U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Solid-State Lighting R&D Plan

June 2016

Prepared for:

Solid-State Lighting Program
Building Technologies Office
Office of Energy Efficiency and Renewable Energy
U.S. Department of Energy

DOE/EE-1418

[This page has intentionally been left blank.]

DOE SSL Program, "R&D Plan," edited by James Brodrick, Ph.D.

Contributors

Norman Bardsley	Bardsley Consulting
Monica Hansen	LED Lighting Advisors
Lisa Pattison	SSLS, Inc.
Morgan Pattison	SSLS, Inc.
Kelsey Stober	Navigant Consulting, Inc.
Victor Taylor	Navigant Consulting, Inc.
Jeffrey Tsao	Sandia National Laboratories
Mary Yamada	Navigant Consulting, Inc.

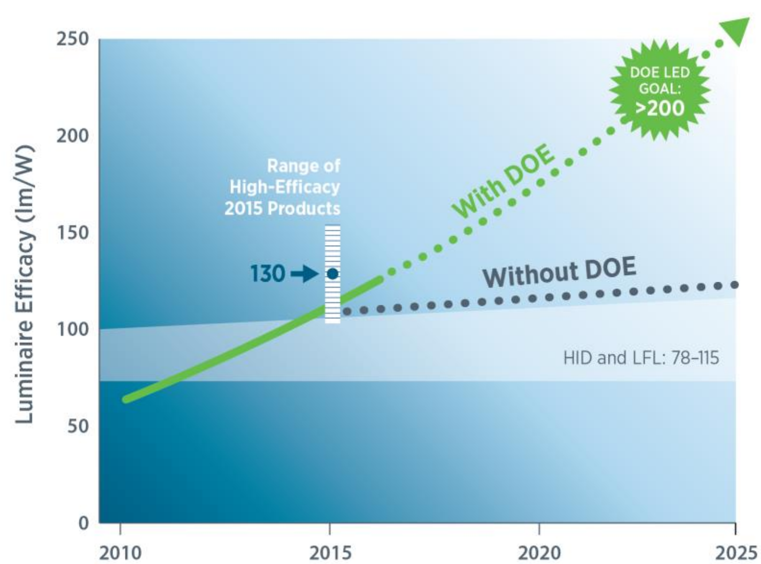
[This page has intentionally been left blank.]

Executive Summary

The solid-state lighting (SSL) revolution embodies a profound shift in how we use and consider lighting, and represents a huge opportunity to generate significant energy savings. The energy being used for lighting represents a significant portion of global energy use. Rising electricity prices, mounting concerns about climate change, and desire for energy independence are causing the global lighting market to shift toward more energy-efficient light sources.

In most regions of the world, even with government policy support, less than 10% of existing lighting installations use SSL products. For example, the Department of Energy (DOE) estimates that in 2015, light-emitting diode (LED)-based lamps comprised just 6.4% of the U.S. installed base [1]. Nevertheless, most forecasts project extraordinary growth of SSL technology over the next 5 to 10 years with SSL becoming the dominant lighting technology in terms of sales, total amount of light generated, and installed units. These are dramatic growth projections for a large market and present significant challenges for the industry. Remaining challenges include ongoing efficiency improvement, continued price reduction, manufacturing scale-up, effective building integration and installation, and incorporation of new value and features that can accelerate adoption and provide further energy savings, such as controls and connectivity. Addressing these challenges also offers the United States the opportunity to secure a dominant role in the technology and manufacturing of these products.

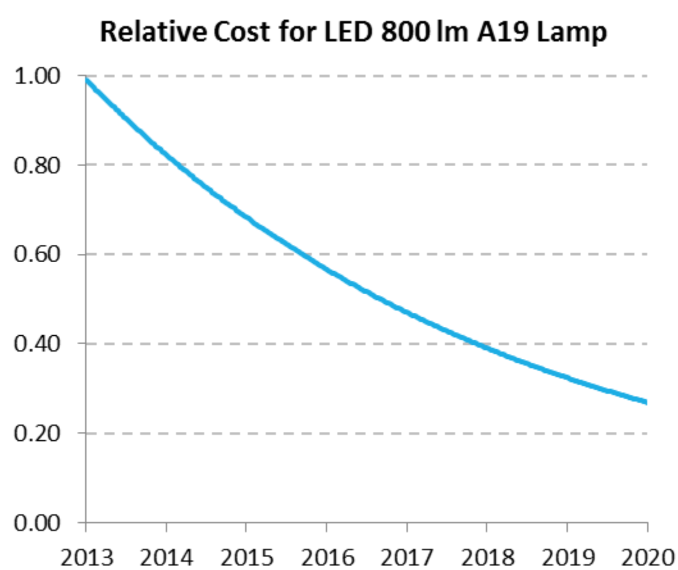
In the United States, LED lighting is forecasted to account for the majority of installations by 2030, representing 88% of the lumen-hours produced by general illumination [2]. The high efficacy of SSL sources is a critical factor in the drive for higher adoption. LED lighting already can be more efficient than all incumbent technologies, but there is still room to improve. Using fairly conservative projections for performance improvements, DOE has determined that by 2030, LED technology can potentially save 261 terawatt-hours (TWh) annually, a 40% reduction of the site electricity consumption forecasted for a "no-LED" scenario. Assuming the more aggressive projections, outlined in this report, can be realized through continuing investment in R&D, the total annual savings would increase to 395 TWh by 2030, a 60% reduction of the site electricity consumption [2]. This electricity savings corresponds to about 4.5 quads of primary source energy, which is nearly twice the projected electricity generation of wind power and 20 times that of solar power in 2030. At an average commercial price of $0.10/kilowatt-hour, this would correspond to an annual dollar savings of about $40 billion [2]. However, in order to reach the performance levels



assumed in this analysis, substantial, continued improvements to efficacy and pricing are necessary. This underscores the importance of SSL and SSL R&D in any discussion of energy policy, due to its unprecedented opportunity to reduce energy consumption, thereby improving domestic energy security, reducing greenhouse gas emissions, and saving money on electricity.

The DOE SSL Program has set aggressive targets and has fashioned its program to remove technology barriers and accelerate adoption. DOE support is essential to achieving the greater than 200 lumens per watt (lm/W) luminaire efficacy program goal by 2025, reducing SSL manufacturing costs, and realizing huge energy savings. To achieve these goals and maintain the pace of development of the underlying LED and organic light-emitting diode (OLED) device technologies, DOE advocates continued focus on R&D. Improvements in LED package efficacy are becoming harder to achieve, and R&D is required to address fundamental technological barriers such as current efficiency droop, the efficiency gap of green LEDs, and the need to develop new high-efficiency, narrow linewidth down-converter materials.

Still, SSL offers so much more than just improved efficacy. It represents a huge opportunity to improve the performance and value of lighting through enhanced controllability, new functionality, application specific lighting performance, novel form factors, and targeted improved well-being and productivity. SSL sources are inherently dimmable and instantaneously controllable; they can be readily integrated with sensor and control systems, thus enabling further energy savings through the use of occupancy sensing, daylight harvesting, and local control of light levels. SSL is at the heart of recent innovation in the lighting industry with respect to smart, connected, intelligent, and adaptive lighting. New functionality within the lighting system can add value by providing optimal lighting for the occupants and the tasks being performed through real-time controls, programmed sensor-driven responses, or learning algorithms. The high speed modulation capability of semiconductor light sources has introduced new opportunities and features such as indoor positioning capabilities. SSL offers the prospect of full color control over the light spectrum and will enable precise control over the delivery of light to reduce glare, reduce stray light, and optimize useful light. SSL affords new levels of control to create new lighting opportunities in areas as diverse as horticulture and human health.



Most LED lighting technology to date has been engineered to address the near term market opportunities in the form of replacement lamps and retrofit luminaires. With an estimated 50 billion sockets in the world, these form factors clearly represent an enormous market and energy savings opportunity, but moving beyond these form factors will expand the concept of lighting and create entirely new lighting paradigms. Similarly, OLEDs offer a whole new approach to lighting based on their low luminance, thin profile, and potential for surface shaping.

Inevitably, the discussion of SSL often focuses on first cost as one of the main barriers to adoption. Excellent progress has been made over the past year for LED lighting products. LED package prices are down to $1/kilolumen (klm) and the LED-based dimmable A19 60 W-equivalent replacement lamp has dropped below $8 ($10/klm). While this is still more expensive than conventional incandescent or compact fluorescent lamps (CFLs), rebates and incentives have and can further reduce the price to below $5. It is expected that SSL products will remain more expensive than conventional lighting on a first-cost basis for some time, but higher operating efficiency and longer operating lifetime (reduced maintenance and replacement costs) ensure that LED lighting is already highly competitive on a total cost of ownership (TCO) basis in many lighting applications; payback periods of less than 2 years in certain high-usage applications. Additionally, with the ability to provide new value-added functionality, price parity is no longer as important for consumer adoption.

OLED pricing has been static over the last year, with a shortage of new panels and products being released. The rapid advancement of LED technology has created a moving target for OLED products in terms of lighting performance and pricing. Still, OLED manufacturers are optimistic that with a few key breakthroughs, including advancements in light extraction and manufacturing yield, OLEDs will offer a value proposition complementary with LED lighting approaches.

The DOE SSL Program has developed a comprehensive R&D strategy to support advancements in both LED and OLED technology and maximize energy savings. This document, the DOE SSL R&D Plan (hereafter referred to as the R&D Plan), is a consolidation of the DOE SSL Multi-Year Program Plan (MYPP) and the DOE SSL Manufacturing R&D Roadmap. The R&D Plan is developed in conjunction with community experts through inputs received at roundtable meetings held in September and October 2015 and at the DOE SSL R&D Workshop, held in February 2016 in Raleigh, NC. The plan reflects SSL stakeholder inputs on key R&D topics that will improve efficacy, reduce cost, remove barriers to adoption, and add value of SSL solutions over the next 3 to 5 years. The discussions covered R&D needs for LED and OLED technologies, ranging from core technology research and product development, through manufacturing R&D. However, once R&D topics have been identified, there is no guarantee that suitable R&D approaches will be submitted to address the topics.

The key challenges identified during the Roundtable and Workshop discussions are as follows:

LED-Based Lighting R&D Priorities

- **Emitter materials:** addressing current density and thermal droop, green and red efficiency, and red thermal stability.
- **Down-converter materials:** developing efficient, stable, and narrow linewidth materials.
- **Physiological responses to light:** understanding human, animal, and plant responses to light that enable development of lighting products to improve well-being, increase productivity, and minimize negative impacts of artificial lighting while also saving energy in the application.
- **Encapsulation materials:** targeting approaches that improve LED package efficiency and extended operating ranges in terms of temperature and light output.
- **Power supplies:** developing efficient and robust power supplies with peak efficiency and minimized flicker across the operating range of the luminaire, as well as enabling increased functionality of the luminaire.
- **Advanced luminaires:** developing luminaire concepts to increase efficacy and add value for specific lighting applications.
- **Flexible Luminaire Manufacturing:** developing manufacturing approaches to simplify manufacturing for a broader range of luminaire products

OLED-Based Lighting R&D Priorities

- **Materials research:** targeting emitter systems (i.e., emitters, hosts, transport materials) designed to simultaneously achieve long lifetimes and high efficacy, particularly for blue emitters where performance is lagging.
- **Light extraction:** focusing on cost-effective manufacturable solutions that will allow for substantial improvements in panel efficiency by extracting light trapped in organic/anode wave-guided modes and/or reducing surface plasmonic losses. The ability to control the distribution of the emitted light would be an additional benefit.
- **Luminaire development:** accelerating the marketability of OLED lighting through product differentiation, integrability, ease of installation, or other attributes promoting the appeal and implementation of OLED lighting.
- **Improved manufacturing technologies:** improving yield and reliability.
- **Manufacturing on flexible substrates:** pursuing the advancement of processes and materials required for the production of conformable/flexible OLED lighting, possibly through the use of roll-to-roll (R2R) manufacturing.

Table of Contents

TABLE OF FIGURES

LIST OF TABLES

[This page has intentionally been left blank.]

1.0 Introduction

The Department of Energy (DOE) Solid-State Lighting (SSL) Program was created in response to Section 912 of the Energy Policy Act of 2005 which directs DOE to *"Support research, development, demonstration, and commercial application activities related to advanced solid-state lighting technologies based on white light-emitting diodes."* The DOE SSL Program has developed a comprehensive Research and Development (R&D) strategy to support advancements in SSL technology and maximize energy savings. The specific goal of the R&D Program is:

By 2025, develop advanced solid-state lighting technologies that, compared to conventional lighting technologies, are much more energy efficient, longer lasting, and cost-competitive by targeting a product system efficiency of 50% with lighting that closely reproduces the visible portions of the sunlight spectrum.

In order to maximize energy savings, the DOE SSL Program supports multiple thrusts of R&D:

- Core Technology Research – Applied research encompassing scientific efforts that focus on new knowledge or understanding of the subject under study, with specific application to SSL. Core technology research aims to demonstrate scientific principles, technical application, and application benefits.
- Product Development – The development of commercially viable, state-of-the-art SSL materials, devices, or luminaires using concepts from basic and applied research.
- Manufacturing R&D – Research to develop advanced manufacturing approaches to reduce cost of SSL sources and luminaires and improve product consistency and quality, with the additional benefit of supporting the development of U.S.-based manufacturing.
- Applied Technology R&D – This work monitors SSL technology advances, provides field and laboratory evaluations, and works to eliminate barriers to adoption of emerging products and systems.

This document, the DOE SSL R&D Plan (hereafter referred to as the R&D Plan), is updated annually and is a consolidation of the DOE SSL Multi-Year Program Plan (MYPP) and the DOE SSL Manufacturing R&D Roadmap that DOE published prior to 2015.[a] The DOE SSL R&D Plan provides analysis and direction for ongoing R&D activities to advance SSL technology and increase energy savings.

The DOE SSL R&D Plan annual updates reflect ongoing progress toward DOE SSL goals and the shifting R&D priorities that will have the biggest impact on achieving the program goals. The appendices contained herein provide basic material on light-emitting diode (LED) and organic light-emitting diode (OLED) products, a glossary of acronyms used in this document, and background information on the DOE

---

[a] Previous documents are available at: http://energy.gov/eere/ssl/technology-roadmaps

SSL Program. Details on the legislation and policies defining the program are not included in this document, but may be found on the SSL website at www.ssl.energy.gov/about.html and energy.gov/eere/ssl/partnerships.

