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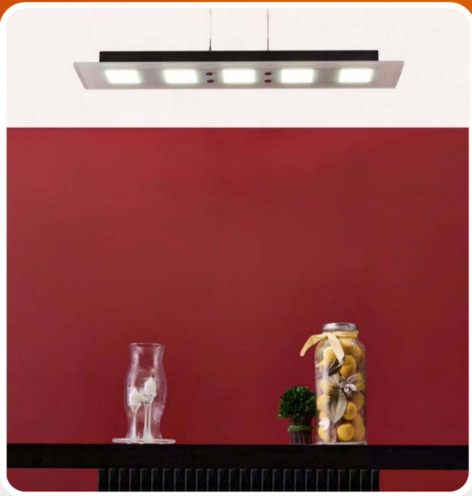

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OLED Lighting Products: Capabilities, Challenges, Potential

May 2016

NJ Miller
FA Leon

U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

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OLED Lighting Products: Capabilities, Challenges, Potential

Report prepared in support of the U.S. DOE Solid-State Lighting Program

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Cover photo: "Blade" luminaire from DesignPlan; photo by Tom Kosa.

Executive Summary

This is the second of three initial reports on organic light-emitting diodes (OLEDs) by the U.S. Department of Energy (DOE), Solid-State Lighting Program. The first was a GATEWAY field study documenting the installation of OLEDs as ambient office lighting. The third will be a CALiPER (Commercially Available LED Product Evaluation and Reporting) analysis of OLED products, based on independent photometric testing and product tear-downs (dissasemblies to identify parts and functionality). This report focuses on the potential for architectural OLED lighting, describing currently available products as well as promised improvements, and addressing the technology and market hurdles that have thus far prevented wider use of OLEDs.

At present, OLED panels for lighting employ flat glass substrates in panels that are approximately 100 mm square, although the range of sizes and aspect ratios is growing. An exciting opportunity is the potential to use thin, flexible substrates in glass or plastic to provide products that can be curved, rolled, or even folded. As these technologies evolve, and the price to implement them drops, non-rigid OLED lighting products may offer a competitive advantage over LED and other lighting technologies.

At this point in time, OLED system efficacy at the luminaire level is well below LED system efficacy, ranging between about 21 and 44 lumens per watt (lm/W). Most OLED luminaires use LED drivers rather than dedicated OLED drivers because they are much more widely available, but may suffer efficiency losses because LED drivers are not optimized for the OLED panel. In addition to driver losses, the driver's dimming method may introduce performance issues such as photometric flicker in dimmed conditions. Generally, the preferred method for dimming OLEDs is to adjust the driving current, or amplitude modulation, using constant current reduction (CCR) drivers.

As OLED panels age, the voltage across the panel for a given design current will rise, and a driver must be able to adjust (i.e., increase the voltage to maintain a constant current) to avoid light output losses due to the inability to maintain the design drive current. It is important that drivers be able to provide the required power to the luminaires, not only at start of life, taking into account worse-case OLED panel voltage variations, but also as the panels age and their voltage increases. Manufacturers must communicate that end-of-life power draw to specifiers so that lighting and dimming circuits can be designed for their full loads, and energy code compliance can be accurately documented.

OLED color characteristics (color rendering index (CRI), fidelity index (R_f), and gamut index (R_g)) range from good to very good, although rendered colors can be somewhat undersaturated compared to the equivalent correlated color temperature (CCT) black body radiator. They are generally available in 2700-3000 K, although 3500 K and 4000 K are offered by some manufacturers, usually at lower efficacies.

Like LEDs, OLEDs are dimmable when paired with dimming drivers with DMX, DALI, and 0-10V protocols. Light output and estimated L_{70} life are linked such that, as a rule of thumb, as panel light output doubles, L_{70} hours drop to a third at that power level. So, a panel operated at a luminance of 3000 candelas per square meter (cd/m^2) may be listed at 40,000 hours, but if operated at 6000 cd/m^2, the L_{70} life drops to about 13,300 hours. (It should be noted that at this point in time there is no testing standard for evaluating and reporting OLED panel life. LM-80-15: IES Approved Method: Measuring Luminous Flux and Color Maintenance of LED Packages, Arrays and Modules; as well as TM-21-11**:** Projecting Long Term Lumen Maintenance of LED Light Sources, apply to LED sources, only.)

The report addresses OLED performance for a range of lighting quality issues: Visual appearance of space and luminaire, including OLED finishes; panel optics and distribution options; direct visual comfort/glare and reflected glare; vertical illuminance and facial modeling; lighting uniformity and lack of shadows/highlights; maintenance issues such as life, replacement, connectors, interoperability, and obsolescence; shipping and installation durability; and cost.

OLED's current competition is edge-lit LED panels, which offer similar appearance and superior performance in several respects including cost, but at the sacrifice of panel thinness. MicroLEDs are rumored to offer competition in the near future.

The early years of LED lighting were fraught with difficulties: low output, rapid light decay, miserable color, short life, driver failures, flicker, clumsy connectors, no standards, etc. OLEDs are struggling through a similar set of difficulties, but OLED manufacturers have the advantage of having watched and learned from the LED industry's working through these problems. OLED systems are increasing in efficacy, but they are not yet within the range of cost, energy performance, high color quality, dimming performance, optical performance, and standardized, interchangeable components that would make OLEDs a viable and desired product. With rapid advances in these areas, this technology could become the complementary solid-state counterpart to LEDs, a dynamic and softly luminous luminaire element and building material.

Contents

1.0 Introduction

Organic light-emitting diodes (OLEDs) are solid-state devices that are dramatically different in appearance and lighting performance from light-emitting diodes (LEDs). They are large in surface area, low in luminance, thinner than LEDs, and usually diffuse in appearance. OLED panels are already showing great aesthetic potential, as tiles, as soft panels for lighting faces without glare, and as task lights. As tiles, they can be used to compose patterns, linear or arrayed, circular arrangements, or random patterns that lead or entertain the eye. They can be incorporated into architectural elements, be arranged to produce words or playful patterns, or support wayfinding in buildings.

This is the second of three initial reports on OLEDs by the U.S. DOE Solid-State Lighting Program. The first was a GATEWAY field study documenting the installation of OLEDs as ambient lighting in a design office near Chicago. The third will be a CALiPER (Commercially Available LED Product Evaluation and Reporting) analysis and report of commercially available OLED products, based on independent photometric testing and product tear-downs (dissasemblies to identify parts and functionality). This report focuses on the potential for architectural OLED lighting, describing the current state of available products, and detailing the technology and market hurdles that prevent wider use of OLEDs. Most importantly, it tries to bridge the communication gap between the needs and goals of the OLED manufacturers, the product needs of the lighting specification community, and the needs of the luminaire manufacturer in committing to OLED products. This report concludes with a list of performance features that may inspire the market to develop components and luminaire offerings that will increase application opportunities and adoption of OLEDs.

Figure 1. Conference room with Acuity Brands' CHALINA™ OLED pendants, installed at the offices of 16500, an architectural lighting agency in Emeryville, CA. (Photo courtesy of Acuity Brands, Inc.)

There are still few OLED architectural luminaires, but there has been a modest expansion of products in 2015 and 2016, with more luminaire manufacturers designing and marketing dedicated OLED luminaires (Figure 1) and luminaires that combine LED emitters and OLED panels into a single luminaire, skillfully combining the controlled intensity of the LED with the soft distribution and comfortable appearance of the OLED (Figure 2).

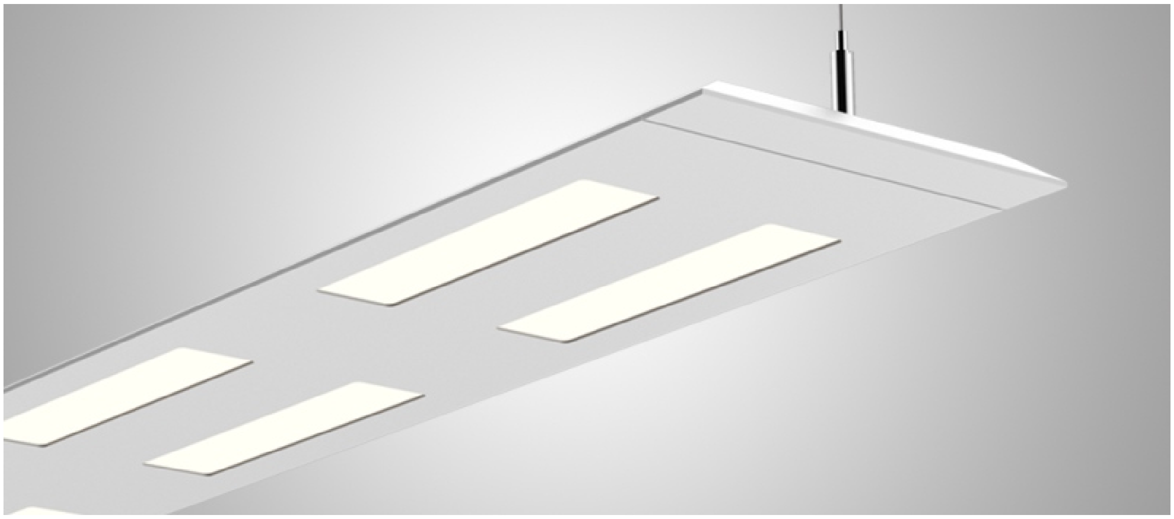


Figure 2. Acuity Brands's Winona® concept product exhibited at LightFair 2016. The product combines OLED panels for downward light with a line of LED emitters for higher-intensity upward light. (Photo courtesy of Acuity Brands, Inc.)

