Magical Mystery Devices or Not: How do LED Lamps and Luminaires Really Measure-Up?

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ABSTRACT

Solid-state lighting products for general lighting applications are now gaining a market presence, and more and more people are asking, "Which of these are 'good' products? Do they perform as claimed? How do they compare? Light Emitting Diodes (LEDs) differ from other light sources enough to require new procedures for measuring their performance and comparing to other lighting options, so both manufacturers and buyers are facing a learning curve. The energy-efficiency community has traditionally compared light sources based on system efficacy: rated lamp lumens divided by power into the system. This doesn't work for LEDs because there are no standard LED "lamp" packages and no lamp ratings, and because LED performance depends heavily on thermal, electrical, and optical design of complete lighting unit or 'luminaire'. Luminaire efficacy is the preferred metric for LEDs because it measures the net light output from the luminaire divided by power into the system.

There is a great deal of conflicting and erroneous information being propagated today about the actual performance of LED luminaires. This paper will provide readers with:

- An understanding of luminaire efficacy and why it is useful and necessary.
- Results from CALiPER testing of SSL luminaires and replacement lamps.
- How this applies under the ENERGY STAR® criteria for solid-state lighting.

Introduction

Depending upon whom you ask about the readiness of LEDs for general lighting applications you will get a range of answers, from "it's here today" to "it's still five years away." Both statements are true: some LED products available today perform well in terms of light output, energy efficiency, and quality; many perform very poorly compared to other lighting technologies. LEDs differ from other light sources enough to require new procedures for measuring their performance and comparing to other lighting options.

Unfortunately, there is a great deal of conflicting and erroneous information being propagated today about the actual performance of LED luminaires. In late 2006, the U.S. DOE Commercially Available LED Product Evaluation and Reporting (CALiPER) Program began testing LED luminaires available in the market to provide unbiased product performance information for high-performance SSL products. Quarterly summary reports from the CALiPER program are available on-line, along with extensive educational resources developed in the context of the DOE's SSL Commercialization Support programs.[1]

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[1] On-line resources for relevant industry and DOE efforts include:

- The Next Generation Lighting Industry Alliance (NGLIA): http://www.nglia.org/

The concepts surrounding SSL product evaluation, such as absolute vs. relative photometry and luminaire efficacy vs. lamp/ballast efficacy, are described in more detail below, along with a discussion of what this means for the lighting industry in general. Using these new measurement concepts, how can we compare SSL products to more traditional lighting products? What do real, direct comparisons between SSL products and others reveal? How will the recent ENERGY STAR® criteria for Solid-State Lighting help us?

Relative versus Absolute Photometry

In a very general sense, photometry is the measurement of light. A multitude of characteristics of light can be measured, using a wide array of instruments and methods. In a practical, market sense, photometric measurements can serve to evaluate luminaires and lamps, to compare potential products, to make design choices—that is, basically to obtain a reasonable sense of a product's expected performance.

With a plethora of lighting applications, fixtures and replacement lamps available, common practices and standards have developed over the past few decades for useful photometric measurement techniques. Traditionally, photometric measurement techniques have developed around the general concept of lighting 'systems' that are based on a luminaire (light fixture) into which a lamp (light source, or 'bulb') is mounted. Different lamps can be installed in a fixture as long as they have the appropriate socket—like an Edison socket—and the appropriate size to fit in a fixture, and do not exceed fixture wattage limitations. Similarly, a given, traditional lamp can be installed in a variety of fixtures, but will shed varying amounts and patterns of light depending on the nature of the fixture, such as, whether it shades the light, has a more or less opaque sheath, etc..

From this context, practices of measurement based on **relative photometry** emerged: lamps are measured and rated independently, while fixture efficiencies—the percentage of light generated by the lamp that leaves the luminaire—and distributions are evaluated using reference lamps. **Relative photometry** is the measurement of the photometric qualities of multiple objects relative to each other or relative to a known source. **Absolute photometry** is the measurement of the photometric qualities of an object with respect to a standard photometric system.

With the advent of light sources such as fluorescent and compact fluorescent lamps that may have ballasts that are separate from the lamp, relative photometry practices evolved to include the concept of lighting *systems* that encompassed the luminaire, the ballast, and the lamp. Using this paradigm, the energy-efficiency community has traditionally compared light sources based on system efficacy: rated lamp lumens divided by power into the system. Luminaire output has been treated separately, based on fixture efficiency information for given rated reference lamps.

