pose a risk with even momentary exposure (< 0.25 seconds). To meet the standard, they are required to include a label that states, "WARNING. Do not look at exposed lamp in operation. Eye injury can result." A blue light hazard classification of RG3 for white light sources is very unlikely, requiring a luminance above 4 Gcd/m^2 and an illuminance greater than 400,000 lux.

Assessment Criteria

There are two methods for establishing the distance at which risk evaluation and classification occurs. The baseline method uses a worst-case 0.2 m (about 8 inches) viewing distance, corresponding to the minimum distance at which an image can be focused on the retina. Alternatively, for products intended for general lighting service (GLS)[1] the value can be equal to the distance at which the light source produces 500 lux, assuming it is not less than 0.2 m. This divergent methodology has led to some confusion, with the 500-lux criterion being criticized as not representing some scenarios appropriately. No white light source would be considered hazardous under the 500-lux criterion (see Figure 4).

In either case, spatially averaged B(λ)-weighted[2] radiance is calculated based on an assumed field of view that varies based on risk group. An alternative irradiance procedure is also prescribed. Importantly, classifications for individual LEDs can be applied to the lamp or luminaire in which they are subsequently used—the risk group for the final product may be lower, but can never be higher. Further descriptions of the assessment criteria and their effect on classifications can be found in the relevant standards documents or supporting guidance documents.

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[1] *GLS products include lamps and luminaires used in buildings and exterior areas/roadways. Not included are specialty lamps such as those used in projectors.*

[2] *The blue light hazard function, B(λ), is applied to a spectral power distribution to weight the damage potential of the different wavelengths (see Figure 2).*

Is all blue light the same?

Light at any given wavelength is the same regardless of what it was emitted from (or reflected off); that is, there is no physical difference in the stimulus, or the resulting visual and nonvisual effects whether the light is from an LED lamp, incandescent lamp, CFL, or any other source. At the same time, visible light is a continuous spectrum of wavelengths. "Blue light" is a simplified term generally referring to the range of radiant energy between violet and cyan, having wavelengths of approximately 400–500 nm. Most sources emit light over a range of wavelengths—including blue—rather than any one specifically. Additionally, our visual system is based on photoreceptors with broad response ranges that integrate spectral information. Hazardous radiation is similarly defined using functions that account for the variable effects across different wavelengths. For example, the blue light hazard weighting function extends from approximately 380–540 nm, with a peak at 435–440 nm (Figure 2). Accordingly, it is important to consider the effects of energy over a range of wavelengths, rather than any local peak.

What we consider "white light" can be made up of many different combinations of wavelengths, and have many different tints. It is also possible that two light sources that look identical to a human observer are comprised of different spectral content—this is known as metamerism. Importantly, there is a basic balance of long- and short-wavelength energy that must occur for a source to appear a certain shade of white, referred to as color temperature, although the specific spectral content may be somewhat different.

Do LEDs emit more blue light?

Often, investigations into the effect of short-wavelength radiation—be it on humans or artwork—suggest that LEDs are dangerous because they emit more blue light than other sources like incandescent bulbs or CFLs. While it is true that most LED products that emit white light include a blue LED pump,[2] the proportion of blue light in the spectrum is not significantly higher for LEDs than it is for any other light source at the same correlated color temperature (CCT), as shown in Figures 2 and 3.[3] This is exemplified by comparing the blue light hazard efficacy ($K_{B,v}$)—the blue light hazard potential per lumen—of sources with similar CCTs. Other calculations could be performed using a different measure of blue content, and as long as the weighting