2.0 Impacts of Solid-State Lighting

SSL offers a huge opportunity to improve the efficiency, performance, and value of lighting and to create new applications and benefits. The initial motivations for the pursuit of LED and OLED SSL were the promise of high-source efficacy and the prospects of low-cost manufacturing. Industry experts held that low costs could be achieved through the adoption of high-volume processing technologies from the semiconductor industry for LEDs, and the adoption of roll-to-roll (R2R) processing technologies for OLEDs. While there is still considerable room for improvement, SSL is starting to fulfill these promises as it continues to demonstrate improved efficacy over conventional lighting sources, low prices that enable a payback within reasonable time periods, and a reduced TCO. These attributes have contributed to increased adoption of SSL, already resulting in significant energy savings. In addition to improved source efficacy, SSL can be more effective in delivering light when and where it is needed, representing an additional level of energy savings. As SSL technology has developed, it has become clear that the impacts of SSL will go far beyond energy savings alone. SSL also has the potential to have profound beneficial impacts on the environment, horticulture, livestock production, transportation safety, human health, and productivity. All of these benefits can be realized while saving significant amounts of energy compared to conventional lighting technologies.

LED and OLED lighting can be engineered to have spectral power distributions that match specific applications, or are actively controllable such that the spectrum of the emitted light can be dynamically changed. For example, recent research has shown that humans have a physiological response to changes in the spectrum of sunlight through the course of a day, and this changing spectrum can now be replicated with LED-based interior lighting [3]. Using static spectra, lighting products can be engineered to enhance visibility or color contrast, and highlight specific colors or types of products (e.g., Lumileds CrispWhite Technology is marketed as “revealing the richest whites, vibrant reds and colors that pop”) [4]. They can also be engineered to enhance production or even the nutritional value of specific types of crops [5].

While SSL holds the promise of energy savings and more, continued R&D is required to fully realize these promises. Key benefits of SSL will be discussed in the following sections.

2.1 Source Efficacy and Energy Savings

With efficacies of certain products nearing 150 lumens per watt (lm/W), LED luminaires can be more efficient than incandescent lamps, halogen lamps, compact fluorescent lamps (CFLs), linear fluorescent luminaires, and high intensity discharge (HID) sources. However, often consumers opt for lower cost, lower efficacy products over the higher priced, top-of the-line products. Table 2.1 shows a comparison between the price and performance of SSL products typically purchased during 2015 and the best-in-class conventional lighting technologies with which they are competing. The table shows that LED products are already as efficient as, or more efficient than, most incumbent technologies, but still have higher purchase prices.

Table 2.1 Typical 2015 Price and Performance of SSL Compared to Best-in-Class Conventional Lighting Technologies

2015 Product Type	Luminous Efficacy (lm/W)	Correlated Color Temperature (CCT) (K)	Usable Life[1] (hours)	Price ($/klm)
LED A19 Lamp (Dimmable, Warm White)[2]	78	2700	25,000	$10
LED PAR38 Lamp (Warm White)[2]	70	3000	28,000	$19
LED T8 Tube (Neutral White)[2]	107	4100	50,000	$10
LED 6" Downlight (Warm White)[2]	64	3000	40,000	$29
LED Troffer 2' x 4' (Warm White)[2]	94	3500	56,000	$29
LED High/Low-Bay Fixture (Warm White)[2]	102	4000	90,000	$23
LED Street Light[2]	96	5000	50,000	$49
OLED Luminaire[3]	43	3000	40,000	$870
HID (High Watt) System[4]	115	3100	15,000	$3
Linear Fluorescent System[4]	108	4100	25,000	$4
HID (Low Watt) System[4]	104	3000	15,000	$4
CFL A19 Replacement	70	2700	12,000	$2
CFL (Dimmable) A19 Replacement	70	2700	12,000	$10
Halogen A19	20	2750	8,400	$2.50
Incandescent A19	15	2760	1,000	$0.63

Notes:

1. For non-SSL technologies, the lifetime values mark the end of life of the product due to failure. Because LEDs undergo gradual lumen depreciation in addition to catastrophic failure, L_{70} values, the time at which products produce 70% of initial light level, are given to define the useful lifetime of the LED and OLED Products **[6]**.
2. Lawrence Berkeley National Laboratory (LBNL) conducted a consumer survey finding that more than 80% of respondents purchased a lamp at or below the 25th percentile price, and more than 90% purchased at or below the median price. From the survey, LBNL concluded that the mean and median are volatile metrics that represent the tail of the purchase distribution and that the 25th percentile of their web-scraped data best represents the characteristic price for LED lamps **[7]**. Based on this assessment, the 25th percentile was used to characterize the typical purchase price for LEDs, and the average efficacy, CCT, and lifetime were found for products matching this price point.
3. Based on Acuity Brands Luminaires' *Chalina 5-Panel Brushed Nickel OLED Pendant* available from Home Depot April 2016 **[8]**.
4. Includes ballast losses.

There is significant room for improvement in terms of performance and price for LED-based SSL products. The analysis in Section 5.1 shows that 255 lm/W is an achievable performance target for LED packages; excellent progress toward this target has been demonstrated in the laboratory and in commercial LED packages. Figure 2.1 suggests that LED luminaires will offer improvements of up to 100 lm/W over the best efficacies possible for incumbent technologies. Figure 2.1 also shows that the current best LED products have good efficacy, but many products from the DOE LED Lighting Facts® database offer lower efficacy with minimal benefit over incumbent technologies. The findings from the Lighting Facts® database show how LED lighting manufacturers can choose to trade efficacy for cost, lifetime, color quality, light distribution, and other performance attributes. OLED technology is still in its infancy but promises high efficacy and low cost, as well as new options for form factor and light distribution. Section 6.1 analyzes how OLED technology could reach 190 lm/W while offering a low-brightness and low-glare light source.

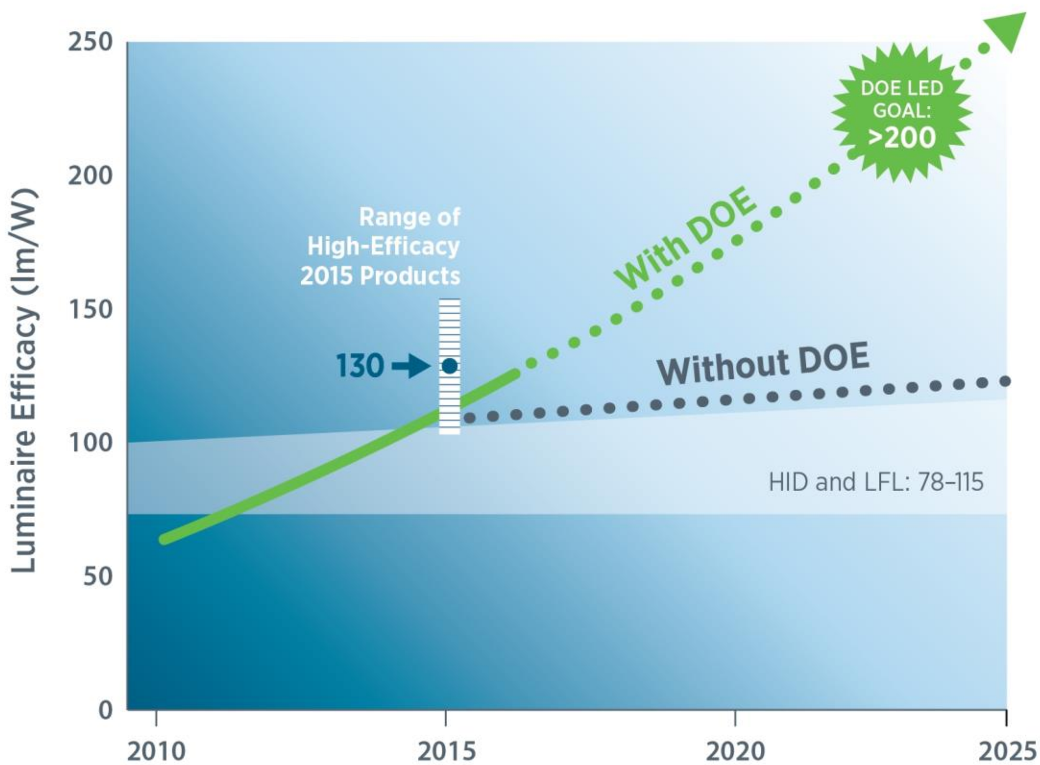


Figure 2.1 Comparison of LED and Incumbent Light Source Efficacies
Source: LED Lighting Facts® Product Database

2.2 Light Utilization

Lamp and luminaire efficacy are important indicators of the energy efficiency of a lighting system, but they do not tell the whole story. The full efficiency of a luminaire is also affected by light utilization, which represents how well the light generated from the luminaire reaches the target application and provides suitable illumination. Two metrics are helpful in comparing light utilization among products for a specific application: application efficacy and utilization efficiency.

Application efficacy indicates the power draw necessary to achieve the specified illuminance criteria at the target area [9]. Utilization efficiency is defined as the ratio of the net light flux reaching the working surface to the total light flux developed by the lamps in the system [10]. For any lighting application, using less light to achieve the required illuminance levels represents an improvement in light utilization. If a luminaire directs a greater percentage of light to the target area, it can provide the required illuminance with less energy. This is especially important given that the characteristics of SSL enable new form factors that may lead to better light utilization, and therefore to additional energy savings beyond improved source efficacy. For example, the small source size of LEDs can enable improved optical control and directionality; conversely the large source size of OLEDs in conjunction with low brightness and low glare can enable their use very close to the task area. Maximizing light utilization for both LED and OLED sources will require a move beyond legacy form factors such as the light bulb and the recessed luminaire, toward form factors that maximize application efficiency as well as optical, electrical, and thermal efficiency.

New LED outdoor area lights have demonstrated the ability to provide suitable illuminance levels using significantly lower total light output than the conventional lighting products they have replaced. This is accomplished through improved light distribution that reduces over-lighting the target area, improves illuminance uniformity, and produces less wasted light falling outside the target area. Figure 2.2 demonstrates a specific example of improved light utilization of LED-based outdoor lighting fixtures. In this example, a parking lot lighting retrofit using Cree LED-based fixtures demonstrated a 66% reduction in energy usage compared with HID fixtures due to improved efficiency and reduced total light generation. In addition, significantly more of the parking lot area is illuminated, which is particularly advantageous for both driver and pedestrian safety.

Figure 2.2 Cree Edge Area Square, Edgewater Marketplace, Edgewater, CO
Source: John Edmond, Cree Inc., SSL R&D Workshop, San Francisco, CA, January 2015 [11]

Effective light utilization is especially important to the value proposition for OLEDs and low brightness planar LED solutions; the low brightness and diffuse nature of these sources enables them to be used very close to the task area without generating excessive glare, enabling adequate illumination using less light, or conversely, more illumination without unacceptable glare. Figure 2.3 shows two examples of SSL desk lamps sold by Workrite Ergonomics, one LED and one OLED, that deliver nearly identical brightness (106 and 108 footcandles respectively) at the center of the incident task area. However, the Natural OLED desk lamp delivers its 442 lumens over a larger area, whereas the Astra 2.0's 306 lumens are much more concentrated [12, 13].

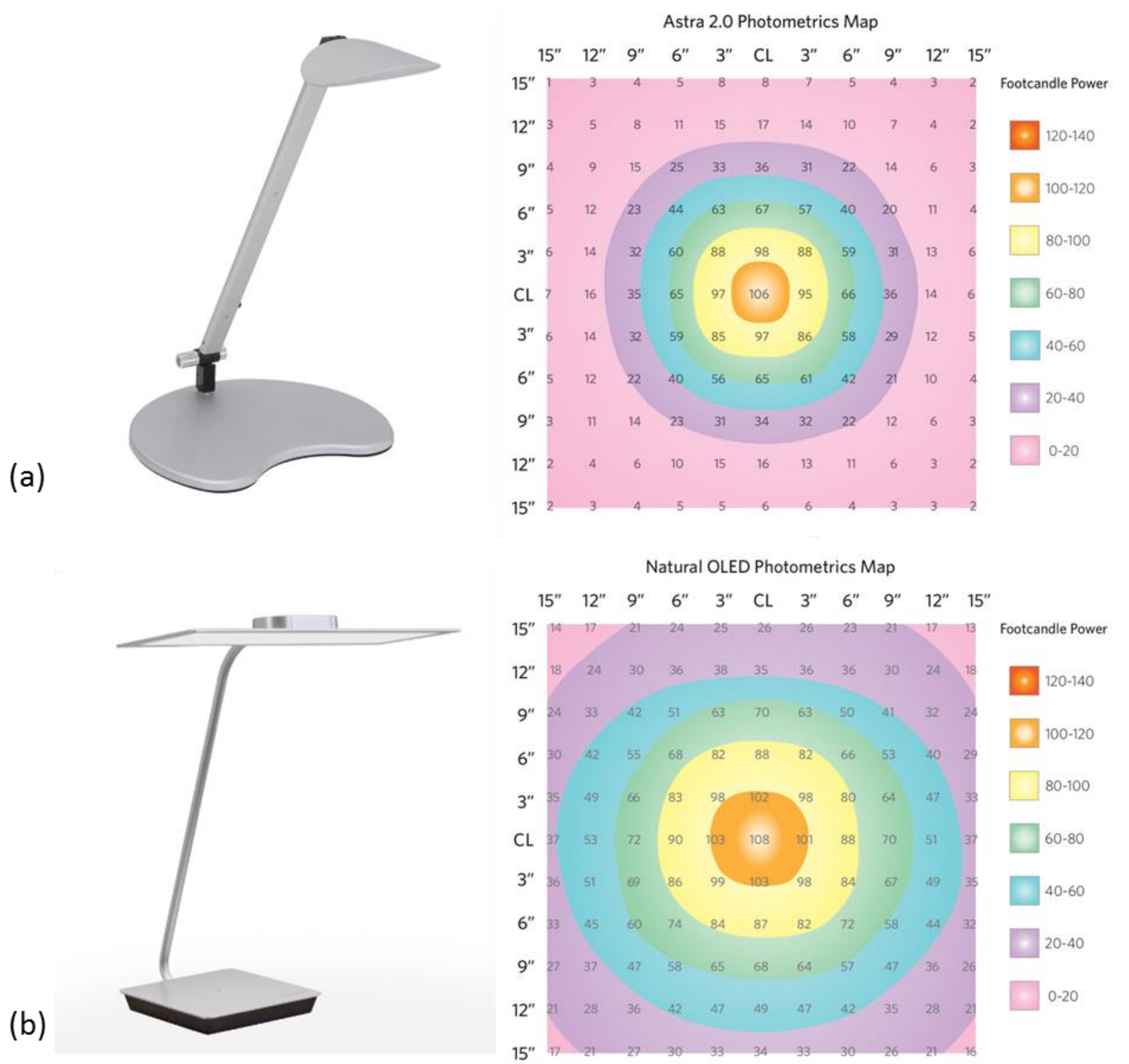


Figure 2.3 Distribution Comparison of Workrite Ergonomics' (a) Astra 2.0 Single Arm (LED) Desk Light and (b) Natural OLED Desk Light

Source: Workrite Ergonomics Website, May 2016 [12, 13]

New form factors, building integration approaches, and lighting layout concepts will further improve light utilization as the design and application possibilities for these lighting technologies are fully explored. Another aspect of light utilization is the use of controls that minimize the power consumption of the light source without affecting the lighting application. LED and OLED sources are inherently controllable (i.e., dimmable and instant on/off), which makes them compatible with the full range of lighting controls. Controls will be discussed further in Section 4.1.