This entire paradigm, using relative photometry to evaluate luminaires and lamps, breaks down when it comes to Solid-State Lighting. For LEDs, there are no standard LED "lamp" packages and no standardized lamp ratings. Also, LED performance depends heavily on the

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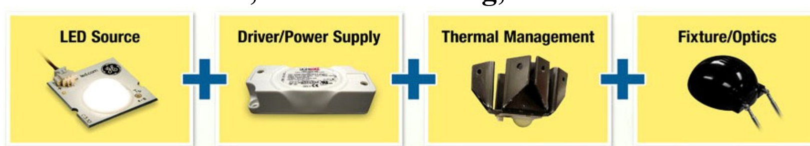
- Fact sheet on LED standards (with links to standards efforts) and other relevant fact sheets: http://www.netl.doe.gov/ssl/publications/publications-factsheets.htm
- Lighting for Tomorrow Competition: http://www.lightingfortomorrow.com/
- ENERGY STAR® for Solid State Lighting Luminaires: http://www.netl.doe.gov/ssl/energy_star.html
- CALiPER quarterly summary reports and detailed test reports: http://www.netl.doe.gov/ssl/comm_testing.htm.

thermal, electrical, and optical design of the complete lighting unit or '*luminaire*'. So, each SSL product must be tested as a whole: using absolute photometry to evaluate luminaire performance characteristics such as total luminaire output and luminaire efficacy.

How is SSL Product Performance Measured?

Luminaire Efficacy is a measure of the net light output from the luminaire as a whole divided by power into the system at the wall socket. For SSL luminaires this measurement takes into account the LED, its thermal management system, the efficiency of its driver and any losses inherent in the final luminaire design, as illustrated in Figure 1. Luminaire efficacy combines both the light system efficacy and luminaire efficiency, allowing for a true comparison of a luminaire regardless of the light source.

Figure 1. Luminaire Efficacy is Effected by the LED, the Driver, the Heat-Sinking, and the Fixture



The LM-79 standard, "IESNA Approved Method for the Electrical and Photometric Measurements of Solid-State Lighting Products" (IESNA 2008), describes the procedures to be followed by SSL luminaire manufacturers and independent testing labs for the measurement of SSL products. It covers SSL luminaires, that is, fixtures incorporating SSL light sources, as well as integrated replacement lamps that use LED devices. LM-79 testing methods must be used to qualify SSL products for ENERGY STAR rating.

LM-79 testing can be used to obtain luminaire photometry such as luminaire output, luminaire efficacy, intensity distributions and color qualities. The key difference between this testing method for SSL and testing methods specified for other light sources is that LM-79 explicitly calls for absolute testing rather than relative testing and it specifically addresses fixtures and integrated replacement lamps as opposed to separate LED chips or modules.

Compared to more traditional testing methods based on relative photometry, testing luminaires using absolute photometry can be more expensive, but it is currently the only standardized, reliable testing method for SSL products. It is possible that in the long run the industry may be able to shift to relative testing for SSL products, but that would require wide spread componentization and standardization.

How Do We Compare SSL Luminaire Efficacy to Non-SSL Products?

In order to compare apples to apples, comparisons between SSL products and conventional luminaires using other light sources need to look at overall luminaire performance, rather than lamp ratings or fixture efficiencies. Overall luminaire performance of non-SSL products can be measured through similar absolute photometry at the fixture level, or estimated based on more traditional data such as lamp ratings, fixture efficiencies, etc.. Standardized measurement methods similar to those used for SSL allow for absolute testing of luminaires using incandescent, fluorescent, or any other light source (IESNA 1998, 2004, 2007). Values for luminaire efficacy, luminaire output, and intensity distributions obtained from absolute testing provide the most accurate points of comparison, but they are specific to the lamp, ballast, and luminaire combination that was tested.