1.1 OLED Panels

OLED panel manufacturers include LG Display, Kaneka Corporation, Konica Minolta, MC Pioneer, and OLEDWorks. OLEDWorks is the only U.S.-based manufacturer, maintaining a manufacturing facility in Rochester NY as well as the former Philips' OLED facility in Aachen, Germany (acquired in 2015). Panasonic has invested research and development (R&D) funds for OLED development, but withdrew from the OLED lighting market in 2014 because of the high cost of production.[1] Sumitomo has announced a polymer OLED[2] and Osram is manufacturing panels for automotive applications.

The performance of OLED panels in laboratories is thoroughly discussed in DOE's *Solid-State Lighting R&D Plan*, published May 2015.[3] The promise of efficacies as high as 133 lm/W has not yet reached products available for specification and installation in the architectural lighting market. Based on DOE CALiPER testing, the luminaire system efficacies available in 2015 ranged between about 21 and 44 lm/W, well below the LED luminaire system efficacies of 67 to 108 lm/W listed in Table 2.1 of the *R&D Plan*.

A general overview of OLED technology is available on the DOE website.[4] The focus of this report is aspects of the technology that are particularly important or challenging to lighting applications. Figure 3 illustrates a typical structure of an OLED lighting panel, which includes a substrate on which all layers

[1] OLED-Info. "Panasonic to withdraw from the OLED lighting market." March 30, 2014. Available at http://www.oled-info.com/panasonic-withdraw-oled-lighting-market.

[2] OLED-Info. "Sumitomo to show their latest P-OLED lighting panels at L+B 2016." February 16, 2016. Available at http://www.oled-info.com/sumitomo-show-their-latest-p-oled-lighting-panels-lb-2016.

[3] DOE. 2015. *Solid-State Lighting R&D Plan*. Prepared for the Solid-State Lighting Program, U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Washington, D.C. Available at http://energy.gov/sites/prod/files/2015/06/f22/ssl_rd-plan_may2015_0.pdf. A new *Solid-State Lighting R&D Plan* is expected to be released in June 2016.

[4] DOE (n.d.). *OLED Basics*. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy. Available at http://energy.gov/eere/ssl/oled-basics.

are coated, a cover glass or metal that protects the multiple organic layers from the environment, and an external light extraction film, which may both improve the panel's efficacy and create a more aesthetically pleasing appearance. The organic layers are sandwiched between a transparent anode, which is typically indium tin oxide (ITO), and a metal cathode, which is typically aluminum or silver. The metal cathode material may be either highly reflective or transparent, depending whether the panel is intended to emit light through the substrate only or through both the substrate and a transparent cover. While transparent OLEDs are not yet commercially available, they represent a unique opportunity in applications where a combination window and light source is desired.

Exposure to moisture and oxygen are known to degrade OLEDs and may create artifacts, such as dark spots, that can grow over time and dramatically shorten panel lifetime.[1] The most common approach to protecting OLEDs from the environment is to use glass as both the substrate and the cover, and to seal these around the edges with an epoxy adhesive to prevent moisture and oxygen permeation. A metal cover can also protect against the elements. Another common practice is to use desiccant to capture any moisture and oxygen trapped inside the panel during manufacturing or that may leak into the panel through the edge seal over time.

An exciting opportunity for OLED lighting panels, and OLED displays, is the potential to use flexible substrates to provide products that can be curved, rolled, or even folded. The most commonly selected substrate material for non-rigid OLED applications is some form of plastic, such as polyethylene terephthalate. However, the rate at which oxygen and moisture permeates plastics can challenge OLEDs, given their sensitivity noted above. Various thin film encapsulation techniques have been developed and implemented, both as methods to eliminate the need and cost of a cover glass and as a way to enable flexible devices on plastic substrates.[2] Thin, flexible glass substrates are another material that may open opportunities for OLEDs. As these technologies improve, and the price to implement them drops, non-rigid OLED lighting products may offer differentiation and a competitive advantage over LED and other lighting technologies.

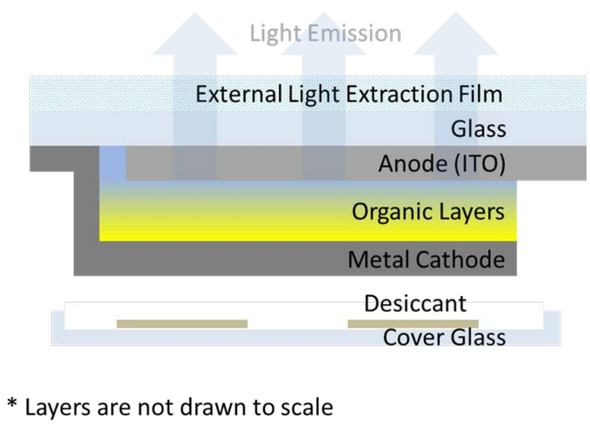


Figure 3. Illustration of OLED layers. (Illustration: PNNL)

[1] McElvain J, H Antoniadis, MR Hueschen, JN Miller, DM Roitman, JR Sheats, and RL Moon. 1996. "Formation and growth of black spots in organic light-emitting diodes." *Journal of Applied Physics* 80, 6002. Available at http://scitation.aip.org/content/aip/journal/jap/80/10/10.1063/1.363598. doi:10.1063/1.363598

[2] OLED-Info (n.d.). *OLED Encapsulation: technological introduction and market status*. Available at http://www.oled-info.com/oled-encapsulation.

OLEDs typically use an extraction layer applied to the OLED substrate to improve efficacy and prevent light from being lost through inter-reflection and absorption inside the panel. OLEDWorks, for example, offers a 100 x 100 mm, 2500 K and 26 lm/W panel without an extraction layer, resulting in a shiny finish. This panel is mirror-like when off and exhibits significant color shift when viewed from multiple angles, which can be an attractive design choice for some applications. If an extraction layer is added, the panel appearance is a diffuse white, nominally at 2900 K, with little color shift over angle, and an efficacy rise to 46 lm/W. Thus, the extraction layer dramatically affects appearance, color, and efficacy.

Table 1 shows May 2016 manufacturer-reported capabilities of OLED panels: sizes, lumens, luminance, panel watts, system watts with driver (if available), correlated color temperature (CCT), color rendering index (CRI), R_9, panel appearance and finish (shiny or matte), and estimated L_{70} life. The entries are based on a manufacturer's most commonly available white panel. The values may not represent all panels offered by that manufacturer.

Table 1. OLED system characteristics for white light panels, based on LG Display and OLEDWorks website data, and Kaneka Corporation product literature. Characteristics based on highlighted panel size and finish.

	LG Display N6S Series	OLEDWorks FL300	Kaneka Corp.
Panel size	**100 mm square**, 200 x 50 mm, 53 x 55 mm, 213 x 113 mm, 200 x 200 mm, 320 x 320 mm, 140 x 140 mm, 110 mm round, 320 x 110 mm, 210 x 50 mm flexible; all **matte finish**	**102 mm square,** 50 x 200 mm; shiny and **matte finish**	**80 mm square**, 100 mm square, 143 x 23 mm; all **shiny finish**
Color (CCT, CRI, R_9)	3000 K, 90 CRI; 4000 K, 90 CRI	2500 K (shiny) 2900 K, 80 CRI, $R_9 = 0$ (matte)	3000 K, 86-92 CRI; 4000 K, 92 CRI
L_{70} panel life, panel lumens	40,000 hrs at 3000 cd/m^2 (75 lm), 3000 K; 30,000 hrs at 3000 cd/m^2 (75 lm), 4000 K	50,000 hrs at 3150 cd/m^2 (115 lm); 10,000 hours at 8300 cd/m^2 (300 lm)	50,000 hrs at 3000 cd/m^2 (60 lm), 3000 K; No data for 4000 K
Panel efficacy (new)	55 lm/W, 3000 K 60 lm/W, 4000 K	42 lm/W at 0.368A 50 lm/W at 0.040A	40 lm/W, 3000 K 29 lm/W, 4000 K
Appearance	Matte white on or off	Panels with extraction layer: matte white on or off; panels without extraction layer: shiny on or off	Shiny finish, becomes mirror when off
Panel luminance, panel wattage	3000 cd/m^2, 2.5 W, 3000 K 3000 cd/m^2, 2.7 W, 4000 K	3150 cd/m^2, 2.5 W at 0.135 A; 8300 cd/m^2, 7.4 W at 0.368 A (new), 10 W at 0.390 A at end of life	3000 cd/m^2, 1.5 W, 3000 K No data for 4000 K