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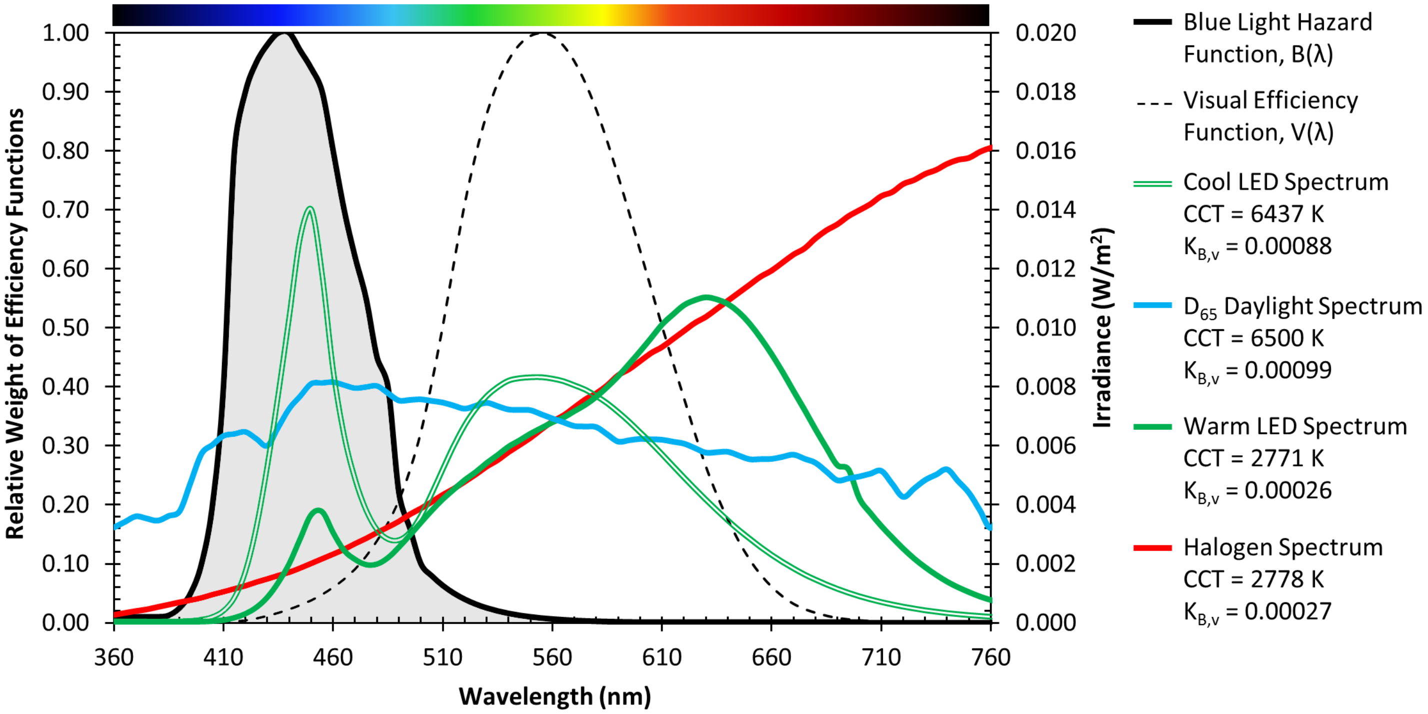
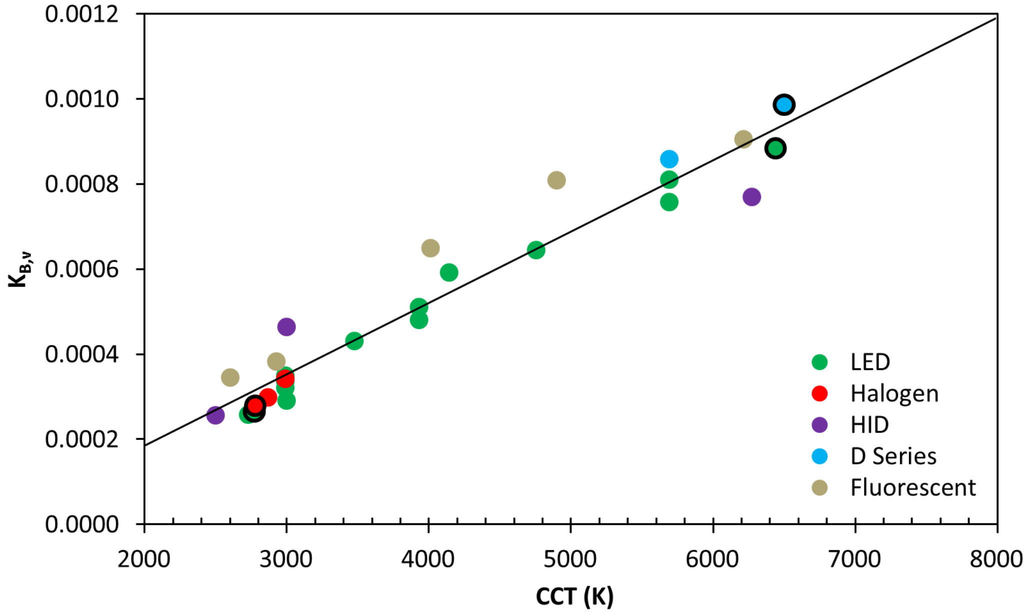
[2] The predominant method for creating white light with LEDs is to use a blue LED and convert a portion of the emission to longer wavelengths using phosphors. This same approach is used with fluorescent lighting, although the initial emission is in the UV, instead of blue.

[3] This is mathematically predictable because the blue light hazard function $B(\lambda)$ is very similar to the $z(\lambda)$ color matching function that is used to calculate chromaticity coordinates and subsequently CCT.



▲ Figure 2. Four spectral power distributions equalized at 500 lumens and the blue light hazard and visual efficiency functions. The two cool white sources (Cool LED and D_{65}) and the two warm white sources (Warm LED and Halogen) have comparable areas under the $B(\lambda)$ curve.



◄ Figure 3. Regardless of source type, there is a strong linear correlation between blue light hazard efficacy ($K_{B,v}$) and CCT. The points with black circles correspond to the four spectral power distributions shown in Figure 2.