If absolute photometry for comparable luminaires is not available, the luminaire output and efficacy can be estimated using relative photometry provided by the fixture manufacturer and lamp ratings, as shown in Figure 2. Essentially, luminaire output can be estimated starting with the output of the lamp, and discounting that output for fixture losses; the luminaire efficacy can be estimated by dividing the estimated luminaire output by the estimated power input to the luminaire. When estimating luminaire performance in this way, a few caveats and rules of thumb apply. First, take care that the geometry and distribution of the lamp is similar to that of the lamp used to obtain the fixture efficiency. Fixture losses will be much higher for directional applications using omni-directional lamps, for example, the fixture efficiency of a downlight fixture will be considerably less with an A-lamp or spiral CFL than with a PAR30 or reflector CFL. Second, check that ballast factor or driver losses are applied correctly to obtain luminaire input power. Third, ensure that losses from fixture optics are included in fixture efficiency, or apply a separate loss factor for additional optics if need be. For example, if a Total Internal Reflection (TIR) optic is used to shape the beam pattern, it will impact the fixture efficiency. Also, apply an appropriate thermal loss factor as needed depending on the type of lamp source and luminaire environment. Finally, be wary of implicit implications of lamp rating values: whether you are using 'initial' lumens, 'mean' lumens, or 'typical' lumens can make a large difference.

Figure 2. Example of Rough Estimate of Luminaire Efficacy

Lamp source rated output: 900 lm

Lamp rated power: 15 W

Fixture efficiency: 40%

Driver or ballast efficiency: 85%

Luminaire Output = 900 lm * (40%) = 360 lm

Luminaire Efficacy = 360 lm / (15 W / 85%) = 20 lm/W

If relative photometry is not available, ball-park estimates can provide some points of reference, but should be used with caution. Based on luminaire benchmark tests conducted by the CALiPER program, or based on lighting expert knowledge, approximate or typical values for fixture efficiency can be identified and applied for most product categories depending on whether a directional or non-directional source is used.

Other Important Factors for Comparing SSL Products to Non-SSL Products

Luminaire efficacy is only one point among many to use when evaluating products. For example:

- Some light sources have very fast depreciation rates so initial lumens as tested with LM-79 may not be as important as mean lumens. Metal halide sources, for example, experience significant lumen depreciation over their rated life, so the initial lumens are not as useful as mean lumens. Mean lumens or "design mean lumens" are defined as lumens at 40% of rated life for fluorescent, and at 50% of rated life for HID sources.
- Some sources may work better with specific applications: Is the color appearance critical? Is a distinct spectrum required? Are focused or minimum illuminance levels needed for a specific application area? Are too many lumens getting lost in the fixture? Placing an omni-directional light source in a directional fixture may not make sense.

- Expected source life. How long does the life need to be? Is the cost for the manual labor to replace the source going to overshadow the cost of the original fixture? Are there external conditions that will affect source life like extreme heat or cold? SSL sources should last a very long time, but the fixture design and inappropriate conditions, especially high heat and humidity, can have a huge effect on that life. Fluorescent sources also can have problems with external conditions – particularly cold environments.
- Other characteristics to remember when evaluating light sources include: resistance to vibration; environmental requirements (cold or hot); and ease of replacement.

Results from CALiPER Testing of SSL Luminaires and Replacement Lamps

SSL is an emerging technology, unfamiliar to many users and requiring new testing methods and unfamiliar testing paradigms. The CALiPER program was established to provide objective, high quality performance information, to support DOE planning, to reduce long-term risks in the SSL market, and to support the lighting industry test procedures, standards development and product performance reporting practices. About 100 commercially available SSL products for the general illumination market have been selected and tested through the CALiPER program since its inception in 2006. A snapshot of CALiPER results provided below illustrates how to apply the concepts introduced in the preceding section.

First, an example of a series of three tests on recessed wall lights reveals how manufacturer information can be erroneous if the concepts of absolute photometry and luminaire testing are misunderstood. Second, a series of results for a variety of replacement lamps helps to illustrate how performance can be impacted by designs which do or do not take advantage of the inherent strengths of LED sources. Third, a discussion of results from task light testing warns of characteristics to keep in mind when evaluating SSL desk lamps and undercabinet lights. Finally, a brief summary of key take-away points from the first five rounds of testing is provided.

