Application Efficacy for Comparing Energy Demand in Lighting Applications

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Application efficacy for comparing energy demand in lighting applications

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ABSTRACT

The light-emitting diode (LED) is a rapidly evolving, energy-efficient light source technology that holds promise to address the increasing need for energy conservation. However, the common belief that a high-efficacy light source equates to lower energy demand in application is incorrect. Generally, when a new light source technology replaces an existing light source in an application and claims energy savings, the inherent assumption is that all of the requirements of the application are met. In the case of directional lighting applications, what matters ultimately is the amount of luminous flux illuminating the task area. Therefore, when quantifying the performance of a luminaire, ideally one must consider only the amount of flux reaching the task area and the total power demanded.

The objective of this paper is to introduce an alternative concept, *application efficacy*. This paper will demonstrate the concept's usefulness and proposed metrics for three different lighting applications—under-cabinet task lighting, refrigerated display case lighting, and outdoor parking lot lighting—and show how it better relates to energy demand. Details of laboratory experiments and software analysis along with data are presented for the three applications.

Keywords: application, efficacy, lighting, LED, under-cabinet, freezer, outdoor, parking lot

1. INTRODUCTION

Rapid advances in the last ten years have brought white light-emitting diodes (LEDs) to the forefront as a viable replacement for traditional incandescent, fluorescent and high-intensity discharge (HID) lamps in a number of general illumination applications, particularly directional, task, and outdoor lighting. LEDs are well suited to these applications because of their inherent directionality, potential energy savings, long life and low maintenance, and in the case of outdoor lighting, options in spectral power composition that can be more effective for mesopic vision than high-pressure sodium systems.

The growing use of LEDs in these applications, however, brings up questions of how to compare LED lighting to traditional light sources and whether it is appropriate to compare traditional and nontraditional light sources using traditional methods. Traditional methods include light source luminous efficacy (source lumens per input watt) and luminaire system efficacy (system lumens per input system watt). One criticism of LED lighting systems is that they often do not produce the same luminous flux or intensity distribution as traditional lighting systems, and therefore the resulting luminous efficacy and energy savings found in LED lighting systems could be considered misleading. However, a traditional lighting system, when evaluated using traditional methods, could also prove misleading when installed in its intended application. For example, a given lighting system evaluated for its luminaire system efficacy could show very good values compared with other systems; therefore, one may conclude this system would provide the most energy savings. Yet when installed in the application, the system may not provide much energy savings at all if a good portion of the light emitted is directed where it does not belong or if it does not provide the recommended uniformity for the application, resulting in the installation of a larger number of luminaires. In the case of an outdoor lighting application such as a parking lot, wasted light would include the light emitted up toward the sky or that directed onto a neighboring property. For a task lighting application such as under-cabinet lighting, this may include poor uniformity with alternating bright and dark spots on a kitchen counter, leading to poor illumination and visibility for some tasks.

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Rea and Bullough in 2001 introduced the concept of *application efficacy*, which they defined as the average luminous flux within a specific solid angle per unit of power.[1] Generally, application efficacy is concerned with how well a lighting system delivers light to where is needed, which is specific to the application and its task area. The basic application efficacy concept can be augmented, where appropriate, to include conformance of photometric requirements specific to a task, for example light levels and uniformity. The application efficacy concept is in direct contrast to the traditional metric of luminaire system efficacy, which is specific only to the luminaire and does not consider the application. The Alliance for Solid-State Illumination Systems and Technologies (ASSIST) has implemented the application efficacy concept in a number of its recommended metrics, as a means to provide appropriate comparisons among all lighting technologies serving a given application.[2–5]

This paper summarizes ASSIST's proposed application efficacy metrics for three different lighting applications—under-cabinet task lighting[2], refrigerated display case lighting[4], and outdoor parking lot lighting[5]—and shows how application efficacy better relates to energy demand. Details of laboratory experiments and software analysis along with data are presented here for the three applications. For full details of ASSIST's application test methods and procedures, please refer to the relevant *ASSIST recommends…* documents, available online for free download (www.lrc.rpi.edu/programs/solidstate/assist/recommends.asp).