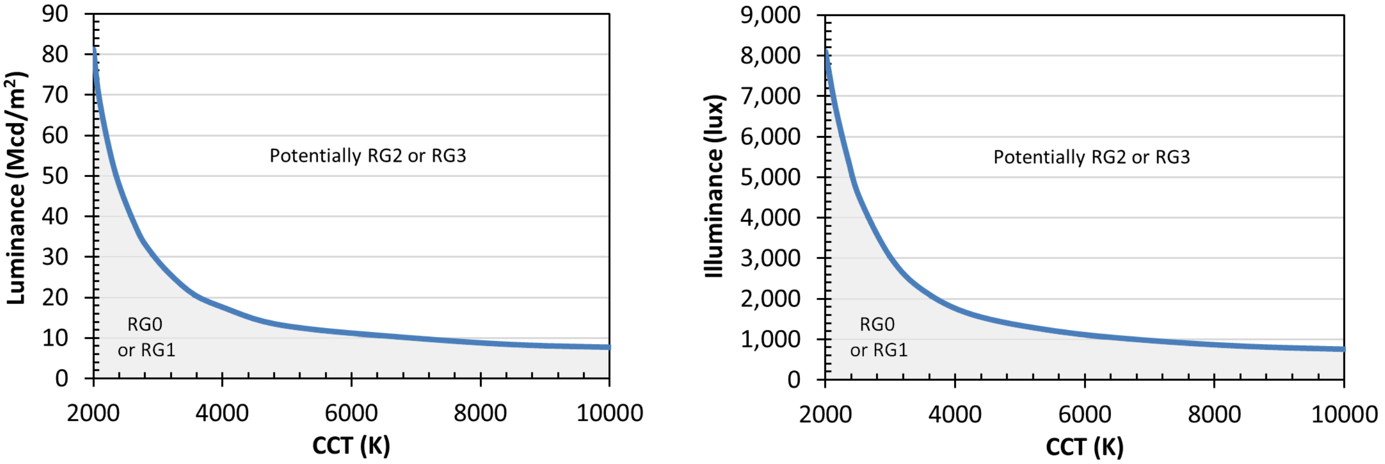


Figure 4. Calculated threshold conditions for white light source classification as RG2 or higher, which requires a label (see page 2). The curves use CCT to approximate the boundary. Products near the threshold should be properly evaluated. A product must be above the boundary for *both* the luminance and illuminance conditions to be classifed as RG2 or higher. *Source: IEC TR 62778*

function is appropriately broad, the results will be similar. LEDs may emit more energy at a given wavelength, but it is important to remember that all visual and nonvisual phenomena are based on responses to a range of radiant energy, rather than a single wavelength.

The misconception that LEDs emit more blue light may have several contributing factors. The blue pump results in a visible "spike" in the spectral power distribution at short wavelengths, a feature that is especially noticeable at high CCTs, which were common in the earliest LED products. At lower CCTs, the spike may be barely noticeable at all. Although most LED products sold today have CCTs that are similar to their counterpart products—2700 K or 3000 K for screw-base lamps, 3500 K or 4000 K for fluorescent-replacement products—it is possible to create LED products with a wide variety of spectral power distributions. This is in contrast to standard incandescent lamps, which are essentially all the same.

How much light is a concern?

Given that CCT is highly predictive of blue light content, it is possible to use photobiological safety standards to determine a threshold for hazard based on CCT.[4] Figure 4 shows the calculated threshold between Risk Group 1 and Risk Group 2 based on luminance (left) and illuminance (right). Importantly, a product must exceed the threshold for *both* the luminance and illuminance conditions to be considered hazardous. The hazard from Risk Group 2, which can include the sun, is mitigated by humans' natural aversion response, so injury is unlikely.

What situations are concerns?

Given the threshold criteria shown in Figure 4, it is easy to conclude that white-light architectural lighting products do not pose a risk for blue light hazard, based on the 500-lux evaluation criterion prescribed by photobiological safety standards. Even under more strict evaluation criteria, it is unlikely that a white light source could achieve classification above Risk Group 1. However, that does not mean that the safety of all light sources is guaranteed. Several situations require further attention, including:

- Non-white light sources (e.g., blue LEDs).
- Applications where infants could be in close proximity to bright light sources, since they have not yet developed aversion responses.
- Applications where those suffering from lupus or eye disease may be exposed to high light levels.
- Applications where intentional exposure to bright light is expected, or viewing conditions may be outside the norm.

While these scenarios may require additional investigation, they are not necessarily hazardous.

Conclusions

LED products are no more hazardous than other lighting technologies that have the same CCT. Furthermore, white-light products used in general lighting service applications are not considered a risk for blue light hazard according to current international standards. Sensitive individuals may have additional concerns, and colored light sources—which may be classified as Risk Group 2 or higher and require a label to meet accepted standards—should be evaluated on a case-by-case basis.

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[4] *Using CCT alone provides an estimate that is accurate within ±15%. For products near the threshold, specific hazard testing should be performed in accordance with the applicable standard.*

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PNNL-SA-96340 • June 2013

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Solid-State Lighting Technology Fact Sheet

Lighting for Health: LEDs in the New Age of Illumination

The proliferation of electric lighting was a hallmark of the 20th century, providing widespread access to light virtually anywhere, at any time of day. In the same way, the 21st century may become the age of lighting for physiological well-being—often referred to with the familiar catchphrase light and health. Recent research has greatly advanced the understanding that light not only enables vision, but is also a critical signal to our biological systems, affecting circadian rhythms, pupillary response, alertness, and more. However, applying early research findings to widespread lighting practices must be done with great caution, if it is ready to be done at all. After all, light as a drug is much different from light as a commodity.

A recent article in the journal *Trends in Neurosciences* argued for a cautious and informed approach when attempting to translate scientific studies to engineering practice and policymaking. In *Measuring and Using Light in the Melanopsin Age*,[1] a diverse group of fourteen leading researchers explored the current state of knowledge on nonvisual photoreception, which is centered on the photopigment melanopsin, and how it can be applied in the field today. This article is an important statement, providing a firm viewpoint from authors at 11 different institutions.