2.3 Improved Lighting Performance and Design

Most LED lighting technologies have been engineered to address nearer term market opportunities in the form of replacement lamps and retrofit luminaires. There are approximately 50 billion sockets in the world, so these form factors represent an enormous market and energy savings opportunity. The lamp and retrofit form factors also promote rapid customer acceptance by offering product familiarity and providing similar usability to existing products. However, typical lamp form factors complicate the integration of LED packages into a lighting product. With most lamp form factors there is no natural thermal path to conduct heat away from the LED packages. Many lamps require light distribution beyond the hemispherical 180° emission that is natural for LED technology. Integrating power supplies into individual lamps can be costly and inefficient. LED product integrators have done a remarkable job developing products that surmount these challenges, but legacy form factors fail to exploit the unique features and design flexibility associated with LED technology, and will always require LED technology to be forced into a sub-optimal form factor.

Retrofit luminaires allow for greater flexibility because they typically have a larger volume for integration. This enables more optimized and cost-effective integration of LED lighting products. But with retrofit luminaires, the lighting layout and required light distribution are often defined by the legacy technology that is being replaced, rather than by what could be optimally achieved if the entire lighting system was reconsidered. Similarly, how a retrofit luminaire fits and connects into the building is defined by legacy lighting technologies. For example, with integrated, recessed lighting, LED products will require less depth and volume and may contribute to more compact building architectures that require less in the way of building materials. The electrical connection of lights can also be improved through the use of direct current (DC) grids in the building, removing the requirement for full alternating current (AC) to DC conversion at each LED lamp or luminaire. This can also facilitate direct connection to renewable energy resources, such as solar or wind power and their battery systems without requiring DC to AC conversion and then conversion back to DC for the LED operation.

Beyond form factor and building integration, SSL offers a new range of features and design flexibility. An example of the design flexibility of LED lighting technology and the effective utilization of light is the OSRAM OmniPoint™, a remotely manageable lighting system (luminaire, driver, and software application) that enables users to instantly shape the light output (i.e., beam angle, direction, distribution, shape, and intensity) with a touch screen wireless interface.[b] As shown in Figure 2.4(a) the luminaire consists of an array of individually controlled LEDs aiming out of a small aperture, which allows one luminaire to serve as ambient and/or accent light for a space on demand. The user interface, shown in Figure 2.4(b) allows users to select portions of the space for ambient or accent lighting, as well as to

[b] For more information on the OmniPoint™ please see: https://www.sylvania.com/en-us/innovation/videos/Pages/OmniPoint.aspx

control lighting intensity. This offers significant improvement over traditional lighting systems that would require manually adjusting multiple fixtures on the ceiling [14].

(a) (b)

Figure 2.4 The (a) OSRAM OmniPoint™ Luminaire and (b) User Interface
Source: Jerry Ryu, OSRAM Sylvania, SSL R&D Workshop, Raleigh, NC, February 2016 [14]

OLEDs are not able to readily replicate most lamp and luminaire form factors, which is both a disadvantage and an advantage. While this creates a barrier for near-term adoption of OLED technology, it also accelerates the development of fully optimized lighting systems and applications that are in alignment with the unique features of this technology (e.g., large area, low brightness, thin form factor, and non-planar surfaces). Ultimately, some combination of large area, low brightness OLED sources with directional LED sources could be an approach that maximizes the features of both lighting technologies and optimizes the lighting design.

Acuity Brands has announced the development of Duet SSL™ Technology, blending the use of OLED and LED light sources in the same luminaire, optimizing both to produce refined photometric performance, improved lighting quality, and cost effectiveness. As shown in Figure 2.5, downward-facing OLEDs are incident on the task surface, while LEDs face upward and provide general illumination that can reflect off of the ceiling to light the space. This combination utilizes the soft diffuse glow of OLEDs where the light interacts with the user, and LEDs provide cost-effective supplementary lumens to fully light the space.

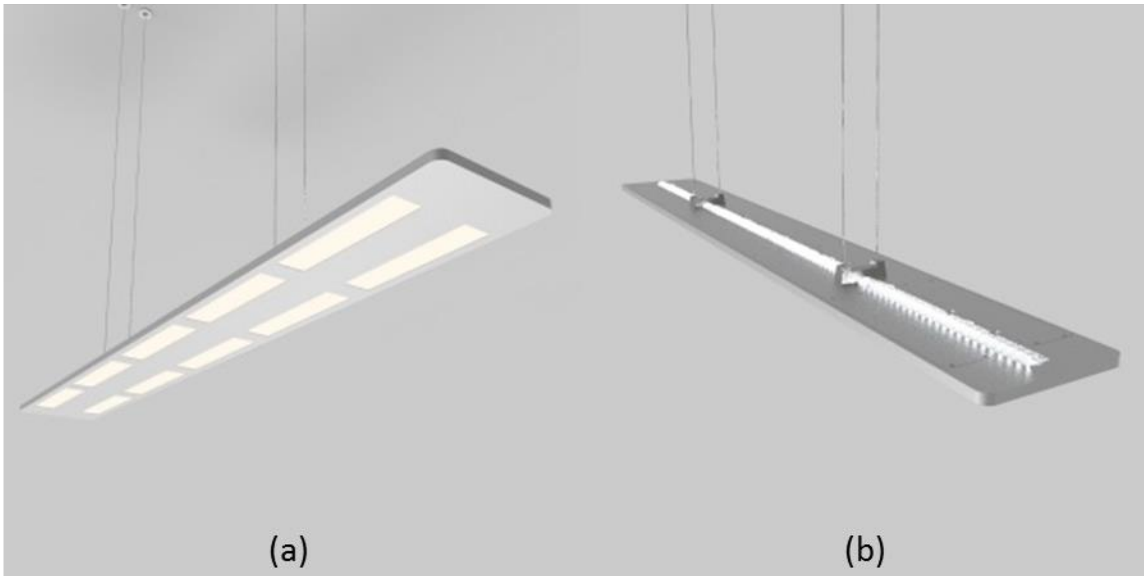


Figure 2.5 Duet SSL™ Concept Luminaire with (a) OLEDs Producing Downwards Illumination to Light the Task Area and (b) LEDs on Top to Produce Light That Fills the Room
Source: Acuity Brands Website, April 2016 [15]

These two examples provide just a glimpse of how SSL technology can improve lighting performance and the value of a lighting system. As product developers, architects, and lighting designers fully embrace the possibilities of SSL technologies, new product form factors, lighting layouts, and building integration approaches will emerge that fully optimize SSL technology not just for source efficiency, but also for optimized utilization efficiency, building and construction efficiency, and lighting performance and value.

2.4 Improved Environmental Sustainability

SSL technology offers significant environmental benefits and possibilities. The benefits of improved efficacy go beyond reduced energy consumption, the cost of energy savings, and energy security. Increased efficacy and the associated energy savings reduces greenhouse gas and other pollutant emissions from the burning of fossil fuels for electricity generation. The transition to SSL will provide a significant near-term contribution to greenhouse gas reduction [16]. SSL technology also offers additional environmental benefits such as a reduced use of toxic, scarce, critical, or energy-intensive materials [17]. In addition, new levels of control of the spectrum and the optical distribution of the emitted light can minimize the impact of artificial lighting on the ecosystem.

The DOE-sponsored life-cycle assessment (LCA) conducted in 2013 showed that LED products reduce the total life-cycle energy consumption, including energy consumed during manufacturing, transportation, and use of the products. Advancements in LED efficacy and lifetime have resulted in a reduction of about half of the life-cycle energy consumption from LED products 5 years ago.

The LCA study also showed that SSL can reduce energy use from lighting and maintain performance levels without using large amounts of toxic or scarce materials.[c] Unlike fluorescent lighting technology, LEDs and OLEDs do not require mercury or lead, and they make much more effective usage of rare-earth materials. The DOE LCA showed that in terms of air, resource, water, and soil impacts, LED-based SSL has a far less negative impact than incandescent lighting, and as LED technology continues to improve, it will have a lower impact than CFLs. The LCA study concluded that LED-based SSL already represents an advancement in sustainability for lighting, and the advantages will continue to grow as further improvements in efficiency are realized [17].

Although LED-based SSL products are already demonstrating improved sustainability, additional efforts could be pursued to further limit environmental impacts. The following are some of the initiatives being pursued within the LED lighting industry:

- Reducing the ecological impacts of providing light at night. For example, tailoring the spectra of LED products has enabled outdoor lighting designed to minimize disruption of sea turtle hatching.[d] In an effort to further understand the impacts of light on animals and identify other opportunities for LED products, DOE organized a meeting in April 2016 with animal researchers, LED technologists, and lighting impact researchers to discuss animal responses to light. A meeting report will be forthcoming with a summary of the discussions.
- Minimizing light pollution from outdoor area lights. The International Dark-Sky Association[e] suggests guidelines to reduce the amount of unusable upward emitted light at night. LED area lighting offers both full dimmability and excellent control of the distribution of the light; both of these features can be used to minimize the impact of light at night on the ecosystem while maintaining safe and effective levels of illuminance. There is some concern that higher blue content roadway and area lighting (high CCT) scatters further into the atmosphere than conventional high-pressure sodium lights, causing increased sky-glow. However, a comprehensive study has yet to be performed that considers both action spectrum for sky-glow impact and the reduction in total amount of light emitted upward due to improved optical control offered by some LED roadway lights.

[c] LEDs enable a dramatic reduction of the use of rare-earth metals for lighting in line with the DOE Critical Materials Strategy available at: http://energy.gov/sites/prod/files/DOE_CMS2011_FINAL_Full.pdf

[d] For more information on approved Sea Turtle Lighting please see: http://www.myfwc.com/wildlifehabitats/managed/sea-turtles/lighting/

[e] For more information on the International Dark-Sky Association and their guidelines please see: http://www.darksky.org/

- “Dematerializing” or reducing the amount of material, particularly energy-intensive materials such as aluminum, used for SSL products. With thoughtful new design, there is an opportunity to dramatically reduce the amount of materials required for an LED lamp or luminaire products. Examples include the Philips SlimStyle lamp,the Cree 4-flow lamp, and filament-style lamps (shown in Figure 2.6), which have no aluminum heat sink.
- Understanding the product life cycle to allow for reusing, recycling, or salvaging luminaires or components at the end of product life [18].
- Improving manufacturing efficiency through yield improvements, material utilization, and equipment energy usage.

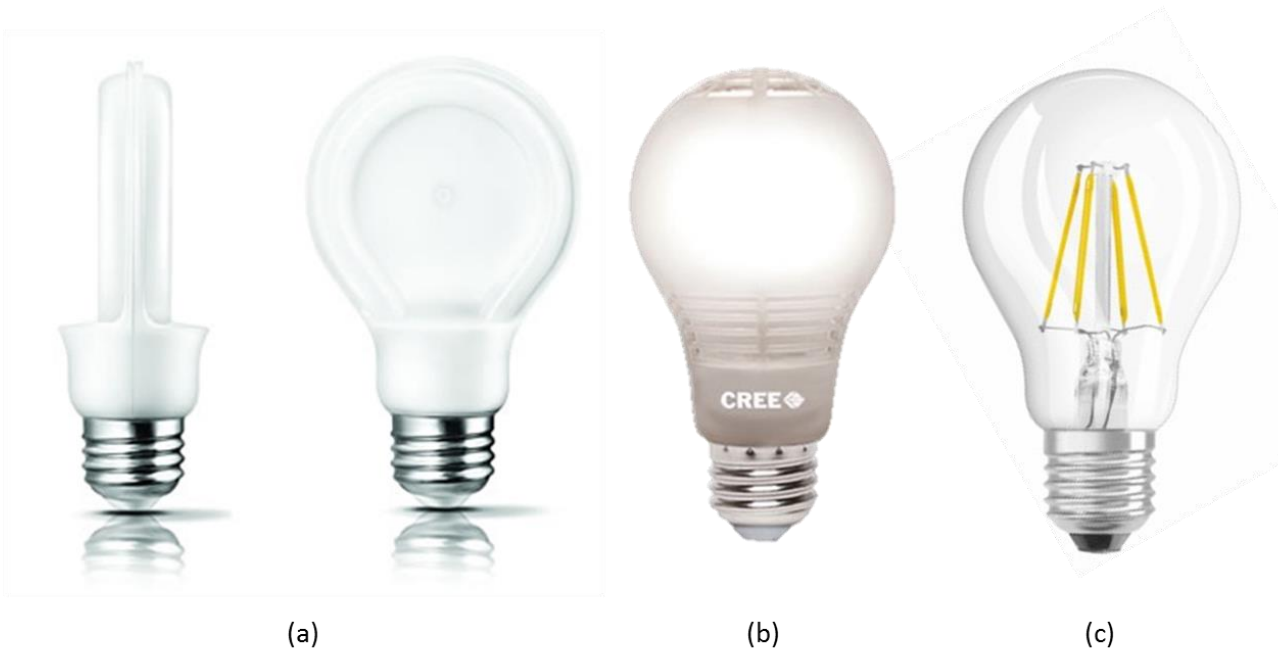


Figure 2.6 Lamps without Aluminum Heat Sinks: (a) the Philips SlimStyle, (b) Cree 4-flow, (c) OSRAM Filament-Style LED

Source: (a) Philips website, May 2016 [19]*; (b) Cree website, May 2016* [20]*; (c) OSRAM website, May 2016* [21]

2.5 Health and Productivity

LED lighting products can be designed to emit almost any spectrum of visible light. Newer commercial products such as the Philips Hue[f] and specialty products such as the Telelumen Light Replicator[g] can

---

[f] For more information on the Philips Hue please see: http://www2.meethue.com/en-us/

[g] For more information on the Telelumen Light Replicator please see: http://www.telelumen.com/products2.html

provide active control of the emitted spectrum with varying degrees of spectral resolution. While LED products can have a tailored spectrum, most LED lighting products do not yet have active control of the emitted spectrum. The ability to dynamically tune the emitted spectrum of an LED or OLED lighting source can unlock a host of value-added features for SSL lighting beyond energy savings. Some new applications that are enabled by LED color tunability and spectral replication include lighting for human health and productivity, horticultural lighting, and livestock lighting.