2. UNDER-CABINET TASK LIGHTING

Under-cabinet task lighting is a common application for kitchens but may be found anywhere that a work surface is mounted underneath cabinets or other storage (e.g., offices and cubicles). Under-cabinet luminaires are typically linear luminaires or individual pucks and may use incandescent, fluorescent or LED lamps.

Luminaire efficacy and illuminance distribution are the most common measures used to evaluate under-cabinet lighting luminaires. Yet these metrics can cause two problems when trying to compare under-cabinet lighting luminaires. The first is that of luminaire efficacy and whether it really describes the energy savings to be found in the application. The second is that of illuminance distribution. The intensity distribution found in the luminaire's IES file is typically measured using far-field distribution techniques; however, the short distance between the luminaire mounting position, the work surface, and the backsplash or back wall of the application area requires near-field intensity distribution measurements. Therefore, far-field intensity distribution may not predict illuminance accurately, and reporting actual illuminance measurements using the application geometry would be more appropriate.

ASSIST's method[2] uses on site illuminance measurements in a test alcove with a geometry typical of residential under-cabinet applications (Figure 1). The test luminaire is mounted underneath the test alcove's "cabinet" and horizontal illuminance measurements are taken at the center of each 4-inch square in the test alcove's grid, on both the horizontal work surface and the vertical back wall. These measurements are used to calculate the luminaire's average horizontal illuminance and the useful luminous flux on both the horizontal and vertical surfaces. The luminaire's input power is recorded and the application efficacy is calculated as:

$$\text{Application Efficacy (AE)} = (\Phi_h + \Phi_v) \div P$$

Where Φ_h is the luminous flux on the horizontal plane, Φ_v is the luminous flux on the vertical plane, and P is the luminaire's input power.

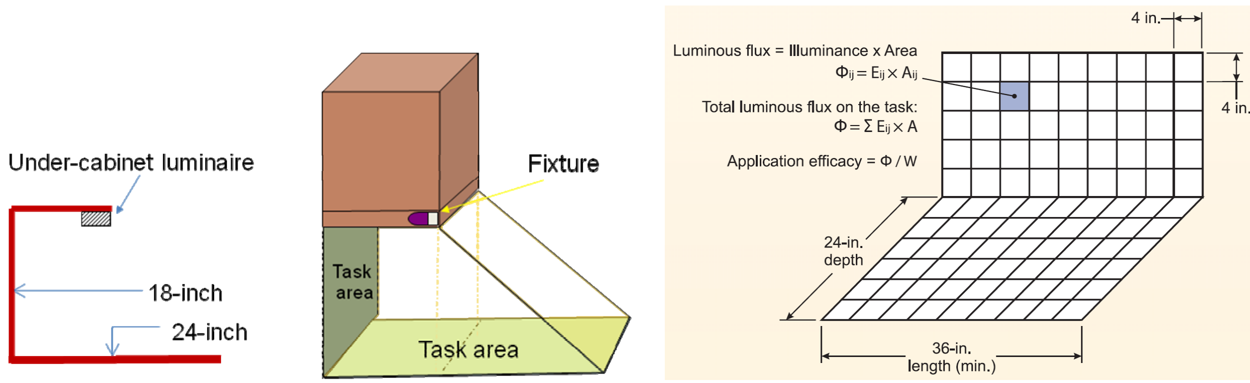


Figure 1. Under-cabinet lighting luminaire test setup and illuminance measurement grid. The width of the horizontal work surface is extended by 12-inches on either side of the luminaire under test.[2]

Several commercial under-cabinet lighting luminaires have been tested following ASSIST's method. Figure 2 shows an example of how luminaire efficacy can be a misleading metric. In the figure, Sample 2 has a 12% greater luminaire efficacy than Sample 4. However, Sample 4 is more effective at directing the light to where is needed, resulting in an application efficacy 32% greater than that of Sample 2. In this example, Sample 4 provides equally acceptable light levels and uniformity ratios as Sample 2 but requires 25% less input power.