Humans are exposed to a substantial amount of electric lighting, all of which has some effect on our physiology—regardless of the type of source. Now there is a rapidly expanding amount of information on light and health, which is leading to a rapidly expanding number of questions on exactly how we should light architectural spaces. Often, uncertainty surrounds the role of LEDs. This largely stems from the timing of LED technology's quick rise to prominence in the lighting world and the outlook for its future. With LEDs there is greater ability to tailor lighting systems to meet both visual and nonvisual needs, which is presenting many new opportunities. At the same time, there is potential for poorly engineered products—including LEDs and other types of light sources—or poorly implemented lighting systems to cause harm.

Current Science and Limitations

The non-image-forming response to light is wide ranging, including circadian, neuroendocrine, pupillary, behavioral, and other physiological effects. Specific outcomes include the daily resetting of circadian clocks (a process called entrainment), as well as acute effects like pupil constriction, increasing alertness, and melatonin suppression. Light has been shown to be an effective clinical treatment for a variety of conditions, such as Seasonal Affective Disorder (SAD), but also plays an important role in maintaining daily physiological function. Importantly, the non-image-forming photoreceptor system in our eyes is different from our visual system. Although it shares some of the same photoreceptors, it has its own unique spectral and temporal response to light stimuli. This is one of the reasons traditional measures of lighting quantity, such as illuminance, do not accurately quantify the nonvisual effect of a lighting stimulus.

In the past two decades, much has been learned about the sensitivity of the nonvisual photoreceptor system. Most notably, intrinsically photosensitive retinal ganglion cells (ipRGCs) were identified, as was the spectral sensitivity of melanopsin, the photopigment they contain. The ipRGCs have peak sensitivity to blue light—which is thus important for light and health—but the total response of the nonvisual photoreceptive system is a composite of input from the ipRGCs, rod photoreceptors, and cone photoreceptors. This composite response can change based on the spectrum, intensity, and temporal pattern of the light, as well as the light-exposure history and circadian adaptation state of the individual, which is one reason why characterizing nonvisual photoreception with a single spectral weighting function has remained elusive.

LEDs and Nonvisual Photoreception

LEDs are often associated with light and health—either positively or negatively—for several reasons. LEDs came to prominence just as knowledge of nonvisual photoreception was emerging, and the rates of adoption suggest that LEDs will soon be in widespread use in architectural applications. This combination has provided an opportunity to develop and evaluate best practices for nonvisual stimulation. Additionally, LEDs offer superior flexibility in terms of spectrum, intensity, directionality, and controllability, compared to most conventional light sources, and all of these characteristics are important factors in designing a system for nonvisual impact—particularly the ability to tune LED spectrum.

Sometimes the unique relative spectral power distribution of LEDs causes worry, simply because it looks different from other, more familiar, light sources. Although most LED light sources have a blue "pump" that may result in more energy per unit illuminance at a specific wavelength, photoreceptors do not process individual wavelengths. Rather, photoreceptors integrate information over a range of wavelengths—the very principle that the triphosphor fluorescent lamp, for example, was designed to exploit. Thus, an important consideration is that LEDs emit no more short-wavelength (blue) energy than other sources *at the same correlated color temperature* (CCT).[2] That is, even though most LEDs have a peak in their

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[1] *Lucas et al. 2014. Measuring and Using Light in the Melanopsin Age. Trends in Neurosciences 37(1). 1–9.*

[2] *This can be mathematically evaluated, and occurs because CCT calculations*

emission around 450 nm, in order to have the same CCT they emit less energy than other comparable-CCT light sources in the regions above and below 450 nm. LEDs are not inherently more hazardous (or beneficial) to human health than any other light source.

Although a 2700 K LED lamp emits about the same amount of blue energy as an incandescent lamp, it is also important to recognize that LED lamps can be engineered to emit light at any desired CCT. Further, while most commercially available LED products have similar spectral output, it would be possible to engineer the relative spectral power distribution to provide maximum benefit if there was a way to effectively and accurately determine the spectrum needed for any given physiological or behavioral benefit. Further, color-tunable products are relatively easily achieved using LED technology, which can offer greater flexibility for changing nonvisual efficacy based on the time of day. At this point, the challenge is identifying exactly what spectral content is the most beneficial—something which is quite possibly application, time-of-day, and user dependent.

Implementing Light and Health Solutions

In many ways, this new age of light and health is a direct reaction to the previous century's transition to illuminated interiors. Now that so much time is spent indoors, there is a need to control the luminous environment to promote health (and avoid harm). However, many architectural spaces serve multiple purposes and have many different users. What may be beneficial for an occupant during the day may be harmful for an occupant at night, and may vary significantly between individuals in a given space. Even more complicated is the need to balance the desire for alertness with preservation of normal circadian rhythms among night-shift medical staff, for example. Therefore, even if a prescription for effective nonvisual stimulation is developed, implementing the solution may not be straightforward, especially if there are users with different histories and needs occupying the space at the same time.