1.2 Drivers for OLED Panels

Unlike lamps and luminaires that use LED technology, OLED products experience minimal losses due to thermal effects, and because they are most often used with the panel exposed, there are few optical losses from the luminaire. However, converting typical residential and commercial building alternating current (AC) line voltages of 120 and 277 V to the direct current (DC) needed to drive LEDs and OLEDs can dramatically reduce overall product efficiency. Generally, the driver converts line voltage into a DC current that drives the luminaire's light emitters. These drivers typically can operate within a range of output voltages. Constant voltage drivers, though capable of providing a source of current to drive LEDs or OLEDs, are not ideal since they would allow the current to the load to vary depending on several factors, such as light emitter characteristics and ambient temperature. As a result, driving OLEDs in constant voltage mode may cause variations in luminous intensity and could potentially damage the OLED panel(s) or reduce product lifetime.[1]

Efficacy at the luminaire level can be reduced by 50% or more relative to bare panel efficacy, depending on panel driving requirements, driver performance, and luminaire optical design. In addition to driver losses, a potential pitfall in selecting drivers for OLEDs is the dimming method. LED drivers typically use pulse-width modulation (PWM) of current at high frequencies to reduce the overall light output, while maintaining the peak current to the LED consistently throughout the dimming range. The availability of such drivers makes it convenient to apply the same approach to OLEDs, but OLEDs do not respond to rapid on-off cycles in the same manner as LEDs.[2]

Some OLED systems have been designed using PWM drivers; however, performance issues such as photometric flicker have been observed under dimmed conditions. The preferred method for dimming OLEDs is to adjust the driving current, or amplitude modulation, using constant current reduction (CCR) drivers. This method is sometimes called "analog dimming."[3]

During a CALiPER evaluation of commercially available OLED luminaires in 2016, the use of two daisy-chained drivers was encountered in a single wall sconce (Figure 4). The first driver's function is to convert the AC line voltage into a constant voltage. This constant voltage is then provided to the second driver, which is dimmable using a 0-10V protocol, and designed with OLED driving and dimming requirements in mind. Pacific Northwest National Laboratory (PNNL) estimated that this approach would reduce overall driver efficiencies. (Details will be provided in the forthcoming DOE CALiPER report on OLED luminaires.)

As OLED panels age, the voltage across the panel for a given design current will rise, and a driver must be able to adjust (i.e., increase the voltage to maintain a constant current) to avoid light output losses due to the inability to maintain the design drive current. Panels may also have manufacturing variations, resulting in slightly higher, or lower, voltage. It is important that drivers be able to provide the required

[1] Maxim Integrated. 2004. *Application Note 3256: Why Drive White LEDs with Constant Current?* Available at https://www.maximintegrated.com/en/app-notes/index.mvp/id/3256.
[2] Jacobs J, D Hente, and E Waffenschmidt. 2007. "Drivers for OLEDs." *Industry Applications Conference, 2007. 42nd IAS Annual Meeting. Conference Record of the 2007 IEEE*. Institute of Electrical and Electronics Engineers, New York, NY.
[3] Philips. 2014. *Philips Lumiblade OLED driver, low voltage D024V 10W/0.1-0.4A/28V D/A.* Koninklijke Philips N.V., Amsterdam, Netherlands. Available at https://www.oledworks.com/wp-content/uploads/2016/03/Data-sheet-Lumiblade-D024V-10W-0-1-0-4A-28V-D-A.pdf.

power to the luminaires, not only at start of life, taking into account worse-case OLED panel variations, but also as the panels age and their voltage increases.

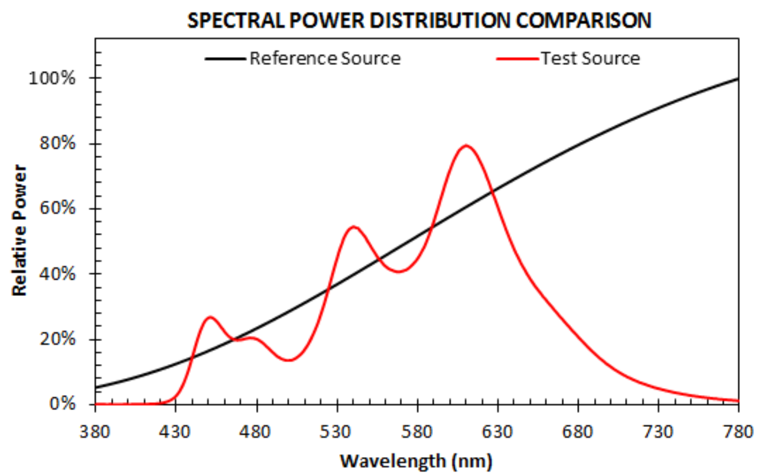
Figure 4. One-line diagram of two-driver OLED system design. (Illustration: PNNL)

2.0 Capabilities and Challenges

2.1 Color Characteristics

Light source color metrics such as CCT, CRI (R_a), R_9, and the Illuminating Engineering Society (IES) TM-30-15[1] color indices of R_f and R_g are derived from the OLED panel's spectral power distribution (SPD). The SPD signature for the OLED is different from that of LEDs because the light is created by the emitting layers, rather than phosphor-converted energy from a blue- or violet-pump LED, or than from combining multiple LED primaries to create white or colored light. The following graphics show the color metrics for two 3000 K OLED products tested for the DOE CALiPER Program, using the IES TM-30-15 calculator and visualization graphics (Figure 5, Figure 6).

R_f	**86**
R_g	**98**
CCT (K)	2974
D_{uv}	0.0019
x	0.4417
y	0.4105
CIE R_a	89



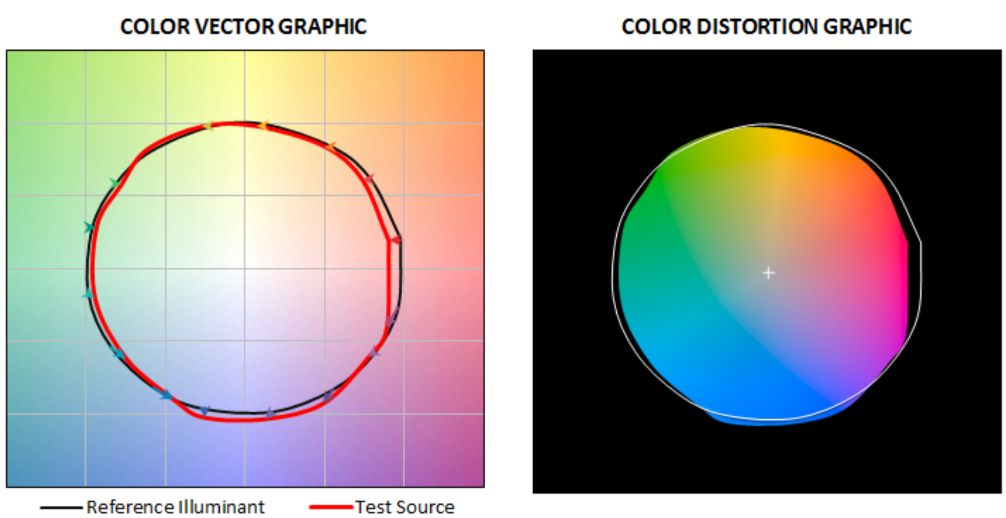
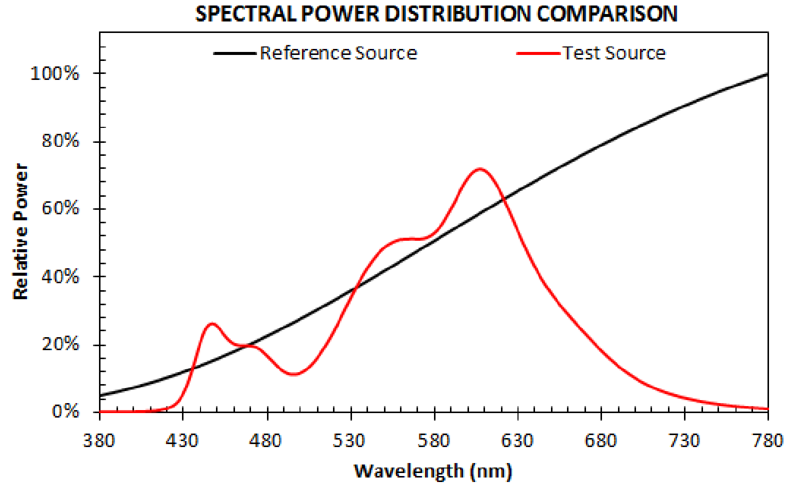


Figure 5. TM-30-15 color metrics and graphics for the LG 3000 K panel used by Acuity Brands, Inc.

[1] IES TM-30-15: IES Method for Evaluating Light Source Color Rendition. Available at: https://www.ies.org/store/product/ies-method-for-evaluating-light-source-color-rendition-3368.cfm.