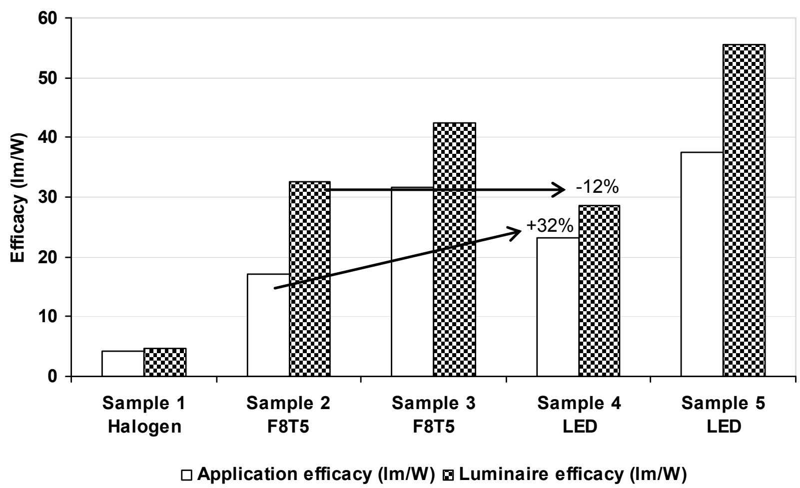


Figure 2. Comparison between luminaire efficacy and application efficacy values for sample halogen, fluorescent and LED under-cabinet luminaires.

3. REFRIGERATED DISPLAY CASE LIGHTING

Supermarkets use lighted display cases to store and display refrigerated and frozen foods. The luminaires in these cases are mounted vertically at the door mullions or horizontally on the top or bottom of the case. These luminaires produce localized lighting on the displayed merchandise (i.e., task or accent lighting). Traditionally, linear fluorescent lamps have lit the interiors of these cases, but LEDs have become much more common recently. One advantage LEDs have specific to this application is that they are not affected by cold temperatures. Fluorescent lamps operated in cold temperatures can suffer from diminished light output, lower efficacy, and reduced lamp life.[6] However, energy-efficiency organizations presently reward freezer lighting products for their luminaire efficacy measured at 25°C. To obtain realistic performance data for a luminaire, the test environment should mimic the actual environment where the luminaire would be used. In other words, the test environment for refrigerated and freezer display cases must consider the light output on the display and the performance under cold temperatures.

The ASSIST method[4] calls for near-field photometry illuminance measurements of the luminous flux reaching the task plane (i.e., the front face of the freezer case merchandise). In this method, a 60-inch by 60-inch display grid with 6-inch grid squares is built for near-field illumination measurements from a 6-inch distance (Figure 3). Measurements are first taken at room temperature (25°C). A scaling factor is then calculated using the relative light output measured at the proper cold temperature and is applied to the room-temperature measurements to estimate the cold application's luminous flux. The luminaire input power and the extra freezer power required to dissipate heat from the luminaire are used to calculate the luminaire's application efficacy:

$$\text{Application Efficacy (AE)} = \Phi_{Application} \div (P_{Luminaire} + P_{Freezer})$$

Where $\Phi_{Application}$ is the luminous flux on the measurement grid at the cold temperature, $P_{Luminaire}$ is the input power to the luminaire at the cold temperature, and $P_{Freezer}$ is the additional power required by the freezer to dissipate the heat introduced to the display case by the luminaire.