As the authors of *Measuring and Using Light in the Melanopsin Age* state, "Simple prescriptions are as likely to do harm as good, and even experts may have divergent ideas about best practice under some situations." That said, lighting practitioners may choose to follow some basic guidance provided by the authors: if minimizing nonvisual response is a goal, the amount of light reaching the eye—especially short-wavelength (blue) radiation—should be limited; if activating nonvisual responses is a goal, increasing short-wavelength radiation and total illuminance levels at the eye should be the focus. Understanding when to apply each scenario should be the role and responsibility of the specifier. There are many details to be considered, but few definitive answers to important questions about the effect of light level, spectrum, or otherwise customized solutions on different users or user groups.

Future Development

In the early days of understanding the human visual system, there were dueling theories of color vision: trichromacy and opponent channels. It was not until decades later that scientists were able to decipher that the two theories were complementary, rather than mutually exclusive. It is difficult to say exactly where things are in the maturation of understanding nonvisual photoreception, but it is likely that numerous theories that exist today will continue to be refined, and may even converge. An important question to ask is whether sticking with the status quo is more acceptable than altering design practice based on early research findings, especially when either approach may be determined in the future to be detrimental to health and wellbeing.

While the science may still be building, the lighting industry is already seeing LED products marketed for their health benefits. This is not unique to the technology though, as "full-spectrum" incandescent and fluorescent lamps have been marketed for decades, but there is unprecedented momentum to address light and health thanks to the customizability of LEDs. Specifiers and consumers must understand that no lighting product is a panacea; in fact, any benefit derived is dependent on the proper use of the product. Further, it is possible that no benefit is achieved, or worse, that harm is done. Like many health questions, there is no easy answer. One thing is for certain, however: the lighting industry cannot ignore nonvisual needs indefinitely.

Conclusion

Lighting systems are conventionally designed to meet the task performance needs of users, with comfort, aesthetics, and energy consumption also being important considerations. Thanks to recent scientific advancement, it is clear that nonvisual needs should also be considered, but there remains much to be discovered before widespread implementation of nonvisually-effective solutions is possible. While today's LEDs are generally no more beneficial or dangerous to human health than other, similar light sources, they have the potential to be carefully tuned to meet the diversifying demands placed on lighting systems.

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rely on the CIE 1931 Color Matching Functions, one of which covers the blue region of visible light—mainly between 420 nm and 500 nm. This concept is also very important in understanding Blue Light Hazard (i.e., light-induced retinal damage), which is explored in a DOE SSL fact sheet, Optical Safety of LEDs, available at http://www.ssl.energy.gov/factsheets.html.

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PNNL-SA 102586 • May 2014

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Flicker

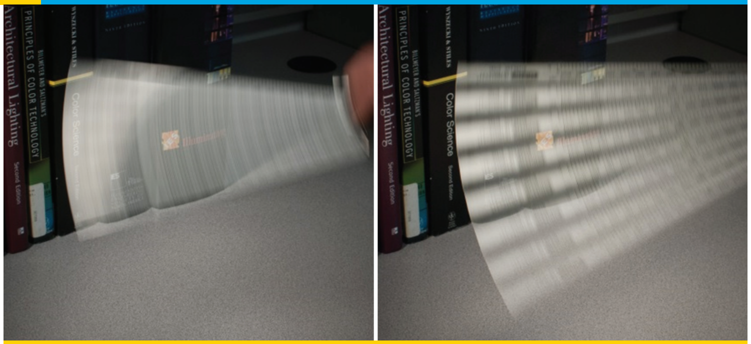
The advancement of commercially available LED products is reopening discussions on how the performance of light sources should be evaluated. This includes questions about the necessity of characterizing light sources for flicker, the (potentially visible) temporal variation of emitted light. While conventional light sources operating on alternating current (AC) modulate light output, the variety and severity of modulation seen with LED products—from good to poor—has sparked new interest in quantifying and understanding its impact.

Introduction

All conventional light sources—including incandescent, high intensity discharge (HID), and fluorescent—modulate luminous flux and intensity, whether perceptible or not. Many terms are used when referring to this time-variation, including flicker, flutter, and shimmer. The flicker produced by electric light sources can be a function of how it converts AC electricity to light, or the result of noise or transient events on AC distribution lines. Electrical flicker should not be confused with photometric flicker, which is modulation that is characteristic of the light source itself, rather than disturbances to its electrical input. Light source characteristics that can affect photometric flicker vary by technology; examples include filament thickness for incandescent, phosphor persistence for fluorescent and coated metal halide, and circuit designs for electronically ballasted or driven sources.

LED flicker characteristics are primarily a function of the LED driver. Different circuit architectures present different sets of performance trade-offs for a driver designer, with cost and form factor restrictions further limiting the choices available. For example, a low cost requirement for a small integral lamp may force a fundamental trade-off between flicker and power factor. Dimming an LED source can increase or induce flicker, most notably when phase-cut controls are used and/or pulse-width modulation (PWM) is employed within the driver to reduce the average light output from the LED source.