R_f	**78**
R_g	**95**
CCT (K)	2947
D_{uv}	0.0004
x	0.4413
y	0.4065
CIE R_a	78



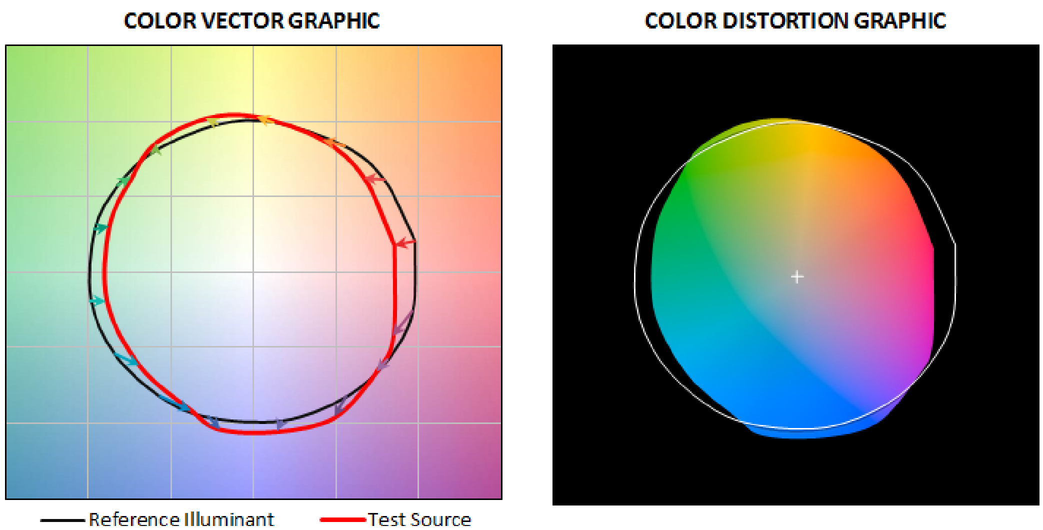


Figure 6. TM-30-15 color metrics and graphics for the OLEDWorks FL300 panel (from CALiPER Test ITL86057).

On first observation, the color metrics and graphics indicate that the LG Display and OLEDWorks 2900 K panels are quite different, even though they are within 50 K CCT of each other. The LG Display panel is likely to produce better overall color rendering because it has a higher CRI (R_a), R_f, and R_g. Both panels tend, on the average, to desaturate colors, including the red hues that are so important for retail applications and skin tones. See Table 2.

Table 2. Color metrics calculated for two commercial OLED panels evaluated through the DOE CALiPER program.

	LG Display Panel	OLEDWorks FL300 WW Panel
CCT	2974	2947
CRI (R_a)	89	78
R_f	86	78
R_g	98	95

The OLEDWorks panels are available in 2900 and 2500 K options, as well as an amber color, with the 2900 K panel being more efficacious. The LG panels are available in 4000, 3500 K, and 3000 K (Figure 7), with the 3000 K panels being slightly more efficacious.

Aside from increasing the red content of the OLED light sources, the OLED industry would do well to consider a dim-to-warm option, where the light source grows warmer at lower output, similar to the way incandescent lamps behave. (PNNL lab testing has shown that this already occurs to some extent. One set of panels shifted from 2951 K at 100% output, and to 2781 K at 25% output. Report pending.) Also, OLEDs with tunable white or tunable color options would be a desirable feature for the hospitality, retail, and commercial markets, especially if they can closely replicate the “dim-to-warm” characteristic of incandescent lamps, or any other desired dimming trend. (MC Pioneer is working to satisfy this niche with their white-tunable and full color-tunable OLED Velve panels.) Both of these capabilities are now readily available in LED luminaires.

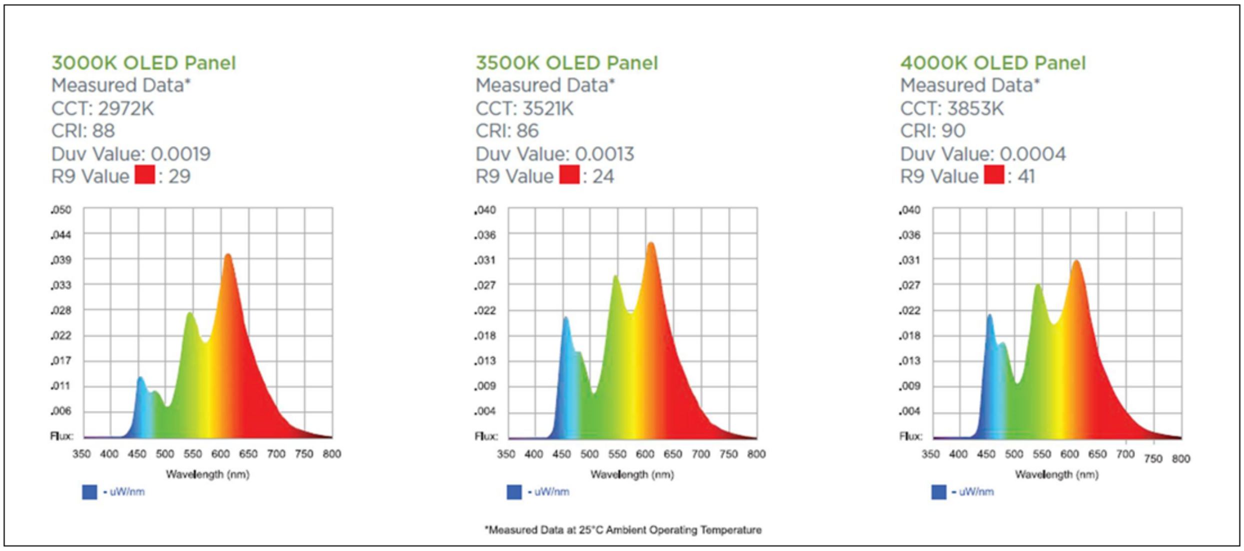


Figure 7. Three color options for OLED panels available from LG Display. Note that the y-axis scale is not identical for all figures.

2.2 Form Factor Options and Panel Size Options

An OLED panel’s greatest asset is its thinness. Most are only about 1 to 2 mm thick, although that does not include additional thickness from connectors and mounting frames, or in one case, a built-in driver. Current panel size options are listed in Table 1.

Some panel manufacturers describe the 600 x 600 mm (2 x 2 foot) panel as the holy grail, since 2 x 2 foot recessed troffers are in high demand in North American commercial, institutional, and retail spaces, and because the light output is similar. (A diffuse 2 x 2 foot OLED panel at 3000 cd/m^2 would produce about 3400 lm, comparable to 3000 to 4500 lm for the LED or fluorescent troffer competitor.) Although this is a noble aspiration, it is well to note that typical 2 x 2 foot recessed troffers in fluorescent or LED lighting cost between $100 and $300 at the contractor level, making the OLED equivalent economically impractical in the near future.[1] It may also be noted that OLEDs provide no real advantage over LEDs in such applications, as thinness is irrelevant, and appearance relative to an edge-lit panel would be similar. Because of the cost barrier, the OLED industry would do well to consider less-commoditized product categories than recessed troffers, downlights, or wraparounds, for example.

The OLEDWorks Keuka™ panel integrates a slender connector, driver, and case into a panel system only 6 mm thick. This panel may be very desirable to luminaire manufacturers because of its integrated design and wiring simplicity. However, it operates at 24 V, so the luminaire manufacturer still has to integrate a transformer into the luminaire for buildings with 120 or 277 V power, or else design for the transformer to be remote-mounted.

2.3 Dimming and Compatibility with Controls Protocols

OLED panels are paired with an electronic driver, and in order to dim the output, the driver must be able to receive input signals from a dimmer, usually using a 0-10V, DALI, DMX, and/or other communication protocol in most commercial spaces, and via a phase-cut AC waveform in most hospitality and residential spaces. The dimming driver interprets this input and may use PWM or CCR technology to dim the OLED panel output. The advantage of a PWM technology is that color output is unaffected as the panel is rapidly switched on and off to reduce the perceived light output. The disadvantage is that when the driver dims the panel to very low levels, such as less than 5% of maximum, the light is OFF for a greater part of the cycle than it is ON, and this can make flicker more apparent.[2]

The advantage of CCR technology is that the driver output is a continuous reduced current and thus flicker is unlikely. The use of CCR also avoids transients that can affect OLED panel lifetime and keeps the luminance stable over a wide range of temperature, panel age, and production tolerances; but dimming by adjusting current can make the color of the OLED output warmer, especially at low dimming levels.

OLED products are commonly marketed with 0-10V, DALI, or DMX compatible dimming drivers, and most can dim OLED panels down to 10% of the peak output. Dimming to even lower levels, such as 1% of peak, which is desirable for some conference rooms, auditoriums, classrooms, and hospitality spaces, may require a more sophisticated and expensive dimming driver. Whether selecting dimmers and dimming drivers for LEDs or OLEDs, the same considerations apply. CCR dimming drivers for OLEDs

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[1] The DOE 2015 *Solid-State Lighting R&D Plan* predicts OLED panel costs at $550/m^2 in 2017. That translates to $198 for a 2- x 2-foot OLED panel, not including luminaire manufacturing costs. (Source: DOE. 2015. *Solid-State Lighting R&D Plan*. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Washington, D.C., p. 114. Available at http://energy.gov/sites/prod/files/2015/06/f22/ssl_rd-plan_may2015_0.pdf .)
[2] Bullough JD, K Sweater Hickcox, TR Klein, and N Narendran. 2011. "Effects of flicker characteristics from solid-state lighting on detection, acceptability and comfort." *Lighting Research & Technology* 43:337-348.

may improve light output stability. (A thorough overview of these is provided in a presentation by Michael Poplawski of PNNL on behalf of the DOE Solid-State Lighting Program.[1])

It is important that OLED system manufacturers and specifiers understand the concept of dimming curves and transfer functions, which are built into electronic devices because some manufacturers are trying to mimic the familiar behavior of incandescent lamps on conventional phase-cut dimmers. A dimmer using a 0-10V protocol, for example, may deliver a linear signal to the driver to communicate expected light output (0 = off, 1 = 10% of maximum output, 2 = 20% of maximum output, 3 = 30% of maximum output, etc.). But a different manufacturer's 0-10V dimmer may deliver a square law signal to the driver to communicate expected light output to simulate the behavior of dimmed incandescent lamps (0 = off, 1 = 1% of light output, 2 = 4% of light output, 3 = 9% of light output, 4 = 16%, 5 = 25%, 6 = 36%, etc. up to 9 = 81% and 10 = 100% of light output). Similarly, the driver may expect to see a linear input from the dimmer and deliver a linear output to the OLED, or it may expect to receive a linear input but deliver a square law output to the OLED panel. This is called the transfer function of the driver, and depending on the dimmer design and the transfer function of the driver, the OLED panel could receive a dimming signal that causes the panel to produce either a linear, square law, or power law (often called "logarithmic") output (Figure 8).