The ability to tailor the spectrum is leading to a better understanding of the most appropriate light for performing a specific task, optimizing horticultural productivity, positively affecting human physiology, and developing new applications. Enabling dynamic control of the emission spectrum can provide further value by allowing the spectrum to change over time in response to changing lighting demands.

While the impact of lighting on horticulture, physiological responses, and productivity is becoming better understood, it is important to acknowledge that much of the supporting research for these effects is at an early stage and that additional research is necessary to fully understand these biological responses. LED technology can support these efforts by offering a new high-resolution tool for better research and understanding of all biological impacts of lighting. In particular, human physiological impacts of lighting, both positive and negative, need to be well understood and controlled to maximize the benefits from lighting, and lighting manufacturers should be careful to only claim well-supported, understood, and verifiable physiological benefits from their products.

2.5.1 Human Health and Productivity

Humans are exposed to a substantial amount of natural and artificial lighting, all of which has some effect on our physiology, regardless of the source. Recent research has advanced the understanding that light not only enables vision, but also is a critical signal to our biological systems, affecting circadian rhythms, pupillary response, alertness, and more, as illustrated in Figure 2.7 [3]. Light has even been shown to be an effective treatment for a variety of conditions, such as Seasonal Affective Disorder (SAD) and dementia [22].

Importantly, the non-image-forming photoreceptor system in our eyes is different from our visual system. Although it shares some of the same photoreceptors, it has its own unique spectral and temporal response to light. The non-image-forming photoreceptor has a peak sensitivity to blue light and controls the release of melatonin. When humans are exposed to light with a high blue content, such as sunlight at mid-day, melatonin release is suppressed. Control of blue light is therefore important for light and health, but further research is necessary to fully understand the impacts.

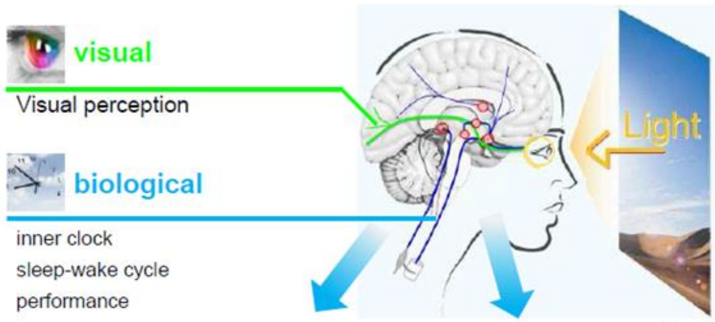


Figure 2.7 How Light Affects a Biological Systems
Source: Andreas Wojtysiak, OSRAM, SSL R&D Workshop, San Francisco, CA, January 2015 [22]

A number of case studies have shown that tuning the spectrum of the lighting throughout the day can lead to improved alertness and productivity, and can help synchronize our internal circadian clock. Light levels in the morning can clearly indicate to our inner clock that the day has begun and that the body should be awakened. This activation phase requires light with a high blue content as shown in Figure 2.8. During the evening, it is desirable to reduce the amount of blue light in the spectrum because it suppresses the production of melatonin and makes falling asleep more difficult.

Studies using spectral tuning have shown the following improvements to [22]:

- Classroom alertness for students
- Daytime activity, alertness, and better sleep at night for the elderly (nursing homes)
- Chronic pain therapy through structuring the day and stabilizing sleep/wake cycles
- Evening and nocturnal relaxation and morning activation for passengers in an aircraft cabin
- The duration reduction in time of therapy to relieve unipolar depression

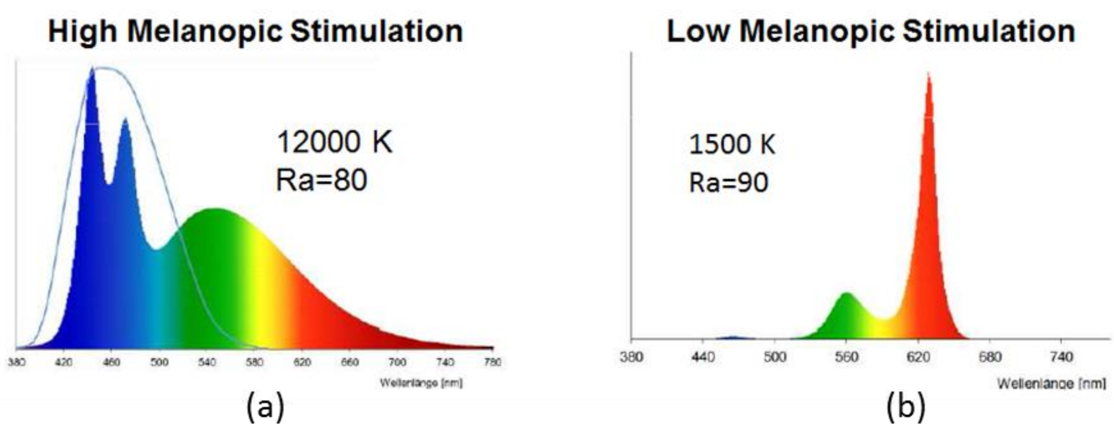


Figure 2.8 (a) Daytime Activation by Light and (b) Less Circadian Light Effects in the Evening and Night
Source: Andreas Wojtysiak, OSRAM, SSL R&D Workshop, San Francisco, CA, January 2015 [22]

The physiological impacts described above could be harnessed to improve health and labor force productivity. It is too early to tell how big of an impact these features may have, but even slight improvements in productivity could justify the added expense of integrating personal controls for dimming or implementing a changing white color spectrum throughout the day. Improved understanding of the physiological impacts of lighting and improved lighting systems could also improve outcomes in educational settings. LED technology can enable the required control of the light output, spectrum, and light distribution to implement such a system.

The impact of lighting on the global economy, as estimated by the International Solid-State Lighting Alliance (ISA) is shown in Figure 2.9. While expenditures on energy are far greater than the costs of buying and installing lighting systems, perhaps the greatest opportunity for the lighting industry is to realize the potential for increases in productivity. These can come directly from improved lighting in the workplace or indirectly, for example, by facilitating access to education and healthcare in developing countries [23].

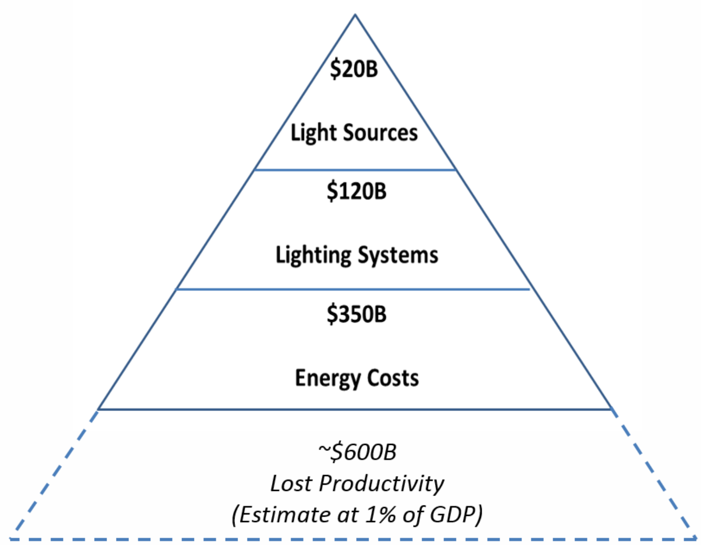


Figure 2.9 Impact of Lighting on the Global Economy in 2014

Source: ISA, Global Solid State Lighting Industry Status Report and Market Trends 2014 [23]

2.5.2 Horticulture

Horticultural lighting is an increasingly important application that takes advantage of the spectral tailoring and tuning ability of SSL sources. As flowering, branching, plant height, biomass accumulation, plant immunity and defense, stress tolerance, and phytoceuticals are all light-regulated attributes, changes in the spectrum of light influence various aspects of plant growth, such as the size of the plant, germination process, flowering, vegetation, and even nutritional value [5].

The blue and red regions of the spectrum are the key regions for photosynthetic activity, as seen in Figure 2.10. Photosynthesis primarily takes place in the leaves of the plants using green pigments, which can absorb a different wavelength of light (primarily in the blue and red regions) and pass its energy to the central chlorophyll molecule to carry out the process of photosynthesis.

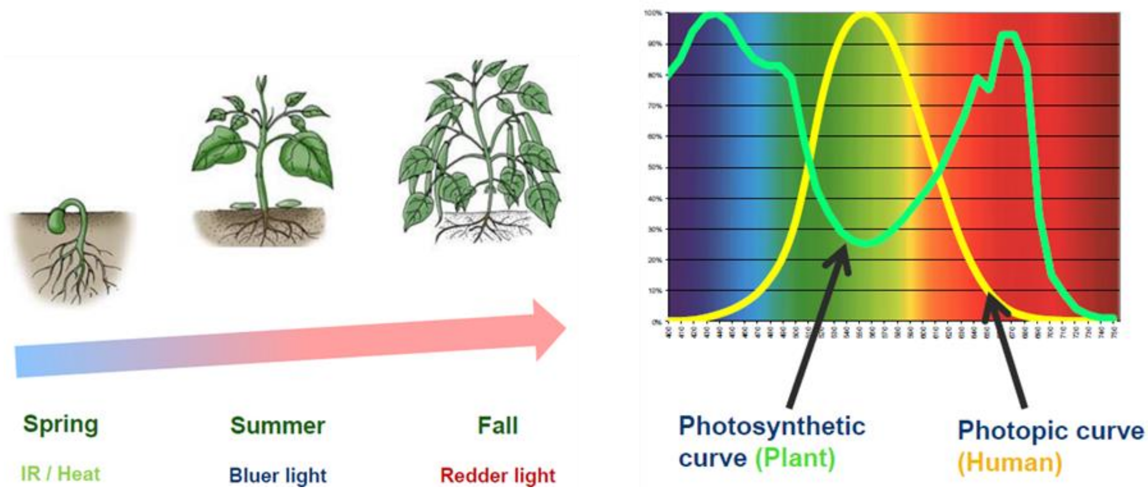


Figure 2.10 Effect of Light on Plant Growth

Source: Robert Spivock, GE, SSL R&D Workshop, San Francisco, CA, January 2015 [24]

The use of tailored wavelength lighting for horticulture can improve the energy efficiency of indoor farms. Dynamic control of the spectrum can improve yield. Installations in eastern Japan have demonstrated impressive results for indoor lettuce production after ground contamination from the Fukushima disaster prevented outdoor cultivation.

The use of targeted wavelength LED lighting in agriculture has led to exemplary results described by GE Lighting at the 2015 DOE SSL R&D Workshop, including [24]:

- 100-fold production increase indoors vs. outdoors (10,000 heads of lettuce produced per day)
- 2.5 times faster growth compared to outdoors
- 40% waste reduction (from 50% to 10%), compared to outdoors
- 1% of water usage compared to outdoors
- 40% reduction in power usage compared to fluorescent light

Research at Rensselaer Polytechnic Institute has indicated the possibility of tailoring the spectra to improve the nutritional value of plants. Anthocyanin, a flavonoid pigment, is responsible for the red color of red lettuce and is thought to have a variety of health benefits including improving eye health, heart health, and cognition [5]. Red lettuce grown under lamps of varying spectral output produced different amounts of anthocyanin production, as shown in Figure 2.11.

Figure 2.11 The Influence of Spectra on Anthocyanin Production in Red Lettuce
Source: Tessa Pocock, Rensselaer Polytechnic Institute, SSL Technology Development Workshop, Portland, OR, November 2015 [5]

2.5.3 Livestock Production

Lighting for the production of livestock represents another opportunity for SSL to improve productivity and well-being in addition to energy savings. Currently, most poultry houses are lit by incandescent lamps due to their low cost, easy dimmability, and ease of installation. However, the electricity required to run this type of lighting can account for a significant portion of the operating expenses for poultry producers. The use of LED lighting could reduce energy costs, reduce the cost of changing short-lived lamps, and, if appropriately designed, could be waterproof and robust in the harsh environment of the poultry house. All of these benefits could be achieved while also offering full dimmability and compatibility with legacy control systems. In addition, it is possible that the spectrum and intensity of the LED lighting could be tuned to modify animal behavior, such as reducing the congregation of chickens in the poultry house and reducing feather pecking, resulting in improved productivity and well-being. Conceivably, active tuning of the spectrum could be used to replicate the daylight cycle, further improving productivity and well-being [25].

Other types of indoor livestock production may also benefit from LED lighting. The lighting impacts on swine production, milk production, and aquaculture are all being explored. However, more research is necessary to fully understand the productivity and well-being impacts and to determine the optimum spectrum, optical distribution, and lighting control. In an effort to understand the status of understanding of animal responses to light, including livestock, DOE organized a meeting of scientists to discuss animal responses to light which was held in Chicago in April 2016. A meeting report describing the discussions at the meeting will be forthcoming on the DOE SSL Program website.

2.6 Barriers to Adoption

The previous sections discuss profound energy, economic, performance, and application benefits enabled by advancements in SSL technology. However, despite the many benefits and additional functionality that can be achieved with SSL, a number of barriers remain that limit the adoption of SSL products. These include first cost, reliability, and compatibility issues. An overview of each of these aspects is discussed in the following sections, and more detailed information on reliability can be found in Section 5.3.5.

2.6.1 First Cost

The primary barrier to adoption for SSL products is the higher first cost of LED and OLED lighting products. The first cost of SSL products has dropped rapidly over the past few years, while the number of available products and form factors has proliferated. SSL products remain more expensive than incumbent sources on a first-cost basis but prices have come down to as low as $2 to $3 for certain replacement lamp products. For replacement lamp products, manufacturers have demonstrated the ability to trade off performance aspects such as efficacy, lifetime, light distribution, and/or color quality for price. This enables consumers to choose the lighting attributes or price points that are most important to them.

However, there is a risk to focusing on low first cost, as product quality could become a concern. As thermal management materials (e.g., aluminum heat sinks) are reduced or eliminated to save cost; the efficiency, lifetime, and color shift of LED lamps may be affected. When fewer LEDs are used and each individual LED component is driven harder, color shift, lifetime, and efficiency again become an issue. Lower cost-assembly techniques can lead to a compromise in quality and an increased early mortality rate. The drive for lower first cost must not cause performance or lifetime deficiencies, or it will reduce consumer confidence in LED technology, reduce adoption, and limit the total energy saved. Fortunately, advancements in the underlying LED efficiency and package technology continue to reduce the performance tradeoffs necessary to achieve lower priced products. These advancements also open up the possibility for more expensive products with excellent efficiency and little or no compromise in other performance aspects.

