Enercare

GUIDE TO LED LIGHTING

2022

In this Enercare PDF guide, the U.S. Department of Energy details the energy efficiency of today's LED lighting technologies, including efficacy, photometry, thermal effects, and much more. In addition, uncover tips on application efficacy, initial and maintained efficacy, and the difference between efficacy and energy use.

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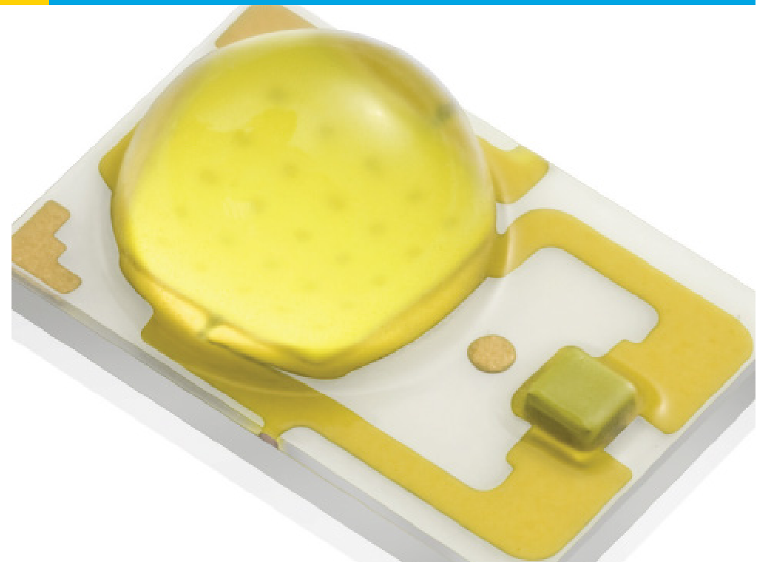
Energy Efficiency of LEDs

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.

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

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

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.

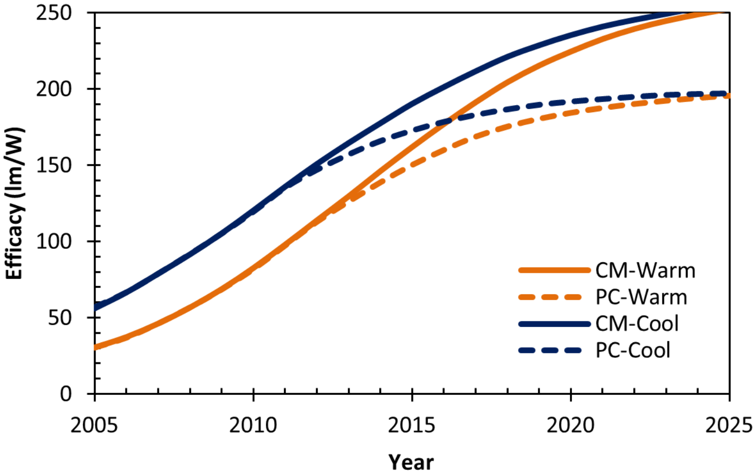


Figure 2. Actual and projected increases in the efficacy of color-mixed (CM) and phosphor-coated (PC) LED packages. CM-LED packages are predicted to have a higher maximum efficacy in the future, and the difference between warm white (CCT 2580 K to 3710 K, CRI 80–90) and cool white (CCT 4746 K to 7040 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

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,

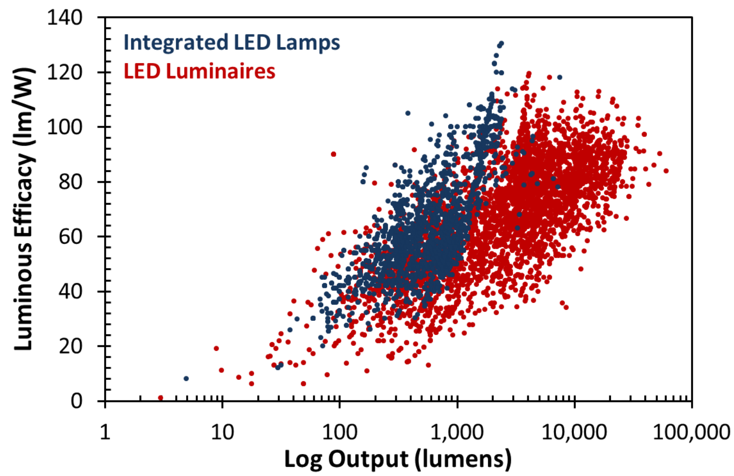


Figure 3. Efficacy versus output for integrated LED lamps and LED luminaires listed by LED Lighting Facts as of February 2013. The range in efficacy is similar for both types of product, but the potential for larger form factors in dedicated LED luminaires allows for more lumen output.