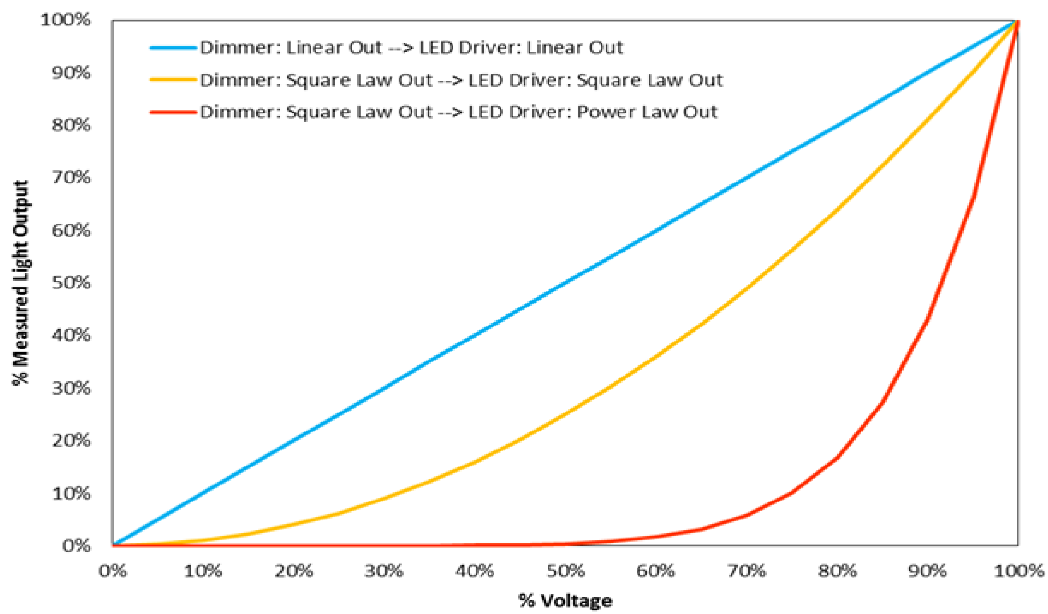

Figure 8. Illustration of linear, square law, and power law (or logarithmic) output due to the transfer function of the solid-state lighting driver.

Manufacturers of dimmers and drivers make a choice in the design of their electronics, but this is not always clearly communicated by manufacturers to specifiers. Consequently, clients could end up with OLED products dimming in unexpected and unsatisfactory ways.

[1] Poplawksi M. 2012. *LED Dimming: What you need to know*. Presented on behalf of the DOE Solid-State Lighting Program, Washington, D.C., December 10, 2012. Available at http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/dimming_webcast_12-10-2012.pdf.

2.4 Light Modulation or Photometric Flicker

Light modulation (aka photometric flicker) is an issue for many solid-state lighting devices. The critical element is the driver, since its output determines the steadiness and consistency of the LED's light emission, and frequency at which the system oscillates in output. The driver operation can be complicated when it is paired with a dimmer or dimming system.[1] Flicker can be detected visually by direct observation, indirectly detected because of the stroboscopic effect induced by the on-off illumination of an object, or it may not be visible at all. Even if the light modulation is not visible, it may be detected neurologically, inducing headaches or migraines, reducing visual performance, and causing seizures or autistic behaviors[2] in a few individuals. Institute of Electrical and Electronics Engineers guidance for mitigating flicker from solid-state lighting published in 2015 (see footnote 2) set a simple guideline for a combination of flicker frequency and percentage of flicker (aka modulation depth).

Flicker has been observed in dimmed OLED systems (Figure 9), just as it has in LED systems. Hand-held flicker meters that cost less than $2500 can quickly and accurately measure photometric flicker so that a driver or luminaire manufacturer can ensure that the system operates within a safe range.

Spaces using video cameras need to pay careful attention to flicker issues, since an interaction between frame capture rates and light flicker can create distracting image artefacts. CCR driver techniques may prove better for these applications.

Figure 9. Flicker top showing "spokes" that indicate some flicker from an OLED luminaire and driver system dimmed with a 0-10V dimmer. (Photo: Leslie North)

2.5 Light Output, Lumen Maintenance, and Life (Both Panel and Driver)

Current lumen output for a 100 x 100 mm OLED panel operated at 3000 cd/m^2 is about 70 to 100 lm in one hemisphere. (This is a panel that is comfortable to view without any glare-controlling media.) This

[1] Poplawski M. 2013. *Standards & Specifications Update: Dimming & Flicker*. Presented at Lightfair, April 2016. Available at http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/poplawski_dimming_lightfair2013.pdf.
[2] IEEE Standard 1789-2015. *IEEE Recommended Practices for Modulating Current in High-Brightness LEDs for Mitigating Health Risks to Viewers*. Available at http://standards.ieee.org/findstds/standard/1789-2015.html.

is about 3% of the lumens emitted by a linear 32 W (4 foot) T8 fluorescent lamp capable of producing 3000 lm. Assuming that the fluorescent lamp is housed in a luminaire with 70% efficiency in redirecting the lamp emission into one hemisphere, a simple calculation shows a dramatic difference in light output that necessitates using at least 21 OLED panels to deliver the downward light of a single T8 fluorescent lamp. This poses a serious reflection on cost; that is, how low does the panel cost have to go for it to be a viable, practical light source compared to fluorescent or LED technologies? It may make sense to increase OLED panel luminance and light output for some applications, controlling the glare with optics and housings, and sustaining some luminaire efficacy losses as a result, in order to reduce the number and cost of panels needed to deliver target light levels. There is a tradeoff between OLED panel luminance (and lumen output) and product life. "Life" has traditionally been defined as the point at which panel output declines to 70% of initial lumens. (As a rule of thumb, doubling luminance cuts lifetime by a factor of three.[1]) The OLEDWorks FL300 WW panel has a published L_{70} life of 10,000 hours at 8300 cd/m^2, 25,000 hours when dimmed to 50% output, and 40,000 hours when dimmed to 25% output.

A panel life of 10,000 hours is comparable to the life of a compact fluorescent lamp (CFL), although only in a few cases will the CFL light output degrade to 70% during its rated lifetime. CFLs also have a different "life" definition, where 50% of the tested lamps will fail to light (B_{50}). OLED panels are more likely to decay in light output, rather than fail to light.

If operated at 50% current, the OLED is expected to have a panel life of 25,000 hours, more comparable to that of a linear fluorescent lamp; and at 25% output the OLED life is expected to climb to 40,000 hours, closer to some reported LED L_{70} life values. Building owners are used to replacing fluorescent lamps, but changing OLED panels is a bit trickier, given the need to avoid static electricity that can damage the new panel. Owners will need to ensure their facilities staff is informed about the OLED product, the connectors, the drivers, and any special care needed in handling.

(It should be noted that at this point in time there is no testing standard for evaluating and reporting OLED panel life. LM-80-15: IES Approved Method: Measuring Luminous Flux and Color Maintenance of LED Packages, Arrays and Modules; as well as TM-21-11**:** Projecting Long Term Lumen Maintenance of LED Light Sources, apply to LED sources, only.)

There is a natural inclination to use maximum panel luminance during the project design phase to achieve target light levels with fewer panels reducing product cost. That may result in a false economy; however, since at full output panels without secondary optics may be perceived as uncomfortably bright if mounted overhead, with panels facing downward. The panels can be dimmed to improve comfort, but the light levels drop proportional to average current delivered by the driver. Thus, the dimmed OLED luminaire may be comfortable to look at, but the space may need supplemental luminaires or task lights to achieve needed light levels.

2.6 Efficacy, Power Draw over Time

Power draw from OLED systems increases over panel life, mostly due to the increase in OLED panel voltage due to aging. Visa Lighting's LIMIT™ luminaire specification sheet estimates the three OLEDWorks FL300 panels deliver a total of 703 lm and draw 25 W when new (28 lm/W), and is projected to rise to 33.33 W at end of rated panel life, that is, L70 = 70% of initial output (Figure 10).

[1] Lisa Pattison, SSL Consultants, Inc., correspondence with Naomi Miller, PNNL, May 27, 2016.