Recessed Wall Lights: Revealing Where Relative Photometry Breaks Down

Three recessed wall lights were tested for comparison, all from the same manufacturer and the same product line, simply using different source technologies—one LED version, one CFL, and one halogen. The manufacturer provided performance data in the marketing literature for these products, along with photometric information, including downloadable IES files. A prospective buyer could try to compare the performance of the three choices by looking at the output lumens, product wattage, and iso-illuminance plots published in the manufacturer's brochure, or by looking at the manufacturer's IES files to compare overall luminaire output and efficacy for each.

As shown in Table 1 below, calculating luminaire efficacy from the manufacturer's data provides an accurate picture of the overall output and efficacy for the halogen version, but it overstates the values for the CFL version and understates the values for the SSL version, suggesting only ½ the output and ½ the efficacy that were actually measured through CALiPER tests. Looking closely at the IES file for the LED version of this product, the manufacturer has presented this performance information as if the LED version has been tested using relative photometry—which is impossible because there is no current method for determining a 'lamp' rating for the LED source outside of the fixture. One can wonder what value was used by the manufacturer to determine the value they have published as output lumens, 195 lm, for the LED device, and how they determined its fixture efficiency of 43%.

Table 1. Manufacturer Photometric Reporting for 3 Different Sources

Source (Power)	Output "Lumens" from Manufacturer Brochure	Fixture Efficiency from Manufacturer IES Files (%)	Luminaire Efficacy Calculated from Manufacturer IES Files (lm/W)	*Luminaire Efficacy from CALiPER Absolute Testing (lm/W)*
Halogen (20W)	350	45 %	8	***8***
CFL (13W)	900	25 %	19	***16***
LED (12W)	**195**	**43 %**	5	***10***

Source: DOE (2008)

In this case, two hints would lead an informed reader to doubt the manufacturer values. First, the IES file shows inexplicable values for 'lamp lumen rating' and 'efficiency'. Correct IES files for SSL products will either show a lamp rating of '-1', or a lamp rating equal to the total luminous flux of the product, with a fixture efficiency of 100%. Second, the manufacturer brochure mentions 'output lumens', but does not explain whether this refers to the LED device manufacturer ratings or to the total luminous flux of the fixture. More correctly, SSL product literature should explicitly state what output values represent and how measurements were taken. This is a rare example where a manufacturer's lack of understanding SSL technology has resulted in understating the performance of the SSL luminaire, but similar flaws can mislead buyers into over estimating SSL luminaire fixture performance.

Replacement Lamps: Good and Bad Applications of SSL Technology

Numerous replacement lamps using LED sources have been CALiPER tested, from lamps that are purported to replace typical A19 lamps, to candelabra-style replacement lamps, to MR16s, PAR 30s, and other downlight retrofit units. Examining performance across this array of replacement lamps highlights some inherent strengths, weaknesses, and constraints of SSL designs. Table 2 below summarizes the performance observed thus far in CALiPER testing for these various types of replacement lamp, showing the ranges of output and efficacy that have been observed and how that may relate to 'comparable' incandescent or CFL lamps.

The following observations may help readers to better understand the nuances between 'good' and 'bad' designs for SSL in replacement lamps:

- LED devices are not inherently omni-directional (i.e., they do not emit light in every direction), so products tested thus far do not provide the light output levels or the broad distributions of typical A19 lamps. Products aiming to replace A-lamps currently provide insufficient output and insufficient color quality for these applications.
- LED devices need a significant amount of heat dissipation to maintain chip temperatures within manufacturer tolerances. Small lamp formats, such as candelabra and MR16 lamps must be contained in a limited volume, so heat dissipation, even with the best heat sink designs reaches practical limits. As LED source efficacies and allowable operating temperatures increase, higher levels of output will be possible, but for now, output levels are limited by the practical constraints of heat dissipation in these small formats. SSL products targeting these applications today are able to provide good efficacy, but

somewhat lower output than traditional products. So SSL candelabra and MR16 lamps may be appropriate choices for some applications, if luminaire or lighting system designs account for the lower light output of each lamp. Larger directional replacement lamps, such as R30 and PAR38 replacement lamps, take advantage of the directional nature of LEDs, but must still contend to a certain degree with the practical limits of heat dissipation in a constrained volume. These products can provide sufficient output to compete with products that are equivalent to 50-60W incandescent lamps, with efficacies that far exceed incandescent and halogen lamps and approximately equal CFL technology.