Why Flicker Matters



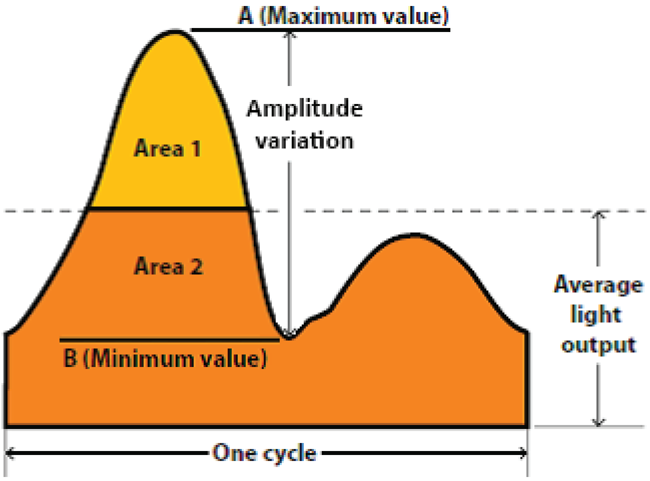
The stroboscopic effect is just one of many potential consequences of flicker. The lamp used for the image on the left does not flicker and thus the moving object is a smooth blur. Because it does flicker, the lamp used for the image on the right appears to create multiple instances of a moving object.

Photometric flicker from magnetically-ballasted fluorescent, metal halide, and high-pressure sodium lamps has been a concern of the lighting community because of its potential human impacts, which range from distraction or mild annoyance to neurological problems. The effects of flicker are dependent on the light modulation characteristics of the given source, the ambient light conditions, the sensitivity of the individuals using the space, and the tasks performed. Low-frequency flicker can induce seizures in people with photosensitive epilepsy, and the flicker in magnetically-ballasted fluorescent lamps used for office lighting has been linked to headaches, fatigue, blurred vision, eyestrain, and reduced visual task performance for certain populations. Flicker can also produce hazardous phantom array effects—which may lead to distraction when driving at night, for example—or stroboscopic effects, which may result in the apparent slowing or stopping of moving machinery in an industrial setting.

When discussing the potential human impacts of flicker, it is important to understand the difference between sensation and perception. Sensation is the physiological detection of external conditions that can lead to a nervous system response, while perception is the process by which the brain interprets sensory information. Some sensory information is not perceived, and some perceptions do not accurately reflect the external conditions. As a result, some people who suffer from flicker sensitivity may not be aware that flicker is the reason they are suffering, or even that the light source responsible for their suffering is flickering. Furthermore, not all human observers are equally sensitive to the potential effects of flicker. Populations that tend to be more susceptible to the effects of flicker include children, people with autism, and migraineurs. While the sizes of some specific at-risk populations have been characterized—approximately 1 in 4,000 humans suffer from photosensitive epilepsy, for example—most have not.

Quantifying Flicker

The photometric flicker found in electric light sources is typically periodic, with its waveforms characterized by variations in amplitude, average level, periodic frequency (cycles per unit time), shape, and, in some cases, duty cycle. Percent Flicker and Flicker Index are metrics historically used to quantify flicker. Percent Flicker is better known and easier to calculate, but Flicker Index has the advantage of being able to account for differences



$$\text{Percent Flicker} = 100\% \times \frac{A - B}{A + B} \qquad \text{Flicker Index} = \frac{\text{Area 1}}{\text{Area 1} + \text{Area 2}}$$

Figure 1. Periodic waveform characteristics used in the calculation of flicker metrics. *Modified from IES Lighting Handbook, 10th Edition.*

in waveform shape (or duty cycle, for square waveforms). Both metrics account for amplitude variation and average level, but since both are based on the analysis of a single waveform period, neither is able to account for differences in periodic frequency. An example of a periodic waveform is shown in Figure 1, along with equations for both flicker metrics.

Measuring and reporting flicker is not a standard practice for commercial light sources. Although industry bodies have developed flicker metrics, they have not produced complementary standardized measurement procedures to ensure appropriate comparisons of reported values. Conventional lighting technologies exhibit little variation in flicker for a given source type; for example, all incandescent A19 lamps behave similarly. However, the type of ballast has a substantial affect, although just knowing whether it is magnetic or electronic has usually been sufficient for flicker characterization. As a result, there has historically been little need for measuring and reporting the flicker performance of a specific product.

Flicker in Commercially Available Light Sources

Evaluating the performance of any new technology should start with an understanding of how the incumbents perform. Figure 2 illustrates the luminous flux variation over time and flicker metrics (Percent Flicker and Flicker Index) of six conventional lamps, including incandescent, electronically ballasted metal halide, and both magnetically and electronically ballasted fluorescent products, as measured by the DOE CALiPER program. For conventional sources (including magnetically ballasted fluorescent), the maximum Percent Flicker is on the order of 40% and the maximum Flicker Index is roughly 0.15.

LED products, by contrast, exhibit a wide variation in characteristics, as shown in Figure 3. These examples were chosen to demonstrate—to some degree—the extent of variation seen in commercially available products, and do not represent a statistical sample of all products on the market or even all products measured by DOE. Note that LED sources exhibit variation across all the flicker waveform attributes, exceeding the ranges exhibited by conventional lighting. Some LED sources produce little to no discernible flicker, while others exhibit large variation in amplitude (as evidenced by waveforms with a Percent Flicker value of 100%) and shape. Perhaps most significantly, some of the periodic frequencies measured by CALiPER are not seen in typical conventional sources, and flicker characteristics do not appear to correlate well with any LED source characteristics (e.g., product type, driver type, or input power). Flicker frequency is not captured by the existing flicker metrics, even though flicker may be less noticeable when the modulation is at a higher frequency.