That’s a 33% increase in power, and combining that with the decrease in light output at L_{70} life, the efficacy of the luminaire at the end of panel life is projected to be 14.8 lm/W. Until OLED panels achieve significantly higher efficacies when new, the erosion of the efficacy due to panel aging may be unacceptable for many applications.

Figure 10. LIMIT™ pendant luminaire by Visa Lighting, with three 100 x 100 mm OLED panels, drawing 25 system watts, estimated at 33.3 W at 70% of initial output. Image courtesy of Visa Lighting.

It is very important for luminaire manufacturers to state the maximum power draw on their specification sheets, because electrical engineers use these numbers to size lighting circuits and to perform energy code calculations (i.e., lighting power densities). Rising wattage over time due to panel aging could trip breakers.

Some manufacturers offer solid-state lighting products that increase in power over life to compensate for the age-related decay in lumens. This is a valuable option for the designer, but it is imperative for the luminaire manufacturer to clearly state the maximum power so that circuit loading is not exceeded over time.

2.7 Other Lighting Quality Issues

2.7.1 Visual Appearance of Space and Luminaire

OLEDs are a different kind of light-emitting device in that they are low in luminance, less than 1/8 inch thick, and most often diffuse in appearance. OLED panels are already showing great aesthetic potential. They can be used as tiles that can be arranged to produce patterns; linear, arrayed, circular, or random arrays that lead or entertain the eye. They can respond to the architecture the same way that ceramic tiles can. They can be controlled individually to produce words or playful patterns, can become markers and signage, or can help with wayfinding. Curved or flexible OLED panels hold great promise for visual delight (Figure 11).

Figure 11. Konica Minolta produced 15,000 OLED panels to create tulips installed at a Japanese tulip festival in 2015. (Photo courtesy of Konica Minolta, http://www.oled-info.com/tags/companies/konica_minolta)

OLEDs are thin and lightweight in appearance, suitable for use in frameless or minimal-framing luminaires and configurations. They can be mounted near the ceiling, which gives them opportunities in low-ceiling applications (Figure 12) such as the Aurora Lighting Design, Inc. offices, where the maximum ceiling height was only 7 feet 5 inches. (This was documented in a 2016 DOE GATEWAY report.[1]) Similarly, the OLED panel is perfectly suited for an Americans with Disabilities Act compliant wall sconce because the sconce is limited to a 4-inch projection from the wall.

Figure 12. The offices of Aurora Lighting Design with a lighting system using OLED panels. (Photo courtesy of Acuity Brands Lighting)

The more common matte appearance of the OLED panel can be beautiful in some applications (like the appearance of sand-etched glass), but may appear dull to some. Without sparkle or highlights that come from small but intense sources or specular reflections, OLEDs can be attractive, but may not be visually exciting (Figure 13).

[1] DOE. 2016. *OLED Lighting in the Offices of Aurora Lighting Design, Inc.* Prepared by Pacific Northwest National Laboratory for the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy. Available at http://energy.gov/eere/ssl/downloads/oled-lighting-offices-aurora-lighting-design-inc.

Figure 13. Visa Lighting LIMIT™ pendant with matte finish panel, as illustrated in *Lumiblade Insider* magazine, Issue 1, 2016. Image courtesy Visa Lighting.

A shiny finish may have more visual appeal, but some observers may dislike the uneven color appearance from panel to panel, or within a single panel. Kaneka Corporation produces 80 or 100 mm squares with a shiny finish that exhibit some of the beauty and visual variability of polished glass. Panels with a shiny finish are visible in Figure 14.

Figure 14. Barkowleibinger.com, “WIND-MILL LUMINAIRE.” This image shows a variety of OLED panels from Kaneka. Those with the shiny finish are seen on the left. (© Ina Reinecke | Barkow Leibinger).

As of this writing, the flat OLED panel size dictates the product form factor, with configurations of square, rectangular, or round panels clustered in creative ways and geometries. Figure 15 shows a Visa Lighting pendant with three 100 x 100 mm OLED panels. It should be noted that similar shapes can be created with LED edge-lit panels, which are slightly thicker but exhibit higher efficacies.

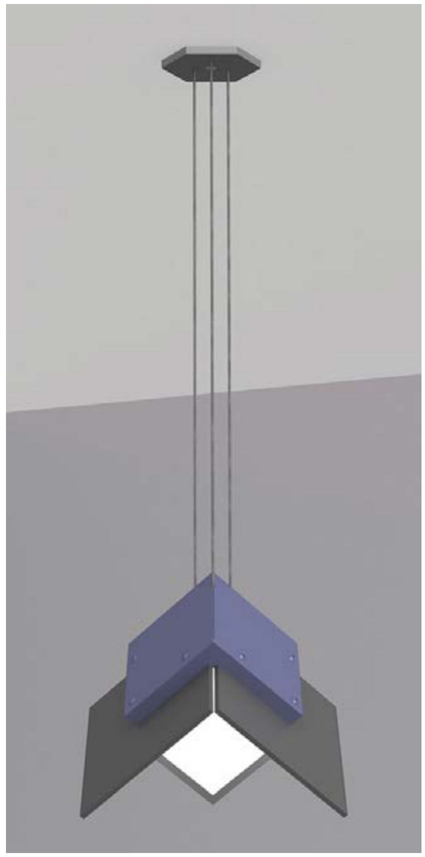

Figure 15. Visa Lighting's PETAL™ pendant using OLEDWorks panels. Image courtesy of Visa Lighting.

2.7.2 Panel Optics and Distribution Options

OLED panels produce a soft, almost spherical, light pattern, technically called a cosine distribution because the candela values, outlined by the circle of light emitted from the origin of the polar plot, can be described as the nadir intensity multiplied by the cosine of the angle from nadir.[1] The cosine distribution gives the panel the same luminance from all viewing angles (Figure 16). That luminance could create the perception of glare, especially when viewed from angles of 60º to 90º from the luminaire's nadir, unless the panel's luminance is held low.

[1] A cosine distribution is one where the intensity at 5° from nadir is the nadir intensity multiplied by the cosine of 5°, the intensity at 10° from nadir is the nadir intensity multiplied by the cosine of 10°, etc. This appears as a circle on a polar plot, drawn from the origin. By definition, the luminance of the evenly lit surface at any viewing angle below 90° is identical, and only small variations from this value are expected from field measurements.

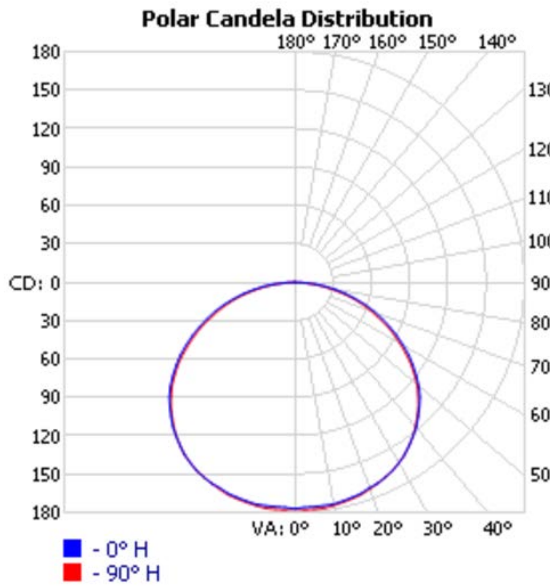

Figure 16. Typical polar plot of the photometric distribution from an eight-panel straight assembly of the Acuity TRILIA™ OLED lighting system. The blue and red lines represent the 0° and 90° measurement planes, and are nearly identical. (Source: Acuity Brands Winona Lighting, Test Report LTL25137)

The cosine distribution of light can be beneficial in that it produces relatively high vertical illuminances on walls and faces in a space, and reduces the sharpness of projected shadows from objects, very much like the effect from indirect lighting.

2.7.3 Direct Visual Comfort/Glare and Reflected Glare on Electronic Display Screens

Acuity Brands has established a threshold of 3000 cd/m^2 to limit direct disability and discomfort glare from exposed OLED panels in typical interior applications. This also reduces (but does not eliminate) screen reflections on computers, tablets, and cell phones, devices that are ubiquitous in modern culture. Luminances above 3000 cd/m^2 may cause perceptions of glare in luminaires where panels are exposed and are parallel to the ceiling, especially since the cosine distribution of light results in the same luminance at all downward viewing angles. So, while a recessed troffer, linear pendant, or recessed downlight can be optically designed to minimize glare by redirecting light emitted between 60° and 90° from nadir, the OLED panel to date has not been optically modified to control candelas emitted in those zones. Optics could be applied through microlenses, microlouvers, optical filters, or other techniques applied to the panel surface, but at this point these techniques reduce the efficacy of the panel.

2.7.4 Vertical Illuminance and Facial Modeling

Although light emitted near horizontal can be a source of glare, it offers some advantages. The cosine distribution from the OLED panel is good at delivering light at high angles (between 60° and 90°) with little glare as long as panel brightness is limited. Candela values at those angles can produce higher vertical illuminances on room surfaces and better lighting of faces than most recessed downlights. OLEDs can also produce higher ratios of face lighting-to-horizontal workplane illuminance (ratios such as 0.2 to

0.5), which may make faces appear more pleasant by softening harsh shadows from eyebrows and noses. This may help improve communication among office or classroom occupants[1], and can be critically important in video studios and conference spaces where cameras capture images for broadcast.