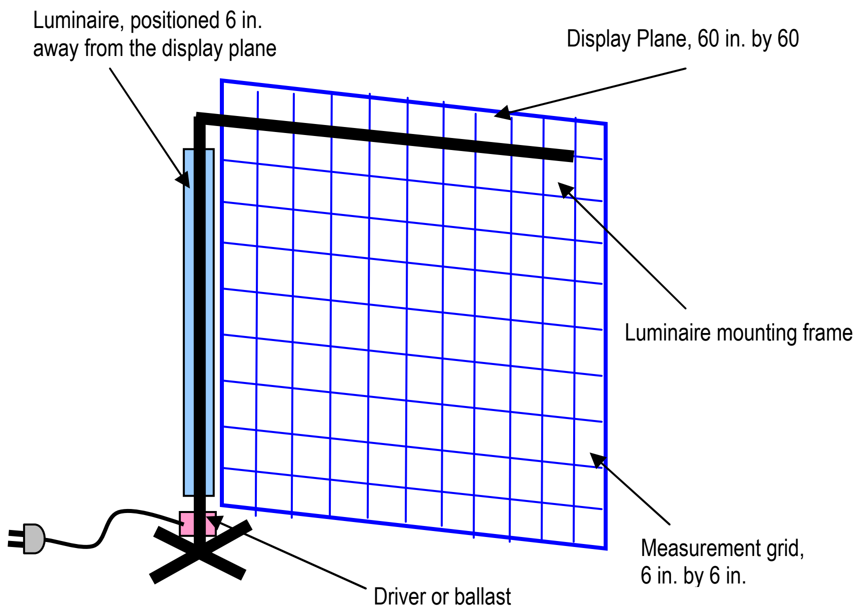
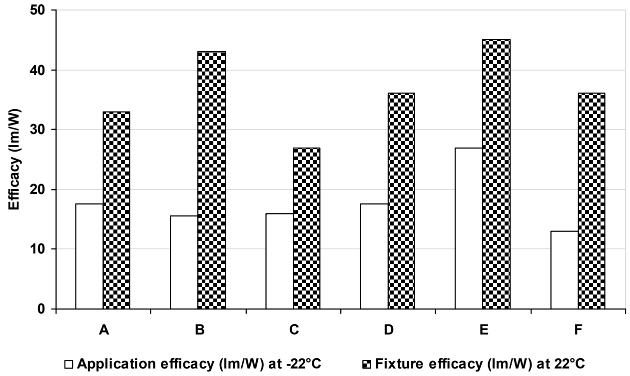


Figure 3. Measurement grid for performance evaluation of refrigerated/freezer display case luminaires.[4]

Several commercial freezer case LED luminaires were tested following ASSIST's method. Figure 4 shows the difference between luminaire efficacy at room temperature (22°C) and application efficacy at freezer temperature (–22°C) for six commercially available LED luminaires. Figure 5 compares luminaire power at room temperature (22°C) with total system power at freezer temperature (–22°C) for the same six luminaires. The results show significant performance differences between room temperature and application temperature. For example, luminaire B has a room temperature luminaire efficacy much greater (42 lm/W) than that of luminaire C (28 lm/W). However, when both luminaires are compared under realistic conditions, luminaire B's application efficacy is slightly lower than that of luminaire C and requires approximately 30% more power to operate at cold temperatures. Similar conclusions can be drawn from comparisons among the other luminaires tested. Overall, application efficacy is a more meaningful metric than luminaire efficacy when assessing energy demand.



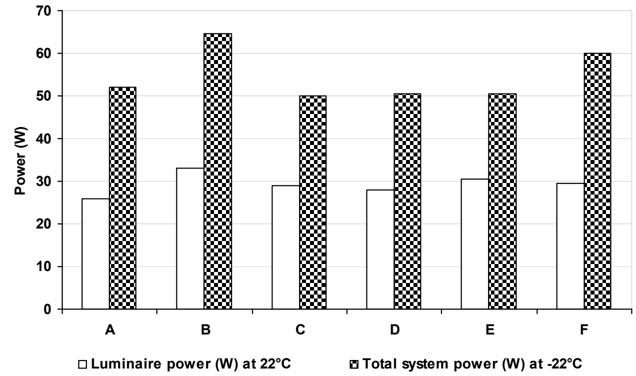


Figure 4 (left). Fixture efficacy compared with application efficacy for six commercial LED freezer case luminaires.
Figure 5 (right). Fixture power compared with total system power for six commercial LED freezer case luminaires.