Recommendations

Flicker can be a significant detriment to lighting quality, but it is rarely considered in the design or specification process. The flicker characteristics seen in some products pose a concern for anyone responsible for human health, well-being, or performance in spaces with electric lighting. Standardized flicker measurement procedures are not yet in place, and existing flicker metrics have inadequacies that may be exposed by LED products. Further, there are no well-defined thresholds that would enable those metrics to be used to identify problematic flicker for specific applications or populations. Nevertheless, flicker metrics can be a first step to compare two sources—lower values are better. If flicker waveforms are available, the specifier can identify better products by looking for less amplitude modulation, a higher average level (relative to the maximum and minimum values), and a higher periodic frequency.

In the absence of flicker metrics and waveforms, specifiers can pursue qualitative means for evaluating flicker. Specifiers should consider how the risk of flicker-related problems is heightened or reduced by a given light source, the type of space, its occupants, and the tasks being performed. LED systems should always be visually evaluated, ideally with flicker-sensitive clients. Waving a finger or pencil rapidly under the LED source, or spinning a flicker wheel, can expose the presence of flicker through the stroboscopic effect, even for those who are not naturally sensitive. Low flicker sources should always be used for both ambient lighting and task lighting in offices, classrooms, laboratories, corridors, and industrial spaces. Minimizing flicker is especially important where susceptible populations spend considerable time, such as hospitals, clinics, medical offices, classrooms, and daycare centers. In contrast, flicker may be less of a concern for parking lots, roadways, or other exterior lighting where light levels are lower and people spend less time. Indoors, sources with more flicker may be acceptable when used for accent lighting of objects, or when mixed with low-flicker lighting systems or daylight. A number of task dependent factors can be considered when evaluating flicker risks, including the duration of direct exposure (longer is worse), the retinal area being stimulated (greater is worse), the contrast with surround luminance (more

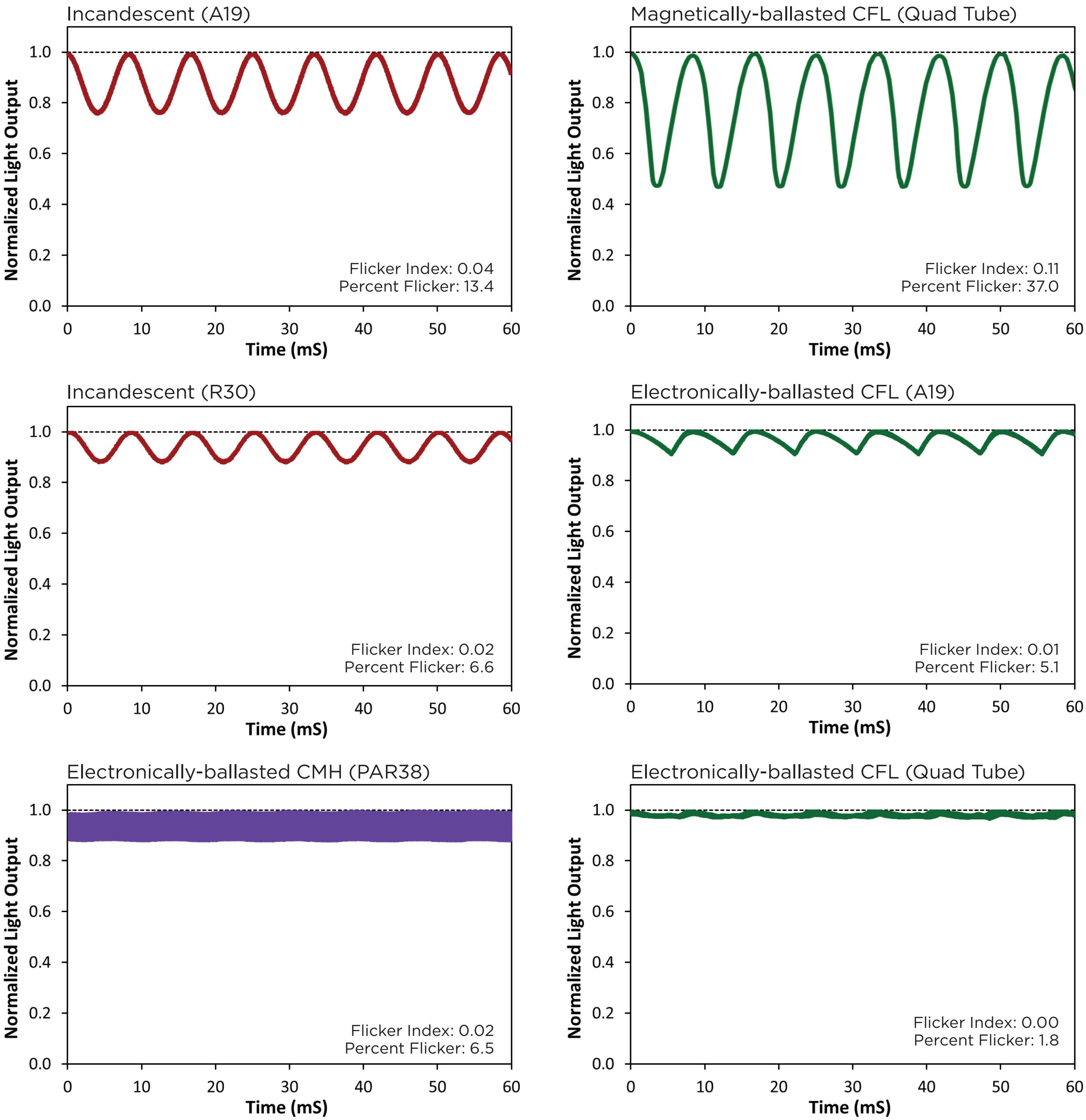


Figure 2. Examples of modulating light output for conventional lamps. The modulation of incandescent sources does not typically lead to perceptible flicker, but magnetically-ballasted fluorescent lamps are known to cause issues for some people.

is worse), the amount of color contrast (more is worse), and the amount of eye or object motion (more is worse).