High vertical illuminances on walls can also be a great advantage in offices, classrooms, factories, retail spaces, and many other applications where the designer wants to create a feeling of spaciousness, make the space look more cheerful, or draw the eye to signage or artwork mounted on walls.[2] This can be accomplished with general lighting luminaires that emit at high angles, or with a separate set of luminaires designed to illuminate walls.

2.7.5 Lighting Uniformity and Lack of Shadows/Highlights

The cosine distribution produces an almost shadowless distribution of light, similar to the effect of indirect lighting reflected from a matte white ceiling. While a lack of shadows can be desirable, the soft distribution of light can also appear dull, much like the "cloudy-day effect" experienced in a space using only indirect lighting. Adding visual highlights through task lighting and accent lighting can visually enliven the space, giving the eye visual destinations and lending a visual hierarchy to task areas or artwork, for example. Although the OLED panels themselves draw the eye because they are among the brightest objects in the space, the photos in Figure 17 illustrate the liveliness a simple decorative table lamp and task lights added to the Aurora Lighting Design, Inc. offices.

[1] Zhou, Y and Boyce, P, 2001. *Evaluation of speech intelligibility under different lighting conditions,* Journal of the Illuminating Engineering Society, Vol. 30, Issue 1.
[2] IES DG-18-08. 2008. *Light + Design: A Guide to Designing Quality Lighting for People and Buildings*. Illuminating Engineering Society of North America, New York, NY, pp. 94-99.

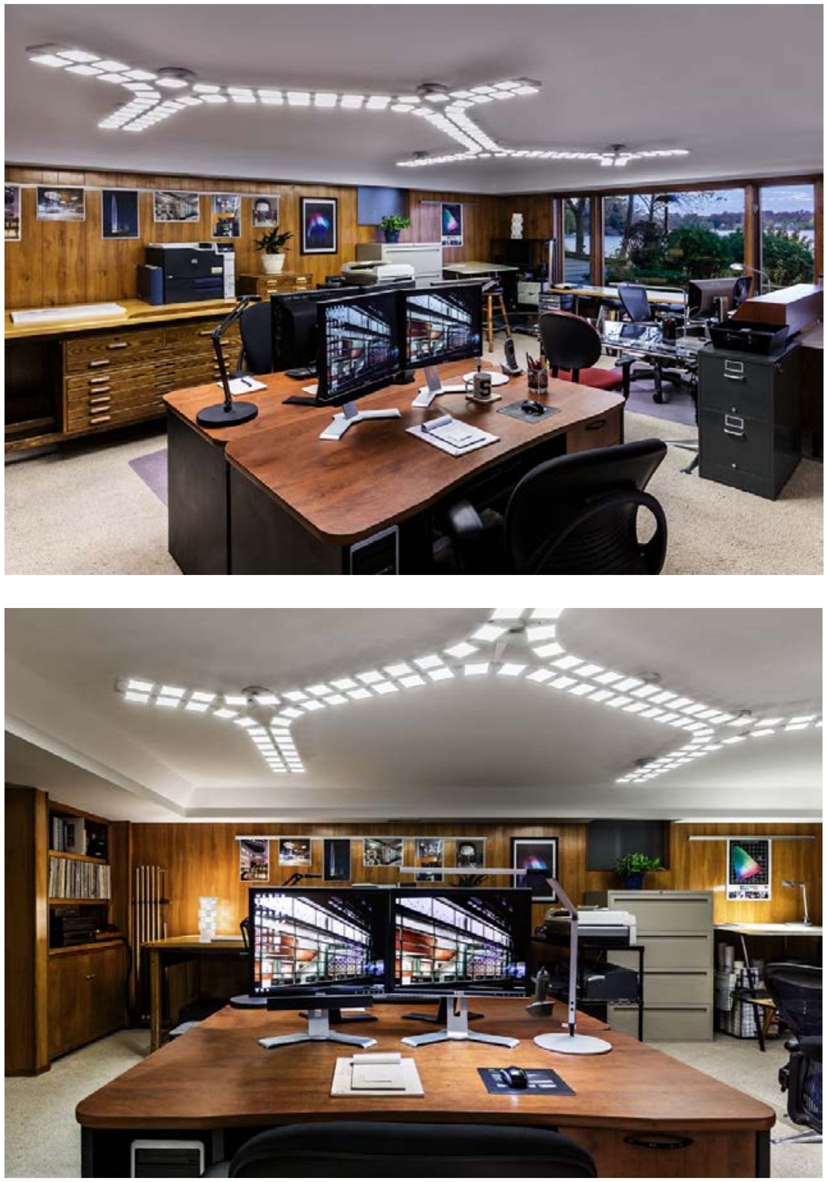

Figure 17. Aurora Lighting Design, Inc. offices with Acuity Brands Trilia™ System. The top photo illustrates the OLED lighting alone, the bottom photo shows visual interest from added task lights and a decorative table lamp. (Photos courtesy Acuity Brands)

2.7.6 Maintenance Issues (Life, Replacement, Connectors, Interoperability, Obsolescence)

Current life (L70) of OLED panels ranges from 10,000 hours to 100,000 hours depending upon the operating luminance of the panel. At the commonly specified luminance of 3,000 cd/m^2, 40,000 hours lifetime is typical. This corresponds to around 10 years of life if installed in commercial and educational spaces operating 4000 hours annually. However, high brightness panels (which may allow lower upfront costs and installation of fewer panels), such as the Brite FL300 OLEDWorks panel operated at maximum luminance (8,300 cd/m^2) offer a lifetime of just 10,000 hours or 2.5 years of use. This translates to a need to replace the panel in the all-too-near future, or else acknowledge that the lighting output will continue dropping over the years of operation.

Connectors for powering and mounting the panels are going to be a critical element, and their use raises several key questions. Are they delicate electronics connectors or robust devices that can withstand rough handling? Will the connectors be easy and obvious to plug in and out? Will replacement panels be available in the same light output, color, and appearance 2.5 to 10 years down the road, that operate on the same driver's electrical characteristics? Will the connectors be the same? Are there standardized panel units so that if a luminaire manufacturer discontinues the product there is a way to get a visually matching, electrically compatible panel from another manufacturer?

These are questions to which any facility manager or owner's representative will want answers before committing to OLED luminaires for a typical long-term commercial or institutional project.

2.7.7 Shipping and Installation Durability

OLED panels and connectors are less robust than most LED and fluorescent luminaires at this time. The CALiPER program experienced an OLED panel seal failure in shipping, even though the product was carefully packed in its original factory packaging. Because the panels are glass, they are more fragile and additional care is needed to avoid damage, especially since replacing a panel is usually not a straightforward task. This will improve with time, as luminaire manufacturers learn to design more resilient OLED luminaires and connectors.

2.7.8 OLED System Cost

This is the elephant in the room. OLED systems, manufactured in small quantities, are far more costly than fluorescent or LED luminaire equivalents, without the energy advantages that might balance the equation. Panel costs are dropping somewhat; dedicated OLED drivers are entering the lighting market. When OLEDs can be produced on flexible substrates, or printed continuously using a rolling process (called "roll-to-roll manufacturing"), or a similar mass-production method emerges, costs may decrease dramatically. Until then, economic viability is strained, especially compared to LED technology.

3.0 OLED's Competition

LEDs are OLED's chief competition. LEDs are a solid-state light source that has matured and miniaturized, with impressive efficacy gains. One capability of LEDs is edge-lighting of thin glass or acrylic panels and waveguides with linear arrays of small LEDs. These components can be incorporated into luminaires, similar to OLEDs, but with smaller, high-efficiency drivers that are more easily mounted in canopies and other mounting hardware. (One manufacturer of a 4 x 4 inch edge-lit LED panel claims 115 lm/W and 250 lm.[1]) Figure 18 shows two Blackjack Lighting products that began as concepts for OLED panels, but the product designer[2] found he could produce the same designs more efficiently and less expensively with edge-lit LED panels. (See one example in Figure 19.) With a small increase in panel

[1] Global Lighting Technologies, Inc. (n.d.). *New 4-in x 4-in LED-Based Light Guide from GLT*. Available at http://www.glthome.com/oled/.
[2] Interview with Stephen Blackman, Blackjack Lighting by Naomi Miller, PNNL, October 22, 2015

thickness, he was able to overcome OLED issues of insufficient brightness, fussy connectors, fragility of the glass panel, limited optical options, low efficacy, unimpressive life, and high cost.

The designer pointed out an additional complication of OLED panels: It is impossible to tell if a panel is damaged or the seal is compromised until oxidation degrades the pixels. The panel can be on the job site and operating for a short time before the degradation is noticed.

However, the main problem is that luminaire manufacturers rarely ship lighting products with glass attached. For example, few luminaires are shipped with glass lamp(s) or glass diffusers already installed. Rather, the lamps and diffusers are packaged separately and the contractor or end user puts them together on the job site. Since many OLEDs today are made with glass panels, there is a risk of breakage when shipped as an integral part of the luminaire. This breakage could lead to a rupture in the seal, or actual visual breakage of the glass surface.

Edge-lit LED panels using acrylic light guides and acrylic diffusers can be shipped permanently attached inside the luminaire.