4. OUTDOOR PARKING LOT LIGHTING

LEDs have received considerable attention recently from municipalities and businesses seeking to upgrade their outdoor lighting installations for both better visibility and energy savings. Again, the concern for LED lighting systems in this application has been whether the light output from these luminaires is suitable for the application and comparable to traditional HID outdoor lighting in terms of illuminance and uniformity. The Illuminating Engineering Society of North America (IESNA) recommends minimum illuminance and uniformity ratios for parking lot lighting.[7] ASSIST's method[5], based on IESNA recommended practice and suitable for all light source technologies, applies the application efficacy concept to parking lot lighting applications to help lighting decision-makers screen potential luminaires for good-quality products in terms of their ability to effectively light the target application area using the least amount of energy.

The ASSIST evaluation method, called Luminaire System Application Efficacy (LSAE), uses a task area of a given size defined by the luminaire's IES lateral and vertical distribution types[8] (Types I to V and very short, short, medium and long); horizontal illuminance on the task area within the recommended range[7]; total flux on the task area within the recommended illuminance range for a given mounting height; the percentage of the task area that meets the illuminance requirements for the mounting height; and the input power to the luminaire. The LSAE metric for parking lot luminaires involves three major steps. The first is to obtain an accurate measurement of the luminaire's intensity distribution in the format of an intensity distribution file (i.e., IES file). The second is to calculate the illuminance on the task area grid and determine which grid cells fall within (conform to) the IES recommended illuminance and uniformity range. The third step is to calculate LSAE based on the illuminance, percentage of conforming cells, and the input power of the system:

$$\text{LSAE} = (\Phi\text{task-conforming} \times (\text{Nconforming} \div \text{N})) \div \text{P}$$

Where Φtask-conforming is the luminous flux inside the target task plane that meets the lighting requirements, (Nconforming ÷ N) is the ratio of conforming cells to the total number of cells in the calculation grid, and P is the total input power to the luminaire.

The calculated LSAE value is for one luminaire on one pole and will vary based on the mounting height. The metric can be extended to multiple luminaires per pole, multiple poles in an area, and an entire parking lot. When comparing LSAE values for a group of luminaires with the same distribution at their optimum mounting height, their rank order will remain the same for one or multiple luminaires and poles (Figure 6).

In terms of energy savings, a higher LSAE value (correlating to higher efficacy) will generally correlate to a lower lighting power density. To demonstrate the correlation between high LSAE and low lighting power density, several luminaires were used to illuminate a 600-ft by 400-ft parking lot to IESNA recommended light levels and uniformity ratios. LSAE values for each luminaire were calculated at different mounting heights with the purpose of finding the optimum mounting height (i.e., the mounting height with the maximum LSAE value). Then, using the optimum mounting height for each luminaire as a starting point, the number of luminaires was determined to meet the required photometric criteria. Finally, the lighting power density associated with each luminaire type was derived from the number of luminaires, the actual input power to the luminaire, and the area of the parking lot. Figure 7 shows that higher LSAE values result in lower lighting power densities as would be expected from a metric used to estimate the energy effectiveness of lighting systems under specific application conditions. To simplify the use of this metric, a free and user-friendly online tool was develop to calculate LSAE, life-cycle cost, and the effects of spectrum on mesopic vision. This online calculator requires the user to input the intensity distribution (in the form of an .IES file) of the luminaires to be evaluated and can be accessed at www.lrc.rpi.edu/parkinglot.