While first cost remains a deterrent, higher operating efficiency and longer operating lifetimes (reduced maintenance and replacement costs) already ensure that LED lighting is highly competitive on a TCO basis. A TCO analysis includes all expenses incurred over the life of the system. The payback period is the time it takes the consumer to recover the higher purchase cost of a more energy-efficient product as a result of lower operating costs. Lower operating costs are persuasive in commercial and industrial applications where lights typically operate for more than 10 hours per day. As a result, typical commercial LED systems have expected payback periods of 5 to 7 years compared to linear fluorescent and HID systems. This payback period is further reduced for higher efficacy, top-of-the-line LED products. The typical payback period of an LED lamp in residential applications is less than 2 years for halogen lamps and dimmable CFLs; however, lighting sold at the consumer level tends to depend less on TCO considerations and more on first cost. Part of the reason for this is that the average residential consumer uses lighting for shorter periods of time and does not factor in maintenance costs to install or replace lights. So, while falling prices have helped drive LED adoption, first cost is still a significant barrier to the residential consumer. As consumers begin to understand the full energy and performance benefits of higher priced products, a market for high efficiency, high fidelity lighting is expected to emerge.

2.6.2 Reliability

In addition to high energy efficiency, LEDs have the promise of long lifetimes that can last well beyond 50,000 hours of operation, much longer than most conventional light sources. For products with lifetimes of many years or even decades, failures may be very slow to appear under normal operation. Detecting these failures in the laboratory or factory also is very difficult, but failures are important to understand and to estimate useful product life.

LED packages typically do not fail catastrophically (i.e., instantaneously stop emitting light), but instead slowly decrease in light output over time. Knowledge of the degradation mechanisms has advanced, but is not complete. The LED package useful life is often cited as the point at which the initial lumen output has declined by 30%, referred to as 70% lumen maintenance, or L_{70}. Previously, it was thought that the degradation of lumen output of the LED source itself determined the lifetime of LED lighting products, but this is not the case. The final product comprises various components and subsystems that can also fail independently of the LED package. Degradation of optics, power supply failure, and solder detachment may occur under normal operation well before the LED light output falls below L_{70}. In addition, catastrophic semi-random short-term failures may be observed due to assembly, material, or design defects. Studies have shown that component and manufacturing failures in the power supply are responsible for the majority of lamp and luminaire failures. Overheating caused by poor luminaire design can also reduce the life of an LED package dramatically. Moisture incursion can be an important mechanism of failure and determinant of life for an outdoor luminaire. The integration of the lights into the building system also needs to be carefully considered. Early adopters have experienced large-scale failures due to misunderstanding of installation procedures or incompatibility between lighting products and a building's electrical system. Proper installation, surge protection, and building system integration are critical for the reliability of the lighting system. However, these are not fundamental barriers to adoption, but rather near-term considerations as products are improved and the impact of the electrical system on SSL products is better understood.

Work is ongoing to understand the various mechanisms and enable the development of new reliability models so that system reliability can be confidently understood, modeled, and communicated. The DOE SSL Program has funded specific R&D in this area and has supported the creation of an industry consortium, the LED Systems Reliability Consortium (LSRC), to coordinate activities and foster improved understanding. The LSRC and its efforts are discussed in more detail in Section 5.3.5. Nevertheless, considerable work remains to establish a full reliability database of components and subsystems to aid luminaire design and convince consumers that LED and OLED products will operate for as long as promised.

2.6.3 Color Stability

Lumen maintenance has dominated discussions about LED package lifetime, but color shift is another important performance attribute that can be a barrier to purchase or cause failure once installed. The color stability of LED lamps and luminaires varies among different products, and potentially for the same product used in different applications. Color stability should not be confused with color consistency. Color stability refers to the ability of a product to maintain a constant color point over its lifetime, whereas color consistency refers to the product-to-product variation within a lamp or luminaire type.

The importance of color stability varies by application. For example, a high degree of color stability is important for light sources in a museum or retail store, but less important for street lighting. Color stability is also important where multiple lamps or luminaires are being used to wash a wall, or where objects are being evaluated based on color, such as in a hospital or factory.

Several factors affect the color stability of LED lamps and luminaires. Ambient air temperature, drive current, and the design of the lamp or luminaire's thermal management system can influence the junction temperature of the LED, which in turn can affect its output characteristics. Of greater concern for long-term color stability is the effect that high operating temperatures can have on certain materials. Depending on the design of the package, the phosphor layers may settle, curl, delaminate, or otherwise change the amount of photons that are converted. This behavior can occur even in the absence of high ambient temperatures. Likewise, other materials in the optical path, such as plastics, glues, or epoxies, may discolor over time. Temperature fluctuations, which are not included in standardized test procedures, also may exacerbate degradation mechanisms for some LED products.

There is currently no standard methodology for projecting future color stability using standard test procedures as there is for determining LED package lumen maintenance. Likewise, there are no established methods for accelerated testing, leaving each manufacturer to develop their own testing methodologies and predictive modeling approaches. A consensus methodology for predicting color shift will be a challenge as different materials of construction and manufacturing processes can affect the results; however, an Illuminating Engineering Society (IES) committee is working on this issue.

2.6.4 Compatibility

The largest near-term market opportunity for LED-based lighting is to replicate existing lighting form factors, but differences in the way light is generated can lead to a number of compatibility issues. Incompatibility can derive from differences in physical appearance, dimensions, and light distribution. This can result in LED products that do not quite fit into existing light fixtures, or light distribution patterns that do not replicate the product they are replacing. Incompatibility can also result from differences in performance characteristics such as light output, color temperature, and color quality. The color temperature of the replacement product can also differ from adjacent lamps of either conventional or LED lighting technologies, especially if the consumer, not understanding the description on the packaging, selects the wrong product. Additionally, there might be differences in the total light output either due to product variations, overstated claims, or selection of the wrong product based on confusion between watts (W) and lumens, as a metric defining light output. These compatibility issues can exist between nominally identical products from different manufacturers, as well as among different products addressing the same application. All varieties of compatibility issues can lead to consumer frustration and disappointment in LED technology, possibly having long-term negative impacts on adoption of the technology.

There is an added level of complexity for linear fluorescent replacement products. LED linear fluorescent replacement tubes will either be compatible with the existing fluorescent ballast, have their own LED-based external power supply, or must be wired directly to mains. Each approach has its pros and cons, but the choices can be confusing to the consumer. The different choices require different levels of installation cost and complexity, and can result in varying lighting performance (e.g., higher losses from the existing ballast than with an LED-designed power supply).

Compatibility with legacy dimmer switches or lighting control is also often a problem with SSL products. LED and OLED lighting typically require efficient conversion of the 120 volts alternating current (VAC) power input to low current DC input. When the input is conditioned by the various dimmer technologies there can be flickering, audible buzzing, non-linear dimming, and/or inconsistent dimming.

2.6.5 Conclusion

While these barriers discourage adoption, LED lighting technology is rapidly gaining market share. These barriers do not represent fundamental limitations to SSL technology, but rather are a normal disruption of a large, entrenched market. As LED and OLED technology continue to improve and mature the significance of these barriers will be further reduced.

3.0 Market Impact of Solid-State Lighting

There is a vast global opportunity for SSL products. Rising electricity prices, mounting concerns about climate change, and desire for energy independence are causing the global lighting market to shift toward energy-efficient light sources. In December 2015, 195 countries gathered in Paris, France, to adopt the first universal climate agreement, under which they agreed to combat climate change and to unleash actions and investment toward a low-carbon, resilient, and sustainable future [26]. Through the en.lighten initiative,[h] the United Nations Environmental Programme (UNEP) estimated that the use of lighting energy had risen to 2,815 terawatt-hours (TWh) in 2010, corresponding to 15% of total global electricity use [27].

The importance of developing and marketing more efficient lighting in efforts to combat atmospheric pollution and global warming was acknowledged by the U.S. Secretary of Energy, Dr. Ernest Moniz, in his comments at the December Conference of Parties (COP21) meeting in Paris. Dr. Moniz described the work of the Clean Energy Ministerial (CEM) and introduced the Global Lighting Challenge to distribute 10 billion LED lamps across the globe over the next few years.

In its 2015 report to the CEM, the International Energy Agency noted that global electricity use has risen by 4% per year over the past decade. It highlighted the contribution made by SSL, but cautioned that "energy efficiency regulations for lighting products have moved sales away from inefficient incandescent lamps, but toward halogen lamps rather than more efficient CFLs or LED lamps." It concluded that "more assertive policies are needed to achieve large savings" [28]. However, advancements in SSL technology resulting from ongoing R&D continue to reduce prices, improve efficacy, and improve lighting performance, thereby accelerating adoption in many markets regardless of policy directives.

3.1 Global Lighting Market: Status and Potential

When comparing estimates of LED adoption rates, it is important to distinguish between unit sales, sales revenues, and the installed base. Because LED lamps and luminaires are typically more expensive than traditional technologies, market share of sales will be greater in terms of revenue than in terms of units. LED penetration of the installed base will follow increasing market share more slowly, as they are used to replace existing installations and become the majority of sales.

Many of the leading lighting companies recently reported that LED lamps and luminaires represent more than 40% of their revenues, including Acuity Brands (55%), Osram (48%), Philips (50%) and Zumtobel (63%) [29, 30, 31, 32]. On the other hand, the impact on the installed base has been small. Both IHS and Strategies Unlimited estimate that by the end of 2015, LED lamps comprised 6% of the global installed

[h] For more information please see: http://www.enlighten-initiative.org/

lamp base. As seen in Figure 3.1, IHS forecasts that penetration of the global installed base will remain below 40% through 2022.

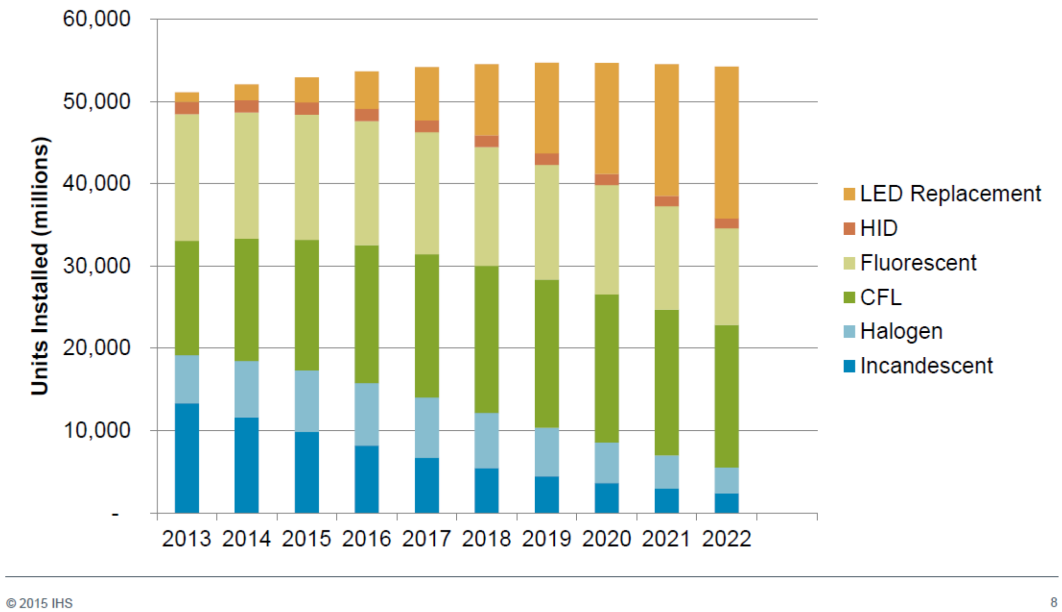


Figure 3.1 Evolution of the Global Installed Lamp Base by Lighting Technology
Source: Will Rhodes, IHS, Smart Lighting Conference, Berlin, May 2015 [33]

Figure 3.2 shows the variations in adoption among geographic regions. Japan led early adoption of LEDs, due to prioritizing energy savings following the Fukushima disaster. Other Asian countries, such as China and India, are now assuming the lead [34]. The national and regional governments in China have invested heavily in promoting companies at each level of the industry, from epitaxy to luminaire assembly. In addition, compared to Europe and North America, the rapid growth of the Chinese economy has given rise to a greater fraction of the lighting business associated with new installations, rather than replacement or retrofit of existing equipment.

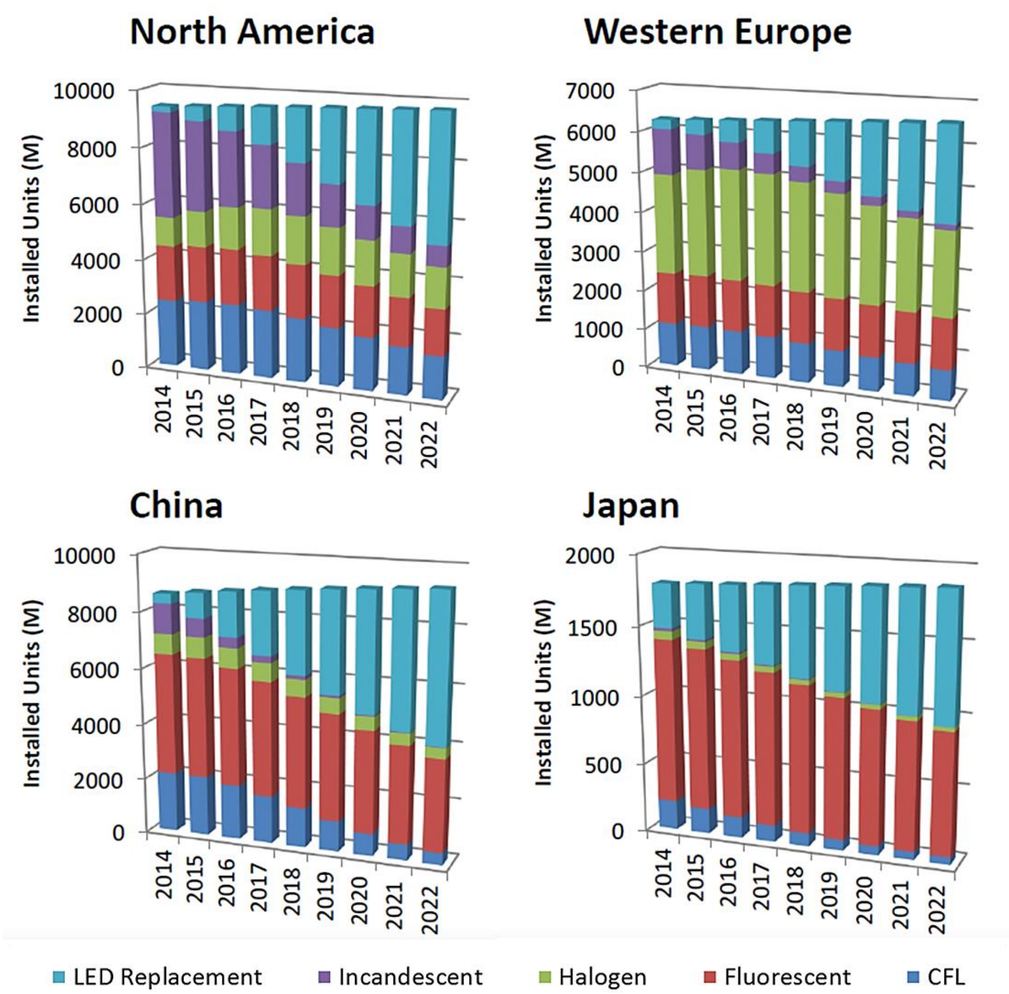


Figure 3.2 Evolution of Regional Installed Lamp Base by Lighting Technology
Source: Stephanie Pruitt, Strategies Unlimited, November 2015 [34]

Aside from LED lighting, there is also an obvious difference among the three continents in the relative appreciation of linear fluorescent lamps versus energy-intensive incandescent and halogen lamps. In 2014, less than 25% of the available sockets in Asia were occupied by energy-intensive lamps, while the rate was closer to 50% in Europe and North America [34]. Furthermore, regulations banning the sale of traditional general service incandescent lamps have been introduced in both Europe and North America. Unfortunately, while the sale of incandescent lamps has decreased, so has the sale of CFLs. Some of this decline in CFL sales is due to consumers upgrading to LED lamps, however, consumers have also downgraded to less efficient halogen lamps [35]. It is likely that these recent sale trends for general services lamps have resulted in few energy savings than originally projected.