Figure 18. Two decorative pendants using edge-lit LED panels instead of OLEDs. (Photo courtesy Blackjack Lighting)

MicroLEDs are a flat panel display technology using microscopic LEDs for each pixel. MicroLEDs may soon compete with OLEDs because these panels can simulate the appearance of the OLED with the promise of thin, light, direct LED panels that can change color more easily and inexpensively than current OLED panels.

Figure 19. Edge-lit LED panel that is 0.31 inches thick. (www.knema.com)

4.0 Applications and Opportunities

At this time, OLEDs are most viable for indoor applications because they are susceptible to degradation from air and moisture outdoors. They are a tempting element for use in decorative luminaires and architectural surfaces, and many creative designs have been demonstrated in concept luminaires. Engineering those concepts into high-volume interior products is slow to occur because of the high cost of the end product.

Outdoor lighting is a challenge because OLEDs are susceptible to damage from excessive exposure to ultraviolet radiation, but it may be the "killer app" for OLEDs. Pedestrian-friendly lighting is small in scale and low in glare, producing soft-edged gradients of pathway illuminance. The soft light emitted by the OLED panels may produce the needed lumens with minimal objectionable glare. The OLED's warm light color may be suited to neighborhoods seeking traditional warm-color light. Because OLEDs are susceptible to air and water infiltration, the panels can't be exposed to the elements, but they could be used in a fixture gasketed to keep contaminants out. There is also an opportunity to use photovoltaic panels on the roof of the luminaire to produce power for the light, so that it need not be connected to the electric grid. There is even a possibility of using one panel to collect solar energy during the day and emit it from the same panel at night.[1]

When roll-to-roll manufacturing is perfected for OLEDs, the options for glowing clothing, creative signage, vehicle bodies, light-emitting roll-up window shades, retail backlighting, wallpaper, and more will explode.

OLEDs hold great potential for architectural lighting, but not for all applications. Here are a few suggestions offered by a panel of lighting designers at the OLED Summit in 2015.

- **Combine LEDs and OLEDs** in lighting systems, so that the LEDs do directional lighting work and the OLEDs do the diffuse work. (Achieving a close color match between the two sources may be challenging.)

[1] http://energy.gov/eere/buildings/downloads/outdoor-oled-luminaire-using-solar-energy-lighting-pedestrian-areas

- Use OLED panels like **ceramic tiles**, used as durable wall covering, but with digital control to create changing patterns, subtle luminance changes, or decorative elements that also contribute to ambient light levels. A shallow, electrified frame would allow tiles to be popped in and out of a matrix, making an electrical connection as it snaps in, so it would be easy to install and rearrange the tiles as desired.
- Use OLED panels as large, **low-luminance surfaces**. An upper band on walls at the ceiling line could be a **functional decorative architectural element**.
- Use OLED panels as **luminous ceiling panels**, suspending 2 x 2 foot, 4 x 4 foot, 4 x 8 foot, or larger panels at different planes below the ceiling. At low luminances, these OLED planes would deliver pleasant light without visual discomfort or significant reflected glare in display screens.
- Use OLEDs as **shelf lighting**. OLED panels and the retail display shelf could be manufactured as a single unit, either for uplighting translucent merchandise (think champagne glasses) or downlighting expensive leather goods. The OLED panel could also be used to backlight objects on a shelf, or be a plane of light mounted in niches or lightboxes in retail, residential, or museum applications. The wire harness could be integrated into the shelving stanchions, offering flexibility for the retailer or display director.
- Use OLEDs as **marker lights** for aircraft cabins, paths of egress in buildings, decorative markings for corporate logos, and similar purposes.
- If roll-to-roll manufacturing of OLEDs becomes a reality, use OLEDs as **lighted laminates**. Imagine dining room table tops or bar counters that glow gently (rather like a cocktail lounge on a space ship of the future illustrated in Figure 20). The question here will be: Can the OLEDs be field-cuttable for custom applications?

Figure 20. Starships and futuristic cultures seem to favor lounges with glowing table tops. (Illustration: PNNL.)

- Use **OLEDs as linear recessed or surface-mounted luminaires with little-to-no recess depth.** This is a possibility as long as drivers can be miniaturized or easily concealed, and if optical films are available to modify the normal cosine light distribution for wallwashing, narrow beams, batwing distributions, and other lighting effects.
- Create **shape-changing panels or luminaires** using flexible OLEDs controlled by servomotors. These would offer a creative medium, especially when curved or folded shapes are possible.
- Develop **color-changing OLED panels tunable to deliver the desired CCT.** Architectural lighting OLED panels with user-selectable CCTs would not only allow color selection according to the application and time of day, it would also reduce the number of SKUs manufacturers would need to stock.
- Apply OLEDs as a **lighted wrap for architectural elements**: columns, walls, beams, facades.
- Locate OLEDs as **luminaires mounted in front of windows on clear substrates** that simulate daytime light direction even when the sun has gone down.
- Consider OLEDs as **off-grid lighting solutions** for developing countries.

5.0 Market Hurdles

There is a very limited offering of OLED products on the U.S. luminaire market today. The following list describes why this technology has not yet been widely adopted, and provides a reminder to manufacturers and specifiers of the enormous opportunities available if these issues can be resolved.

- Too expensive to use for shelf lighting, undercabinet lighting, or routine office and classroom lighting. The cost is acceptable only when it combines decorative appeal with lighting performance, or when owners want to show that they are using cutting-edge technologies
- Too low in luminance to use as a “workhorse” light source, since that necessitates large surface areas, which in turn become uneconomical
- Too poor in efficacy to use as a light engine, so the OLED panel has to be an exposed light source in order to maximize luminaire efficacy
- Clunky remote drivers, too large to be integrated into the sleek OLED luminaire designs
- Lack of interchangeability of panels and drivers among OLED manufacturers
- Panels are somewhat delicate to replace because of static electricity and connectors
- Lack of standardization of panels/connectors/drivers and testing standards for life and lumen maintenance
- Many drivers not optimized for OLED systems
- Chicken and egg problem: Designers don’t want to specify OLEDs because there are limited products on the market that are competitive with fluorescent or LED system performance; manufacturers don’t want to make OLED luminaires that won’t sell because designers aren’t specifying them

A market exists for delicate, custom, decorative luminaires using OLED panels, but the demand will likely continue to be low. Many specifiers currently perceive OLEDs not as practical luminaires but as elements in a feature work of art, so there is an impasse between designer perceptions and OLED industry aims. However, these decorative luminaires are helping introduce OLEDs to the world of architectural lighting.

6.0 Summary

The early years of LED lighting were fraught with difficulties: low output, rapid light decay, miserable color, short life, driver failures, flicker, clumsy connectors, no standards, etc. OLEDs are struggling through a similar set of difficulties, but OLED manufacturers have the advantage of having watched and learned from the LED industry working through these problems. OLED systems are increasing in efficacy, but they are not yet within the range of cost, energy performance and high color quality, dimming performance, optical performance, and parts standardization that would make OLEDs a viable and desired product. With rapid advances in these areas, this technology could become the complementary solid-state counterpart to LEDs.

OLED panel efficacies are disappointingly low for architectural applications, restricting their use to decorative elements rather than the principal light sources in a building, because their energy performance is still half or less of the equivalent fluorescent or LED lighting system, and the pressure to meet energy codes in the architectural market is so high. On the other hand, OLED color characteristics are superior to those of early LEDs. With further efforts to improve red saturation and overall gamut, OLEDs could meet color quality needs even for demanding hospitality interior spaces.

Panel efficacy is only one part of the story of OLED systems. One frustration of luminaire manufacturers is that there is only one dedicated OLED driver on the market at the time of this writing, because driver manufacturers do not see a growing potential OLED luminaire market. Instead, manufacturers have had to work with LED drivers, customizing them as best they can to deliver the current and voltages needed, often outside the optimized efficiency range of the driver. Consequently, the driver is a weak point in the system efficacy.

The OLED panels themselves are thin, light, and deliver a unique quality of light. However, the drivers are still relatively large and brick-like. They do not fit gracefully into the OLED luminaires or mounting canopies, so they must be mounted remotely. That poses extra work for the designer and contractor to find an accessible location hidden from normal view, where drivers (and in some cases, transformers) can be located in compliance with the electrical code. For OLEDs to fulfill their promise, driver elements will need to be integrated sleekly and discreetly into the luminaire or mounting elements.

Electronic circuit design for drivers needs to evolve to minimize flicker for health and human productivity, and energy efficiency gains. Manufacturers and specifiers also need to be aware of power increases as panels age, so that efficacy, building circuit loads, and building lumen power density values are accurately reported and anticipated.

Economies of scale are needed to reduce the cost of manufacturing OLED panels, but the costs are currently too high to achieve the widespread adoption, which would incentivize investment in higher-capacity manufacturing.

For full viability of OLED architectural lighting, the systems will need to deliver higher efficacy, better system components, and lower costs. OLEDs are in their infancy compared to LEDs, but the architectural market is taking notice of a lighting product with an entirely different look and function. The potential for applying OLEDs as a luminous and dynamic building material is exciting, and if OLEDs increase in efficacy, longevity, size, and flexibility, they will give designers and engineers a new tool for creative and effective lighting.

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