Flicker is garnering increasing attention from manufacturers, as well as the standards and specification community. Some manufacturers appear to be giving flicker increased design priority, as evidenced by the improved performance of new product generations. The IES and CIE are considering the development of measurement standards, an IEEE group is working on recommended practices for evaluating flicker risks, and the EPA ENERGY STAR® and California Title 20 programs are considering the adoption of flicker criteria. Collectively, these efforts may make it easier for designers and specifiers to minimize the risk of flicker-induced problems for their clients in the near future.

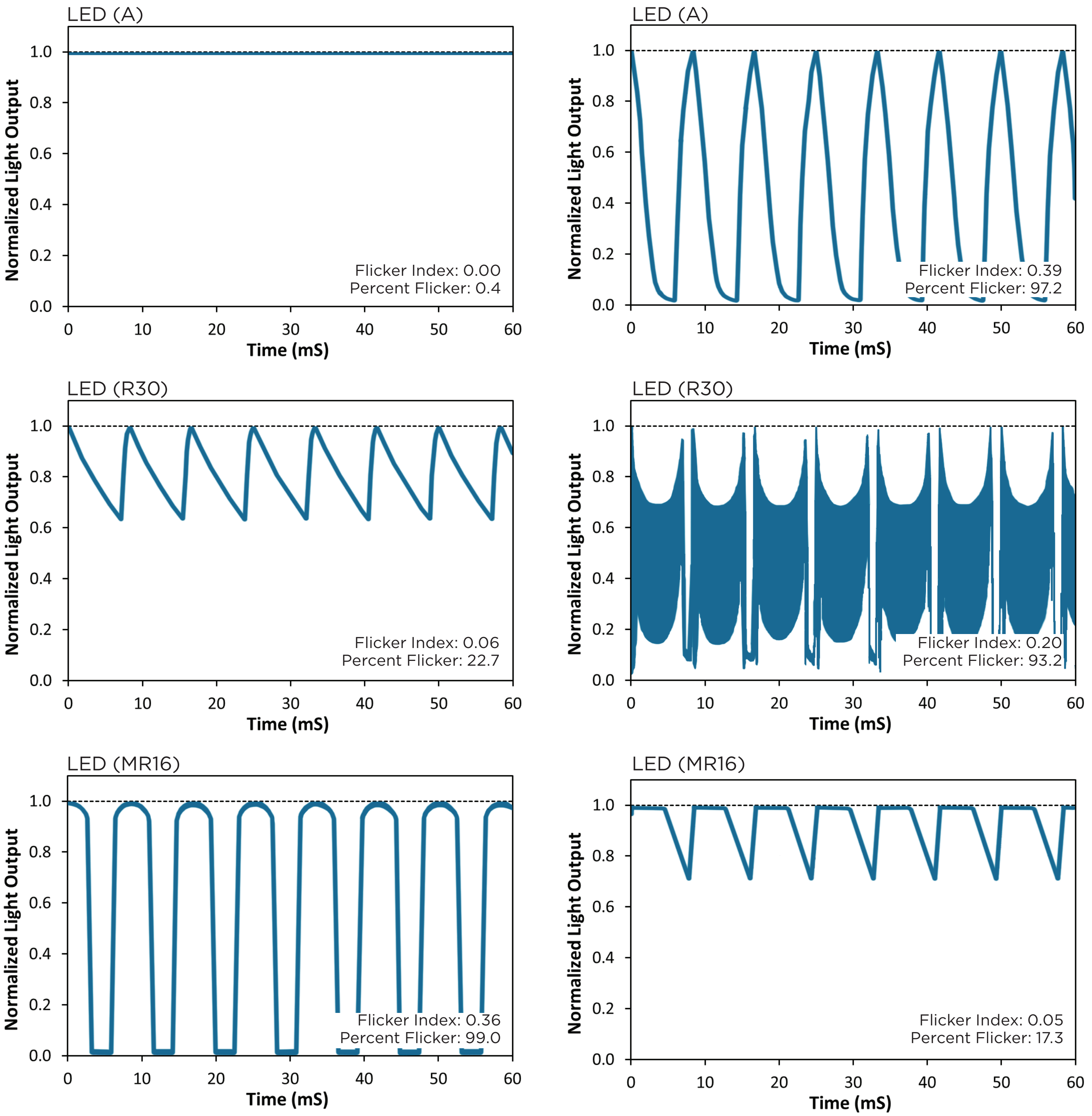


Figure 3. Flicker measurements from LED sources. Examples were chosen to demonstrate some of the observed variation.

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PNNL-SA-94791 • March 2013

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