3.1.1 United States

The DOE SSL Program supports numerous analyses to determine the status and potential of SSL in the U.S. lighting market. Each year, DOE alternates between a “snapshot” of the current LED installed base (most recently the “Adoption of Light-Emitting Diodes in Common Lighting Applications,” published July 2015) and a forecast of the future U.S. lighting market (most recently the “Energy Savings Forecast of

Solid-State Lighting in General Illumination Applications," (aka the DOE SSL Forecast), published August 2014 and due to be updated in late 2016) with each serving as an input for the other. While a high-level overview of the U.S. lighting market will be provided in this section, readers are encouraged to visit http://energy.gov/eere/ssl/market-studies to view these full reports.

Status

By the end of 2015, there were 473 million cumulative LED unit installations in the United States, more than double the number of LED unit installations in 2014. These LED installations contributed 278 trillion British thermal units (Btu) of energy savings, which is equal to an annual cost savings of about $2.8 billion [1]. Table 3.1 provides a detailed breakout of the installations and energy savings by application.

Table 3.1 LED Installations and Energy Savings by Application

Application[1]	2014 LED Installed Penetration (%)	2015 LED Installed Penetration (%)	2015 LED Units Installed[2] (Millions)	2015 Energy Savings (tBtu)	Estimated Saving Potential[3] (tBtu)
A-Type	2.4	6.0	202	42.7	542
Directional	5.8	11.0	127	55.3	321
Small Directional	21.8	32.1	16.3	24.5	34
Decorative	1.5	3.0	36.9	5.0	190
Linear Fixture	1.3	3.2	31.5	59.3	1,819
Low/High Bay	2.2	3.7	5.4	40.5	1,192
Total Indoor	**2.8**	**6.1**	**419**	**227**	**4,097**
Area/Roadway	12.7	20.0	9.1	10.0	210
Parking Garage	5.0	13.0	5.0	6.4	140
Parking Lot	9.7	13.9	4.0	10.2	253
Building Exterior	11.5	21.2	14.7	10.5	71
Total Outdoor	**10.1**	**17.9**	**32.7**	**37.1**	**674**
Other	**3.3**	**8.0**	**21.4**	**13.3**	**196**
Total All[4]	**3.0**	**6.4**	**473**	**278**	**4,967**

1. See Appendix 8.1 for definitions of SSL Lighting Applications and products within each category.
2. Installations are the total cumulative number of LED lamps and luminaires that have been installed as of 2014.
3. The Estimated Savings Potential is the theoretical energy savings that would result from switching all lighting fixtures "overnight" in the given application to the best LED product available in the DOE LED Lighting Facts® database (in 2015). It is important to note that these "best of" LED products have efficacies much higher than those most commonly available.
4. Values may not add due to rounding.

Despite recent progress, there is still a long way to go, as Figure 3.3 shows. Nearly all applications show less than 20% penetration of LEDs and less than 4% penetration in the key linear fixture, and low/high-bay applications. To quantify the potential energy savings available by "moving up the hill," it was estimated that if all 7 billion lighting fixtures in the United States were to switch to the best available LED fixtures (in 2015) "overnight," they would provide 4,967 tBtu, or about 5 quads, of energy savings [1]. Given efficacy improvements of future LED products, this potential will continue to grow.

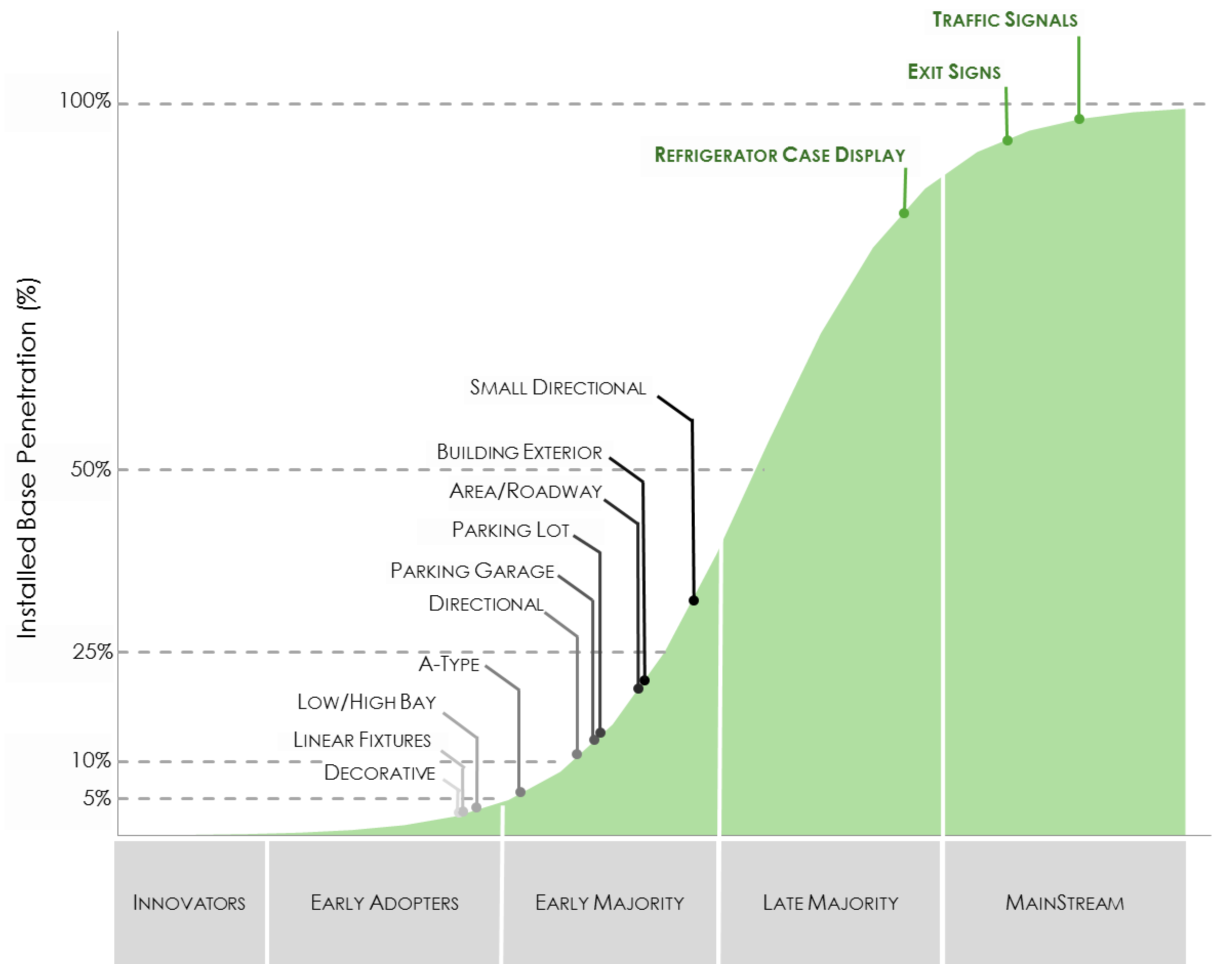


Figure 3.3 2015 Penetration Rates of LED Lighting Applications
Source: Navigant Adoption Analysis, March 2016 [1]

With more than 3 billion A-type lamps in use, general service lamps made up nearly half of all U.S. lighting unit installations, and 6% of these were LED by the end of 2015 [1]. However, the number of installations is just one part of the energy savings equation, with efficiency over incumbent technologies and the operating hours for each installation also being important contributors. For this reason, applications such as linear fixture and low/high-bay, which are used more heavily in commercial and industrial spaces and characterized by long operating hours, contributed equal or greater energy savings in 2015 despite lower LED penetration. They also offer the greatest potential contribution to U.S. energy savings, at over 60% of the total, as shown in Figure 3.4.

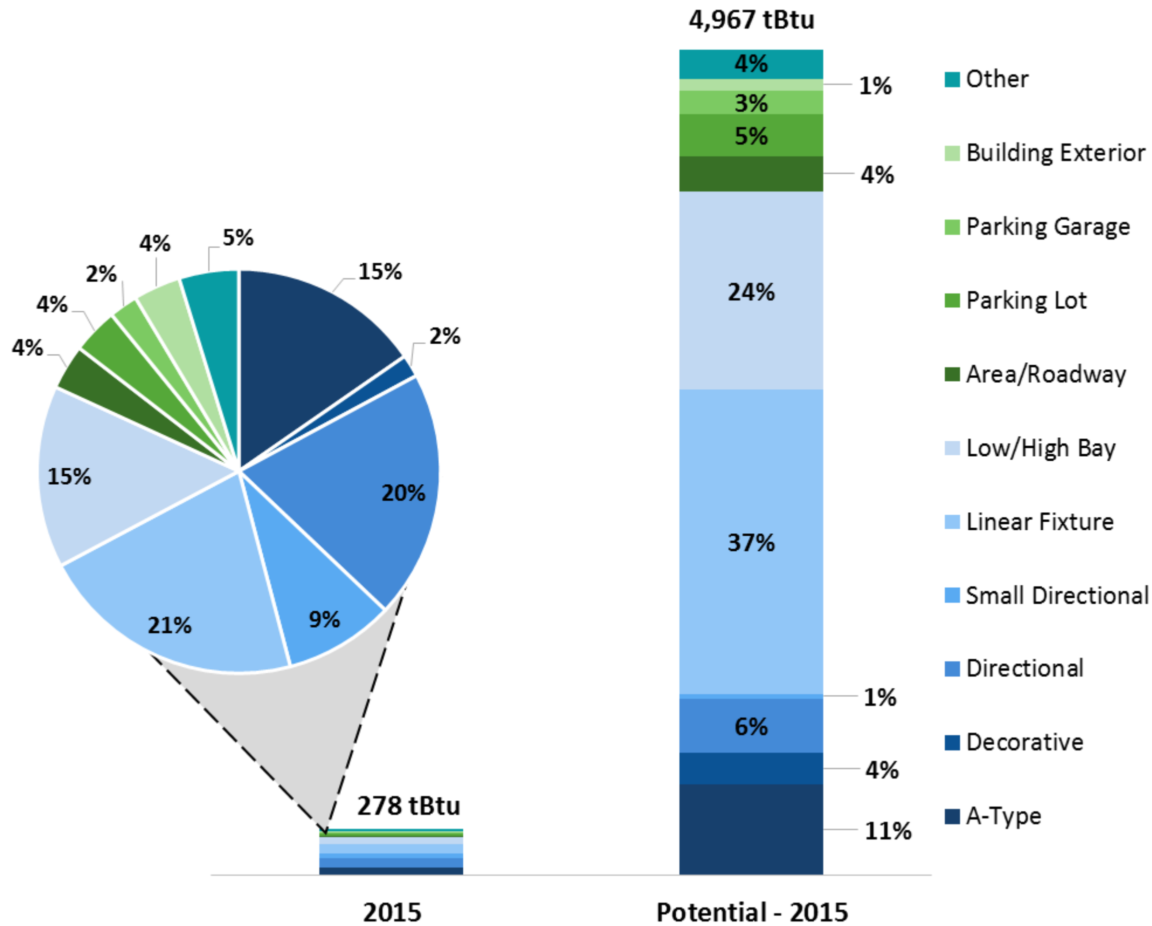


Figure 3.4 Comparison of 2015 and Potential Source Energy Savings from LEDs
Source: Navigant Adoption Analysis, March 2016 [1]

Forecast

Forecasts of LED adoption in the United States are similar to global forecasts, in that LEDs account for a small but increasing share of the lighting market. The DOE 2014 SSL Forecast suggested that SSL could account for nearly half of all lighting shipments in the United States (measured in terms of light production capacity in lumen-hours), and approximately 40% of the installed base (in lumen-hours) by 2020 [2].

Two scenarios presented in the DOE SSL Forecast report are particularly relevant to the DOE SSL R&D program. The first scenario is based on a conservative price and performance trajectory for SSL technology. The second scenario is based on more aggressive price and performance projections derived from DOE SSL program goals. A comparison of the results is used to determine the additional energy savings that may be achieved by aggressive R&D.

The study found that by 2030, given a conservative trajectory based on historical price and efficiency improvement, LED technology offers the potential to save 261 TWh annually, a 40% reduction in site electricity consumption, compared to a counter-factual scenario without LEDs. This 261 TWh of savings in site electricity consumption corresponds to 3 quadrillion Btu of primary source energy saved.

Furthermore, if DOE SSL program goals are realized, the total annual energy savings in 2030 would increase to 60%, an additional 134 TWh in site electricity, or 1.5 quads of primary source energy savings [2].

Figure 3.5 shows the resulting energy savings for each of these scenarios and illustrates the importance of the DOE SSL Program's R&D priorities and milestones (discussed in Section 7.2) to help realize aggressive price and performance improvements.