- Innovative SSL designs, such as retrofit units, which are based on larger volume formats (that is, which are not constrained to match the size or shape of existing replacement lamps), are able to incorporate greater thermal management to produce higher levels of output and can clearly compete with 15W RCFL downlight lamp technologies in color quality and luminaire efficacy.

Table 2. Examples of Comparative Performance of SSL Replacement Lamp Products

	Do SSL Products Produce Enough Light Output Today? (luminaire output in lm)	**What is the Targeted Application for the SSL Product?**	**Can SSL Products Save Energy Today? (luminaire efficacy in lm/W)**	
	Produces output equivalent to about a 3 or 4 W incandescent.	**A Lamps** --watch for color temperatures outside the white range	Luminaire efficacy beats incandescent A-lamps, not CFLs.	
	Produces output equivalent to about a 3 or 4 W incandescent.	**Candelabra Lamps** --one product tested --may serve as low-wattage option	Luminaire efficacy beats incandescent lamps, not CFLs.	
some close, most not	Less than 50% the output of 20W halogen products.	**MR16 Lamps** --competing with halogen, not CFL	Most have better efficacy than halogen MR16s.	most do
some do	Produces output equivalent to about a 45-65 W incandescent.	**PAR30 or PAR38 Lamps**	Surpassing halogen, similar to CFL in luminaire efficacy	
	On average, 50% less output than fluorescent T8 tubes.	**T8 Replacement Lamps** --option to consider for certain applications (e.g., cold temperature)	Close to fluorescent luminaire efficacy in situ.	
	Produces output equivalent to about a 60-75 W incandescent.	**Retrofit Units** --for recessed downlight applications	Surpassing halogen and CFL in luminaire efficacy in downlights.	

In all cases, when considering SSL replacement lamps, users should request data established using LM-79 testing and compare the overall replacement lamp output and efficacy to the overall flux and efficacy of products which they wish to replace. Other factors should also be considered when evaluating SSL replacement lamps, such as: light distribution, color quality, and ability to withstand intended environmental conditions. For example, increased operating temperatures in insulated ceiling cans reduces performance, while cold temperatures operation increases performance.

Task Lights: Revealing Nuances of Luminaire Testing

Task lights, including portable desk lamps and undercabinet fixtures used in offices and kitchens, provide the perfect example of applications that can be most appropriate for the current state of SSL technology because of the inherent directionality of LED devices, but which still often suffer from some design flaws. Table 3 below summarizes the key performance characteristics of SSL undercabinet fixtures and desk lamps. In these application categories, the CALiPER program has also conducted 'benchmark' testing of similar luminaires using traditional sources (fluorescent tubes, CFLs, and halogens). By examining luminaire output and luminaire efficacy even for products using traditional sources, the effect of fixture inefficiencies when used with these traditional sources is revealed more clearly (in fact, the total lumens output by these benchmark fixtures is 60-70% less on average than the rated lumens of their lamps).

These examples serve as a reminder that luminaire performance can provide a much more accurate point of comparison between products than lamp ratings when comparing across different light sources. Going one step further, using intensity distribution values from goniophotometric testing of these luminaires, the portion of light reaching the task area can also be assessed—further highlighting the effectiveness of well designed directional task lamps. In addition to overall light output and efficacy performance, the color quality of SSL task lights should be checked for appropriateness for given applications. Most of the SSL task lights tested thus far have colder color temperatures than in traditional products.

Table 3. Comparative Performance of SSL Task Light Products

Do SSL Products Produce Enough Light Output Today? (luminaire output in lm)		What is the Targeted Application for the SSL Product?	Can SSL Products Save Energy Today? (luminaire efficacy in lm/W)	
some do, some don't	On average, 30% less output than fluorescent tubes per linear foot.	**Undercabinet Fixtures**	On average, SSL undercabinet luminaire efficacy beats fluorescent.	most do
some do, many don't	On average, 50% less output than CFL or halogen products.	**Desk Lamps** --watch for off-state power use --watch for cool color temps	Most beat halogen, but only one beats CFL in luminaire efficacy	one does, most don't

A key drawback in the design of the majority of SSL desk lamps that have been tested thus far is their off-state power consumption. Almost all of these lamps have been shown to draw power when they are turned off—up to 2.5 W. While this may seem small, the effective energy efficiency of these products plummets when this off-state power draw is factored in, so any product with an on/off switch should be checked for off-state power use.