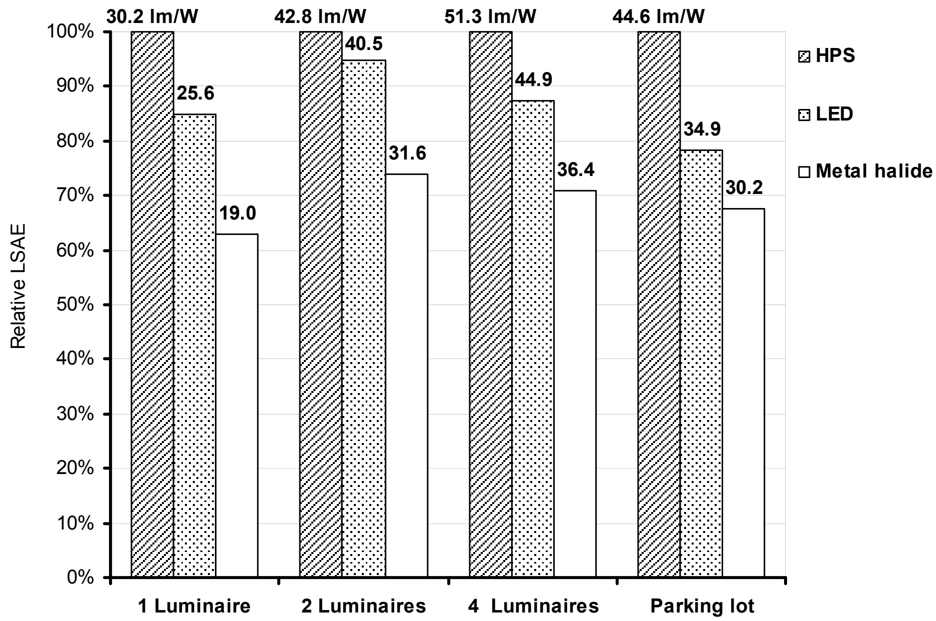


Figure 6. Relative LSAE of three Type III medium luminaires for one luminaire per pole, two luminaires per pole, four luminaires per pole, and multiple poles with four luminaires each in a parking lot. While the LSAE value changes as a function of the number of luminaires and poles, the rank order of each luminaire remains the same when comparing luminaires of the same lateral and vertical distributions.[5]

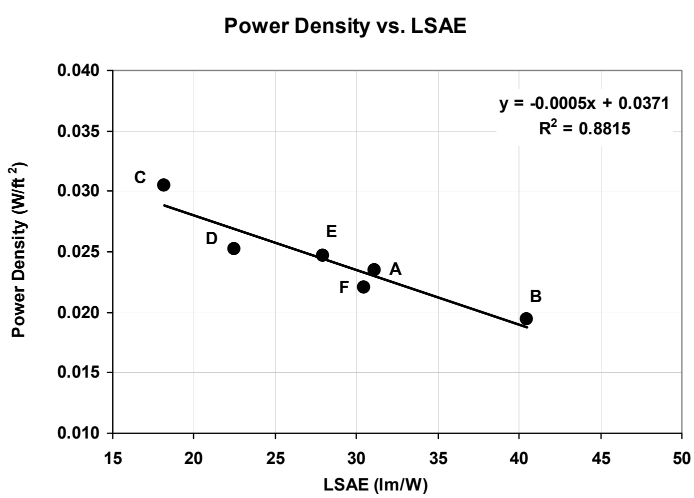


Figure 7. Power density of a 600 ft. by 400 ft. parking lot as a function of LSAE. [5]

5. DISCUSSION

As LED technology quickly becomes a potential light source for general lighting applications, methods are needed to allow a direct and meaningful comparison of the performance of lighting systems under realistic conditions. The examples discussed in this paper show that the common belief that a high-efficacy light source equates to lower energy demand in application is incorrect. In terms of energy efficiency, all that matters to end users is that certain lighting requirements are met with the least amount of energy. To achieve this goal, lighting systems need to be evaluated in terms of how much energy is needed to meet the requirements of the application. This paper introduces the concept of application efficacy as a flexible tool to quantify the energy effectiveness of lighting systems at meeting application specific requirements. The concept of application efficacy can be adapted to different applications. For example, the concept of LSAE, described here in the context of parking lots, can be adapted very successfully to roadway lighting conditions by implementing in the method the photometric criteria expected for roadway conditions. Additionally, in outdoor lighting, the concept of application efficacy can be expanded to include how well the spectrum of the light source matches the spectral sensitivity of end users based on the required light levels (i.e., mesopic vision).[9] Application efficacy can also include other factors, such as the time of operation of the lighting system or the adjustment of light levels if doing so is advantageous.

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