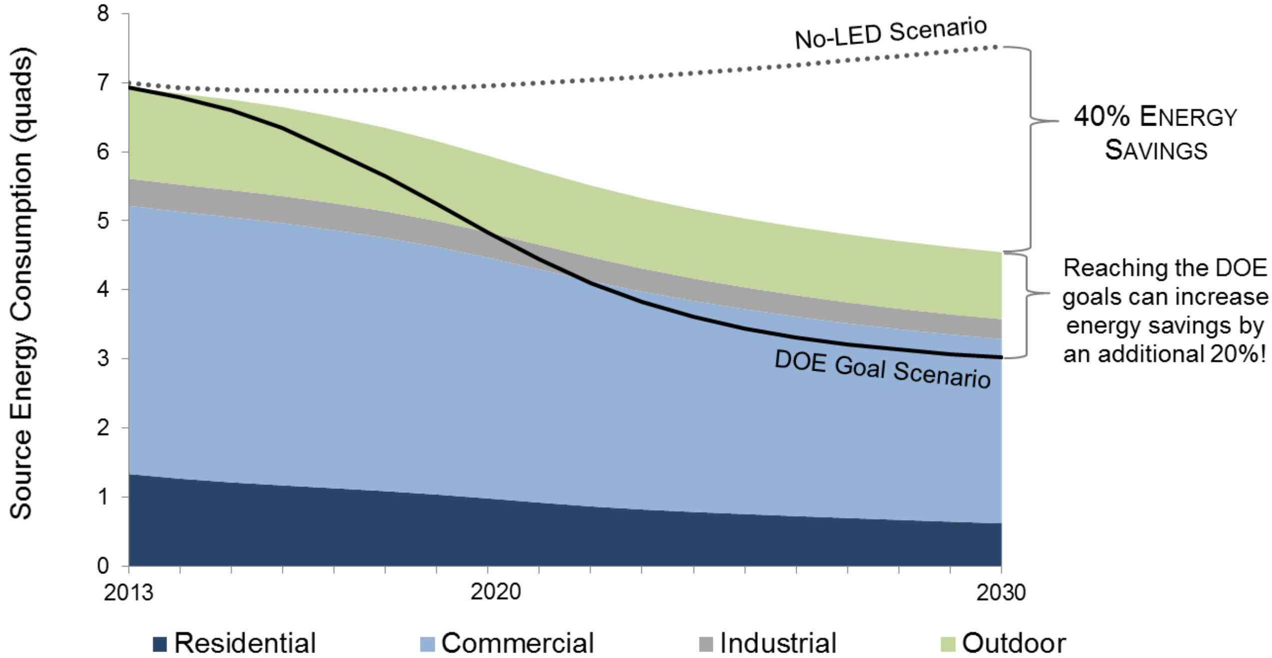


Figure 3.5 Forecasted U.S. Energy Savings if DOE SSL Program Goals are Realized
Source: DOE SSL Program, "Energy Savings Forecast of Solid-State Lighting in General Illumination Applications," August 2014 [2]

The projected savings in site electricity consumption of 395 TWh in 2030 would correspond to about 4.5 quads of primary source energy, which is nearly twice the projected electricity generation of wind power and 20 times that of solar power in 2030 (as shown in Figure 3.6). At an average price of $0.10/kilowatt-hour,[i] this would correspond to an annual savings of about $40 billion [2]. This demonstrates that SSL provides an unprecedented opportunity to reduce electricity consumption, thereby improving domestic energy security and reducing greenhouse gas emissions.

---

[i] Based Table 5.6.B. "Average Retail Price of Electricity to Ultimate Customers by End-Use Sector, by State, Year-to-Date through February 2015 and 2014" found at: http://www.eia.gov/electricity/monthly/epm_table_grapher.cfm?t=epmt_5_06_b

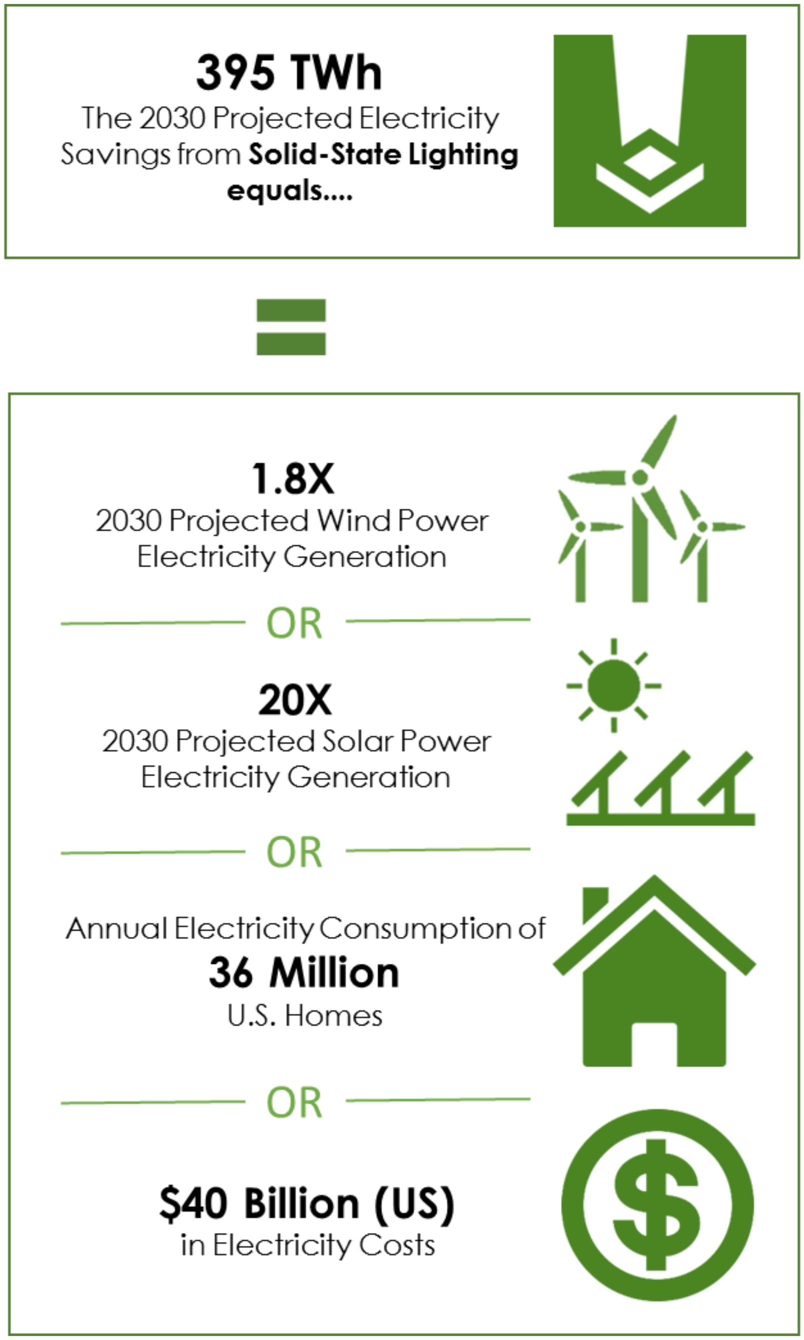


Figure 3.6 Projected U.S. Electricity Savings from SSL in 2030 Compared to Wind Power Generation, Solar Power Generation, or U.S. Household Annual Electricity Consumption

3.1.2 Asia

UNEP estimates that in the absence of new policies, 57% of the lighting energy demand in 2030 would come from Asia [27]. Therefore, developments in Asia will be critical to reducing the global demand for electricity.

Japan

Japan has led early adoption of LED lighting, encouraged by the high cost of electricity, reduced availability of electricity from nuclear power generators, and rapid technological advances by Japanese LED manufacturers. While LED sources light more than 70% of new luminaires, LED replacement lamps are not very popular [36]. In 2015, only 28 million, 8% of replacement lamps sold, were LED [37]. Fluorescent lighting is currently a dominant competitor; however, the government has proposed to ban the production and importation of fluorescent lamps, beginning in 2020 [38].

China

China is now the largest market for SSL and has the largest manufacturing base for LED lighting products. Approximately half of the production is intended for domestic sales. Additionally, about half of the products designed for export are packaged in China using chips made by the leading international chip makers. Exports that incorporate chips made by Chinese companies are mainly sent to regions where intellectual property (IP) protection is not rigorously applied. Table 3.2 shows the Chinese Solid State Alliance's (CSA) 2014 estimates for 2015 domestic sales of LED lighting products and the penetration of the installed lighting base [39].

Table 3.2 Domestic Sales Forecast of LED Lamps and Luminaires in China and Penetration of the Installed Base

LED Product Type	2015 Sales (Million units)	2015 Socket Penetration (%)
Omnidirectional lamps	860	20
Spotlights	400	40
Downlights	180	25
Tube replacements	800	30
Planar lights	120	30
Street lights	8.9	33
Total	**2,369**	**-**

The rapid growth of the SSL industry in China has been assisted by broad support from the national and regional governments, including subsidies for purchases of manufacturing equipment and lighting products, development of industrial parks, and establishment of standards programs. CSA estimated total production of LED lighting products in 2015 to be 6 billion units [40]. Every level of the supply chain is experiencing oversupply, and severe price competition has caused 20% of the 20,000 companies in the industry to withdraw or merge with others [41]. Ex-factory prices for 800 lumen LED lamps have fallen to around $1 and LED tube replacements to $1.50 [42]. The national government is concerned about the excess production and is ending subsidy programs, but competition between regional governments to establish new factories is still strong. For example, Jiangxi province is promoting the manufacturing of LEDs on silicon substrates and has established the "Nanchang Optical Valley" with a revenue goal of approximately $7 billion by 2020 [43].

While China exports about half of the SSL products that they produce, these only represent about 25% of total lighting exports from China. The remaining 75% of China's exports are comprised of traditional, non-SSL, lighting sources [44]. Among the Chinese LED exports, 26% were destined for the European Union and 23% for the United States. Chinese exports to the Middle East (6%), South Korea, and Southeast Asia (9%) are growing, while the fractions going to Japan (5%) and Russia are falling [40, 45].

India

India has an ambitious commercialization and industrialization program that is severely constrained by the shortage of electricity. In January 2015, Prime Minister Norendra Modi launched a national program for LED-based residential, commercial, and street lighting as a key component in a drive toward energy efficiency [46]. The focus of the new government program was on three applications [47]:

- Self-ballasted replacement lamps. Primarily focused in the residential market, which is still dominated by incandescent lamps. The goal is to replace more than 700 million lamps in the next 3 years.
- Downlights. Aimed at showrooms, shop windows, and offices where the poor color quality of CFLs has led to these applications being dominated by inefficient halogen lamps. The goal is to introduce 50 million LED lamps in these applications.
- Roadway and street lights. Targeted to replace most of the 35 million existing street lights in the next few years.

Manufacturing domestically in India is strongly encouraged, although most LED chips and packages are imported. India has a large capacity to produce incandescent lamps and CFLs, and much of it is being converted to make LED products.

In 2009, India's Ministry of Power set up Energy Efficiency Services Limited (EESL), a joint venture of NTPC Limited (India's largest power utility), Power Finance Corporation (PFC), Rural Electrification Corporation (REC), and POWERGRID (responsible for the interstate transmission of electricity) to facilitate implementation of energy efficiency projects.[j] EESL manages the purchase and distribution of replacement lamps and street lights. More than 100 million LED lamps were acquired in a series of tenders, with the procurement price declining from 310 rupees ($5) in January 2014 to 54 rupees ($0.80) in March 2016 [48]. Some of these lamps are distributed by utilities through programs in which residential customers can purchase lamps with a minimal down payment (usually 10 rupees) and pay the remainder (about 95 rupees) through monthly installments along with their electric bills [49]. The LED lamps can also be purchased online for 99 rupees ($1.50) [50]. Distribution of LED replacement lamps has been steadily accelerating, reaching a rate of 600,000 per day and a total of more than 100 million as of May 2016 [51]. The promotion of LED street lights has been less successful due to financing problems, with less than 1 million installations [52].

[j] For more information about EESL, please see: http://www.eeslindia.org/User_Panel/UserView.aspx?TypeID=1025

In 2014, the Electric Lamp and Component Manufacturers' Association of India (ELCOMA) published its "Vision 2020," which describes objectives and strategy for development of the Indian lighting industry. ELCOMA set the following objectives for 2020: generate consumer demand for energy efficient lighting products to enable the reduction of lighting power consumption from 18% to 13%; develop strong domestic manufacturing capability to reduce reliance on imports (increase the proportion of LEDs in use that are manufactured in India from <40% to 80%) and enable exports (increase the proportion of manufactured products for export from <5% to 25%); and promote R&D and education in lighting to build skilled manpower (by establishing educational programs in lighting engineering for 500 students and three research centers by 2020) [53].

3.1.3 Europe

The lighting industry in Europe is undergoing a major realignment. Although Osram and Philips have dominated the global production of traditional lamps, both are planning to divest their lamp businesses to focus upon the provision of lighting services [54, 55]. Osram intends to invest further in LED source manufacturing, expanding its operations in Regensburg, Germany, and Malaysia [56]. Philips Lighting plans to offer a quarter of its shares for sale in an initial public offering with plans to sell its remaining stake in lighting in the coming years [57]. Lumileds, the Philips LED manufacturing operation, which is separate from Philips Lighting, is also planned to be spun off from Philips [58]. The largest European luminaire manufacturer, Zumtobel, does not manufacture LED chips or packages, but seems to have adapted well to the production of LED luminaires, which now account for the majority of its sales [32].

When the restrictions on sales of incandescent lamps within the European Union were first introduced, an exception was allowed for halogen lamps. The exception will be terminated for directional lamps in September 2016; the ban on omnidirectional halogen lamps will go into effect on September 1, 2018 [59, 60]. Other exceptions, such a shock-proof lamps and clear decorative lamps, were removed in February 2016 [61].

In October 2015, VITO, an independent research organization, prepared a comprehensive study of the energy saving potential of SSL in the European Union. VITO estimated that 82 million LED lamps were sold in 2013, representing 5% of all lamp sales, and that this brought the total LED installations to 144 million units and 1.3% of the installed base [62].

In 2015, VITO forecasted that LED lamp sales would increase to 375 million units (22% of all lamps sales) and the penetration of the installed base would rise to around 800 million units (7%). VITO presented various scenarios for later years, with the LED penetration rate of the installed base in 2020 ranging from 42 to 46%. It predicts that the average efficacy of all lighting (the installed base of both traditional and SSL sources) would rise from 65 lm/W in 2015 to between 87 and 94 lm/W in 2020. For 2025, VITO predicts that LED penetration will rise to between 70 and 86%, with the average efficacy reaching between 113 and 169 lm/W. The wide range in these estimates shows the importance of further R&D to raise LED efficiency and promote faster adoption [62].