Key Take-Away Points from CALiPER Test Results

The examples provided above give a snapshot of some of the CALiPER results, but readers are urged to become familiar with the latest summary reports. While more high performance SSL products are observed with each round of testing, a large portion of poorly performing products continue to be found in each round. SSL users and buyers are warned against making broad generalizations or assumptions about SSL product performance: great disparities in performance abound, so buyers must be wary and informed. Key take-aways from testing after 5 rounds include:

- Product literature provided by manufacturers often contains erroneous or misleading performance information. To accurately compare SSL products to others, luminaire output and luminaire efficacy (measured for SSL products using LM-79 testing) are necessary. Product literature should be examined carefully to find values that explicitly indicate total luminous flux of the luminaire or replacement lamp as a whole. Additional application-specific qualities should also be considered.
- For specific directional lighting applications such as downlights, outdoor area lighting, and task lights, the best performing SSL products provide light output levels and color quality that are at least comparable to traditional light sources for those applications, and luminaire efficacies that far exceed luminaire efficacies when incandescent and halogen sources are used, and matching or exceeding fluorescent and compact fluorescent luminaire efficacies.
- Under-performing SSL products (with insufficient light output for a given application, inappropriate color quality, and/or poor design leading to rapid lumen depreciation) can be found in each lighting application category.

Improvements in LED chip technologies are announced on a regular basis. Expertise in SSL luminaire integrated design is increasing across the industry—from drivers to thermal management to optics. And the industry is increasingly using standardized testing methods and appropriate practices for reporting product performance. With this significant progress, the ratio of high performing, high-quality SSL products is expected to increase considerably in 2008-2009. New, innovative design approaches are also expected to make SSL competitive across a broader range of applications. Nevertheless, lower performing SSL products with misleading manufacturer literature can be expected to remain on the market for some time, so buyers must stay vigilant and informed.

The First ENERGY STAR Criteria for Solid State Lighting

On September 12, 2007 the U.S. DOE released the first-ever ENERGY STAR criteria for solid-state lighting (DOE 2007) and established the effective date of September 30, 2008 as the point at which luminaires are eligible to carry the ENERGY STAR label. With establishment of ENERGY STAR criteria DOE has injected information into the market setting thresholds for performance and measurement. The recognition of the ENERGY STAR brand, the perception of SSL as a state-of-the art technology and prevailing concerns about energy use and climate change act together as a natural catalyst for manufacturers to develop and market new products. Manufacturers believe the ENERGY STAR label, along with its supporting marketing campaigns, utility incentives, and consumer awareness, translates into sales. With relatively few products in the market it's no wonder manufacturers ranging from start-up companies to big name traditional luminaire manufacturers see SSL as both a threat and an opportunity.

DOE's Strategy Behind the ENERGY STAR Criteria

Based on the preceding sections about the nuances of SSL technology, measurement challenges and questionable performance claims, how then does DOE reconcile all these issues to maintain the integrity of the ENERGY STAR label? In June 2006 DOE commissioned the study entitled *Compact Fluorescent Lighting in America: Lessons Learned on the Way to Market* (Sandahl et al. 2006) which investigated the market introduction, penetration and transformation of compact fluorescent lighting. A key take-a-way from this study with respect to the application of SSL is to ensure end-user satisfaction with the technology and to not exaggerate performance claims.

With this as a guiding principle DOE established a transitional, two-category approach to the ENERGY STAR criteria. Category "A" identifies near-term applications where SSL currently does or soon will make sense and Category "B" acts as a future target for manufacturers to strive towards. As the technology improves DOE will add additional near-term applications until Category B becomes available. Once there are significant numbers of Category B products, Category A will be dropped entirely and Category B will be the basis of the criteria. DOE has identified a number of Category A applications thus far: under-cabinet kitchen lighting; under-cabinet shelf mounted task lighting; portable desk/task lamps; recessed downlights; outdoor porch lighting; outdoor step lighting; and outdoor path lighting.