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.

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.

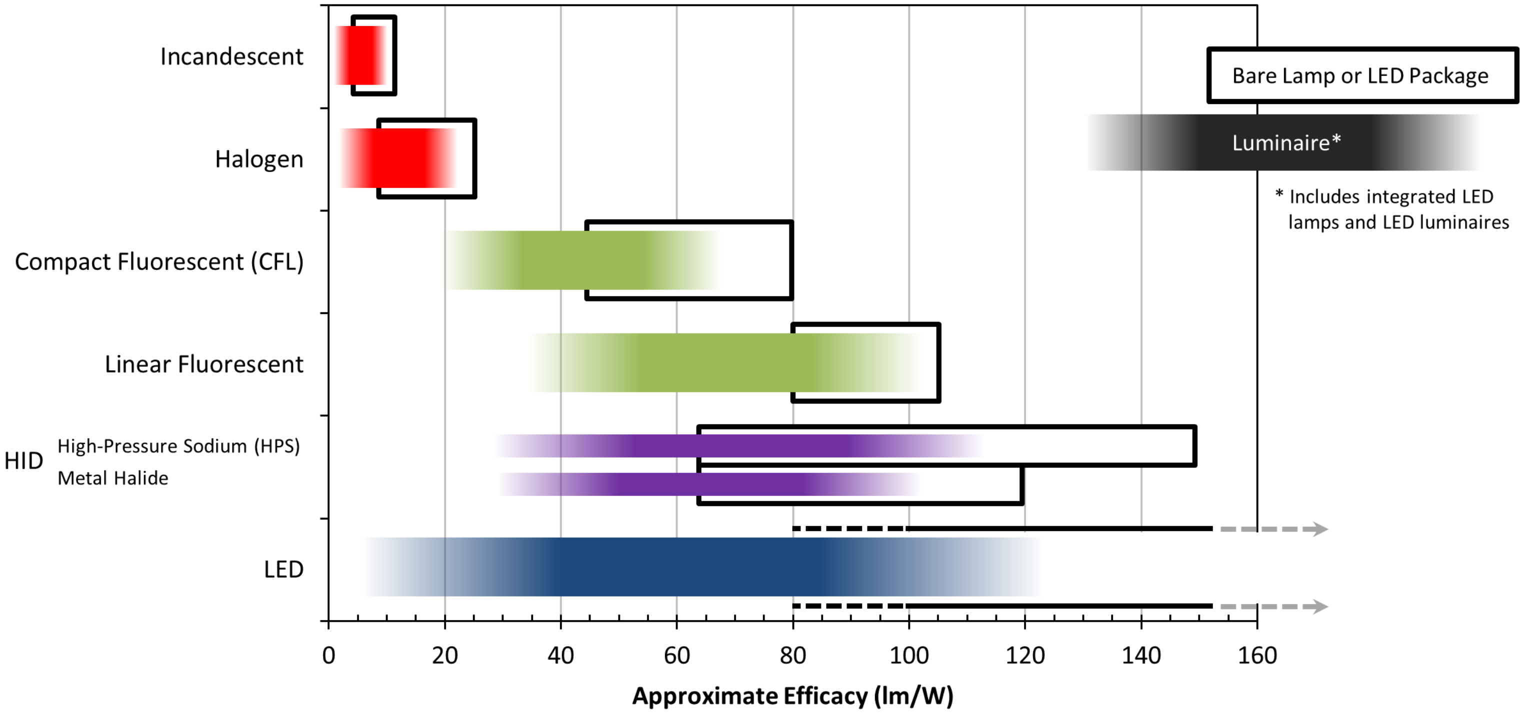


Figure 4. Approximate range of efficacy for various common light sources, as of January 2013. The black boxes show the efficacy of bare conventional lamps or LED packages, which can vary based on construction, materials, wattage, or other factors. The shaded regions show luminaire efficacy, which considers 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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