Luminaire Efficacy Criteria for ENERGY STAR

The ENERGY STAR SSL criteria uses luminaire efficacy as its key metric. How did DOE establish the thresholds for the Category A near-term applications? First, as explained above, luminaire efficacy for traditional lighting technologies are simply calculated by multiplying light source system efficacy by fixture efficiency. With this in mind, DOE established the initial luminaire efficacy thresholds roughly equivalent to the performance of luminaires which meet the existing ENERGY STAR CFL and Residential Light Fixture (RLF) criteria, recognizing CFLs as the current minimum "benchmark" for energy efficiency in the near-term applications. Table 4 summarizes the CFL system efficacy, typical fixture efficiency, and calculated luminaire efficacy for each of the initial niche applications. Determining typical fixture efficiencies proved to be challenging for the simple reason that photometry for residential luminaires is rarely performed, much less reported. Photometry is routine for the commercial lighting industry.

Table 4. Near-Term Application

Niche Application	CFL System Efficacy[2] (lm/W)	Typical Fixture Efficiency (%)	Calculated Luminaire Efficacy (lm/W)
Under-cabinet Kitchen	58.8	40%	24
Under-cabinet Shelf-mounted Task	58.8	50%	29
Portable Task	58.8	50%	29
Recessed Downlight (residential)	58.8	60%	35
Recessed Downlight (commercial)	58.8	60%	35
Outdoor Wall-mounted porch	58.8	40%	24
Outdoor Step	50	40%	20
Outdoor Pathway	50	50%	25

Minimum Light Output, Zonal Lumen Density, Color Quality, and Reliability

Luminaire efficacy, while critically important for the energy conservation community, does not in and of itself guarantee performance. If DOE remained silent on minimum light output it is entirely possible (and likely) for a luminaire to have very high efficacy and yet deliver very little light. Hence, DOE also prescribes minimum light output for the Category A applications. Minimum light output levels to achieve recommended illuminances based on a number of factors including benchmarking of existing traditional light source products in the market, currently available SSL products (CALiPER studies) and computer modeling/simulation to obtain necessary light levels to meet IES guidelines and recommendations.

One of the key challenges for SSL to make significant penetration into the traditional lighting fixture market is to deliver light levels and light qualities identical to or at least similar to existing products. SSL manufacturers group (or array) their LED devices together to increase light output often at the expense of higher operating temperatures, which can in turn lead to accelerated lumen depreciation. Underperforming and unreliable products increase the risk of alienating the end-user to the technology and slowing market penetration. To reduce this risk, the luminaire must be engineered with a systems approach with due consideration to all aspects of the design (thermal management, secondary optics, etc.) and attention to the final product performing as well as or better than its traditional counterpart. In addition to minimum light output, DOE believes the distribution of light for the intended application and the color quality of the light are also of critical importance to end-user satisfaction. ENERGY STAR criteria for SSL are framed to ensure that the SSL luminaires provide good efficacy, while also providing suitable lighting levels, quality, and reliability for their intended applications.

[2] The values for CFL system efficacy resulted from work conducted by the IESNA/ASHRAE 90.1 sub-committee working on lighting standards. 58.8 lm/W was determined to be the prototypical system efficacy for pin-based CFLs with matching ballasts. In applications typically using lower wattage CFLs system efficacy was lowered to 50 lm/W reflecting the reduced efficacy and ENERGY STAR minimum threshold.

Conclusion

CALiPER test results confirm the increasing viability of SSL products as energy-efficient choices for lighting needs. But, the wide range of performance and suitability of SSL luminaires calls for continued vigilance on the part of buyers and continued innovation and due diligence on the part of manufacturers. To adequately assess SSL products and compare them to incumbent technologies, it is essential to understand the concept of absolute photometry (as opposed to relative photometry) and draw comparisons at the level of overall luminaire performance (as opposed to lamp ratings). With input from the CALiPER program and ENERGY STAR, the lighting industry and stakeholder groups are continuing to improve and develop metrics and standards that are appropriate for SSL technology.

The ENERGY STAR criteria for solid-state lighting will take effect in September, 2008, providing an assurance regarding the relative efficiency of qualified SSL products and their ability to provide suitable levels and qualities of light for specific niche applications. As SSL products and the new ENERGY STAR category progress, the criteria will encompass additional lighting applications and higher general levels of performance.

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