3.1.4 Off-Grid Communities in the Developing World

Reductions in lighting electricity use through SSL adoption are expected to provide substantial relief from the pressure to construct additional power generation in almost all developed economies. In under-developed countries, the major impact of SSL might be to provide high-quality lighting in communities where lighting has previously been inadequate. For off-grid communities, the growth of SSL sources and photovoltaic technology offers a far more affordable solution for electric light sources than developing the grid to deliver electricity.

Approximately 1.2 billion people throughout the developing world do not have access to the electrical grid and must spend $27 billion each year on fuel such as kerosene for lighting. In comparison, replacing this source with solar LED lanterns would reduce these costs by a factor of 10, to an estimated $2.7 billion annually [63].

In addition to the financial savings, solar-LED lighting offers substantial environmental and health benefits. The burning of kerosene lamps produces black carbon, which is the second largest contributor to global warming, with current usage producing the equivalent of 240 million tons of CO_2 each year. The use of kerosene lamps is also dangerous due to the risk of fires and toxicity of the fuel, which contains a high proportion of heavy particulates [64].

According to a 2016 report prepared by Bloomberg New Energy Finance and Lighting Global for the Global Off-Grid Lighting Association, the off-grid solar lighting market has experienced impressive growth in the past 5 years, with more than 100 companies selling 20 million branded products. These lamps have provided light for about 100 million people, or less than 8% of the potential market. Kenya, Tanzania, and Ethiopia are Africa's prime markets, while India is leading the way in Asia [65].

The major barrier to more rapid adoption has been the shortage of financing to set up the necessary distribution infrastructure and to provide loans for potential customers. The cost of solar panels and batteries has not been falling as rapidly as that of the LED light sources. Thus the major further contribution that the SSL industry can make would be to increase the efficacy of the LED packages to 255 lm/W, which would halve the necessary capacity of the panels and batteries or double the light output of the solar lanterns.

4.0 Connected Lighting

SSL is creating an opportunity for a whole new lighting system paradigm. Connected lighting, smart lighting, and adaptive lighting are some of the terms that describe recent innovations in the lighting industry enabled by the emergence of SSL. SSL is fundamentally controllable, can be designed to be spectrally tunable, and can easily and inexpensively accommodate additional functionality through the integration of sensors, processors, and network interfaces. The convergence of SSL, low-cost sensors, smartphones and apps, and the Internet of Things (IoT) is expected to facilitate new lighting functionality and an unprecedented exchange of data among lighting and other building systems, the Internet and other devices (e.g., mobile phones). The ubiquity of lighting in the built environment, in overhead locations, provides a unique and valuable opportunity to create a dense grid of network nodes for data collection and sharing in and near buildings. This can enable not only improved lighting control, but improved management of building energy systems, security systems, space utilization, and other functions that have yet to be identified.

Although SSL is still developing and represents only a portion of the installed base, there is now near-universal acknowledgement that it will eventually become the dominant technology for most lighting applications. As a result, lighting product developers are starting to consider how they will leverage this opportunity by adding additional functionality and value to SSL luminaires that are rapidly replacing existing luminaires. Developing connected lighting products is a key part of that strategy.

4.1 Lighting Control

Lighting control has the potential to deliver significant energy savings by adjusting the amount of light to the real-time needs of a particular space and its occupants. Control systems might be based on occupancy sensing, daylight harvesting, high-output trim, personal area controls, or any combination of these approaches. Control systems are particularly well suited to SSL and have been shown to provide energy savings of as much as 20 to 60% of SSL power consumption, depending on the application and use-case [66].

In recognizing the energy savings potential of lighting controls, California expanded its requirements for the use of advanced dimming controls and occupancy and daylight sensors in nearly every application covered in its most recent Title 24 building code.[k] In particular, the code has expanded the requirements for demand-response, daylight harvesting, and aisle and open area occupancy sensing. To meet these requirements, controls must reduce lighting power in some spaces by at least 50% during unoccupied periods. For the first time, lighting in parking garages, parking lots, and loading and unloading areas will also be required to have occupancy controls, with at least one additional level between 20 and 50% of full lighting power.

---

[k] For more information on Title 24 please see: http://www.dgs.ca.gov/dsa/Programs/progCodes/title24.aspx

While many products for controlling light have been commercially available for quite some time, their deployment and resulting energy savings have been limited due to their complex configuration, high cost, limited interoperability among devices from competing manufacturers, and a narrow range of people who know how to design, install, commission, and operate them. Figure 4.1 shows the percentage of commercial buildings using control strategies and what type of controls system are installed. With such a small fraction of buildings currently using controls, there are significant opportunities to increase energy savings through embedded controls in LED luminaires.

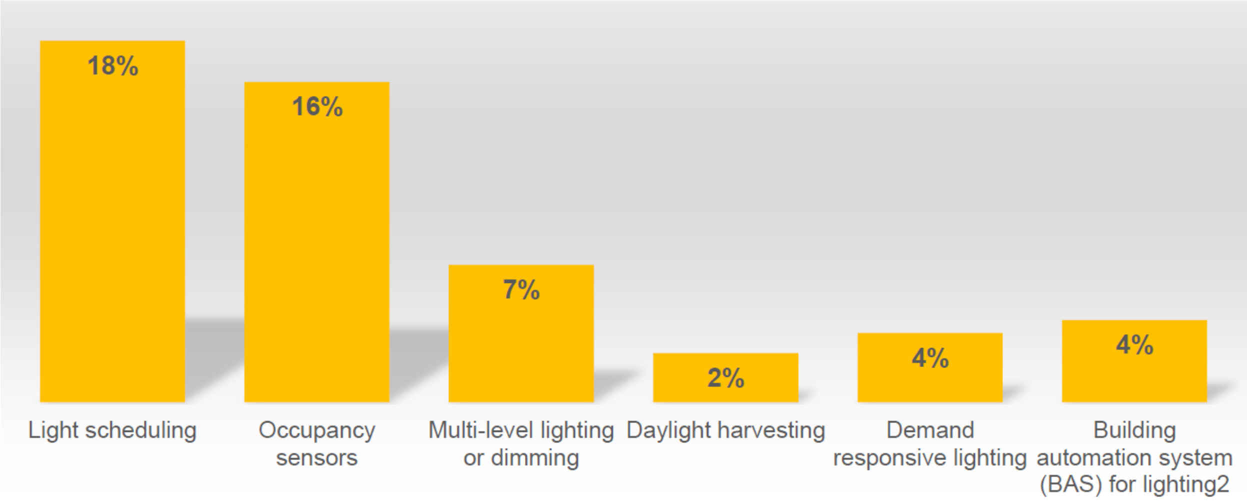


Figure 4.1 Percentage of Commercial Buildings with Controls Strategy according to the 2012 Commercial Buildings Energy Consumption Survey by the U.S. Energy Information Administration
Source: Gabe Arnold, DLC, DOE Connected Lighting Systems Meeting, Portland, OR, November 2015 **[67]**

SSL products are poised to be the catalyst that unlocks the energy savings potential of lighting controls due to their unprecedented controllability—not only for light output, but also the spectral composition of that light—as well as the low cost at which additional sensing, data processing, and network interface hardware can be integrated into LED luminaires compared to traditional light sources. While fluorescent sources have long been capable of delivering variable light output when paired with dimming ballasts, the significant cost of those ballasts has been a barrier to adoption. Other reasons why lighting controls systems have not reached their full potential include:

- Installation, start-up and commissioning complexity, which have limited the ability of building owners and operators to leverage the full capability of installed systems, or to modify them (by either re- or retro-commissioning) in response to changes in space configuration or occupant activity.
- User interface complexity, which sometimes results in disabling systems because maintenance staff cannot set the lighting controls to operate as desired.
- Lack of interoperability among system components offered by different vendors, which has limited the ability of building owners and operators to modify the installed systems (e.g., by installing new or better sensors or software with a better user interface). This is especially critical to accommodate changes in space configuration or occupant activity, or to merely

expand them if the original vendor has changed technologies or protocols or has exited the market.

- Limited ability to quantify and report performance (in particular, energy consumption), which has driven some utility energy efficiency programs (in some cases, owners and operators) to implement expensive and time-consuming measurement and verification programs.

Intelligent, networked lighting devices with integral sensors could collect and exchange data with each other so that lighting control can be implemented in a whole new way: leveraging new data streams, algorithms, and data analytics services. Figure 4.2 shows how these systems could work together. The value of services made possible by data from networked SSL systems might partly or fully offset the incremental costs of the sensors, network interfaces, and other additional components.

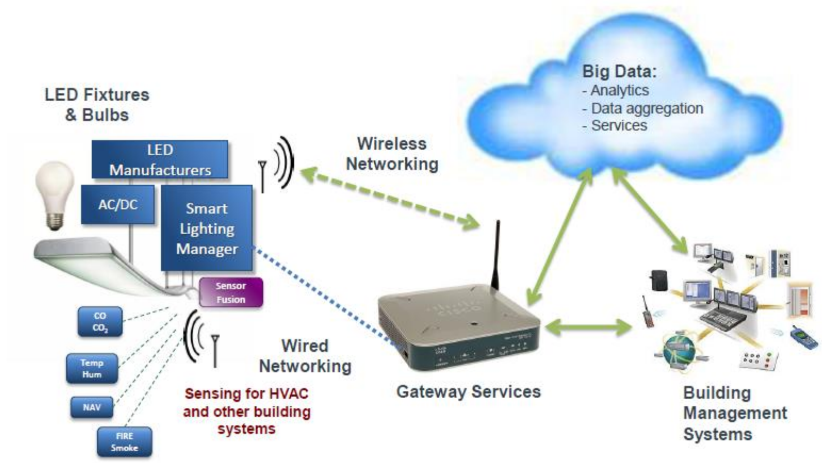


Figure 4.2 Lighting as Part of an Integrated Control System

Source: Tom Griffiths, LEDs Magazine, Integrating the Internet of Awareness into our Smart SSL Systems, February 2015 [68]

Systems made up of connected lighting devices could become data collection platforms that enable even greater lighting and non-lighting energy savings in buildings and cities, and much more. This ability to collect and exchange useful data and possibly even serve as a backbone of the fast-emerging IoT offers the potential to enable a wide array of services, benefits, and revenue streams that enhance the value of lighting systems and bring that improvement to building systems that have long operated in isolation. Right now, however, that potential is still on the table, as technology developers jostle with competing ideas for how much to collaborate in their industry, and how much to compete.

As controls have become increasingly important, a number of lamp and luminaire manufacturers, either on their own or in partnership with a controls company, have begun integrating control devices within their products. Some examples of luminaires with fully integrated lighting controls include Cree's SmartCast and Philips' SpaceWise. Cree's SmartCast lighting controls technology platform provides occupancy sensing and daylight-harvesting capabilities, in addition to field-tunable color temperature. The luminaires are equipped with occupancy and ambient light sensors, dimming controls, and are interconnected with a wireless mesh. The scheme enables automated commissioning of fixtures within a room using a Cree remote control. Philips' SpaceWise lighting controls technology provides a similar solution, with embedded sensors and wireless controls that provide plug-and-play mesh network capabilities with easy grouping of luminaires, automated calibration, and daylight commissioning.[l]

Other available controls products include building management solutions that use advanced sensors packages embedded in LED lighting fixtures, such as Enlighted's Energy Manager, which provides the data analysis for all data harvested by the advanced sensor package.[m] In addition to being the collection point for the energy, occupancy and environmental data captured by the sensors, the system provides a web-based user interface for lighting system management and optimizing building system performance. With insights from real-time data, facilities managers can make informed adjustments to energy consumption or improve comfort in individual areas.

4.2 Communication

Most of the major lighting companies have implemented a control system architecture using either wired or wireless interfaces to link lighting to sensors, switches, dimmers, and control panels. Even though there is not a common accepted architecture, there are many legacy communications protocols used in lighting control systems such as DALI (digitally addressable lighting interface) or DMX512. Basically, communication protocols allow devices to communicate with each other using a mutually comprehensible, standard language.

Over the past decade, the use of wireless connected devices has become widespread. Technologies such as Wi-Fi, Bluetooth, and ZigBee are now found in many devices, improving their ease of use and capabilities. The rapid market adoption of smartphones and tablets has also initiated a change in the way people control devices. With this shift toward wireless connected systems, lighting controls can become easier to use and can create opportunities to add valuable functionalities in addition to reducing energy use. For example, a user can access an existing control system through a software application (app) that can be downloaded on a smartphone. This ease of connecting devices in a network has led to organizations such as The Connected Lighting Alliance to champion open wireless protocols such as ZigBee (IEEE 802.15.4), Bluetooth, and Wi-Fi.

In addition to these wireless technologies, power over Ethernet (POE) is a wired solution gaining more consideration for lighting controls. Proponents, such as Cisco, predict lighting will go the same path as other technologies that converged with IP workplace service –e.g., telephony, security, and current building management systems based on BACnet. POE-capable LED luminaires have entered the market

---

[l] For more information on Cree SmartCast and Philips' SpaceWise please see: http://www2.cree.com/smartcast-landing-page and http://www.usa.lighting.philips.com/products/product-highlights/spacewise-wireless-lighting-controls.html

[m] For more information on Englighted's Energy Manager please see: http://www.enlightedinc.com/products-page/#energy-manager

with recent announcements by Cree introducing its SmartCast POE LED troffers and downlight fixtures, and Philips' PowerBalance POE LED troffers.

4.3 Interoperability

Just as SSL technology brought many new players (e.g., semiconductor manufacturers and microelectronic system developers) to the lighting industry, the coming intersection of lighting, communication networks, big data, and advanced analytics—all facilitated by the IoT—will significantly alter the lighting industry landscape. The challenge is agreeing on common platforms and protocols, which will facilitate the transfer of useable data among lighting devices, other building and control systems, and the Cloud. The need for interoperability is crucial, so that multiple devices, applications, networks, and systems can work together and reliably and securely exchange data.

Most of the current lighting control systems use proprietary hardware and software, essentially forcing the user to source all products from a single vendor to ensure interoperability. Because specifications are likely to change over time, heavy reliance on a single supplier increases user risk when considering new installations, creating dependency on a vendor that may not be able to support these changing needs. In this situation, the user is faced with the decision to start over or live with the existing, increasingly unsuitable system.

A networked control system comprises many layers, as illustrated in Figure 4.3; there are the physical and data link layers (where data are created), followed by the transport and network layers (where data are handled and understood) [69]. Within these various layers many issues can occur, such as interoperability between luminaires and sensors, between luminaires and controllers, and between central management system and device network. These issues are illustrated in Figure 4.4. Specifically, application-level interoperability is needed to ensure that devices and systems can not only "hear" each other, but can also understand what is being said. Many existing lighting protocols focus on lower-level interoperability, which is akin to ensuring that multiple parties can dial in to a teleconference without first making sure that they all speak a common language. If they do not, information cannot be exchanged without a translator.

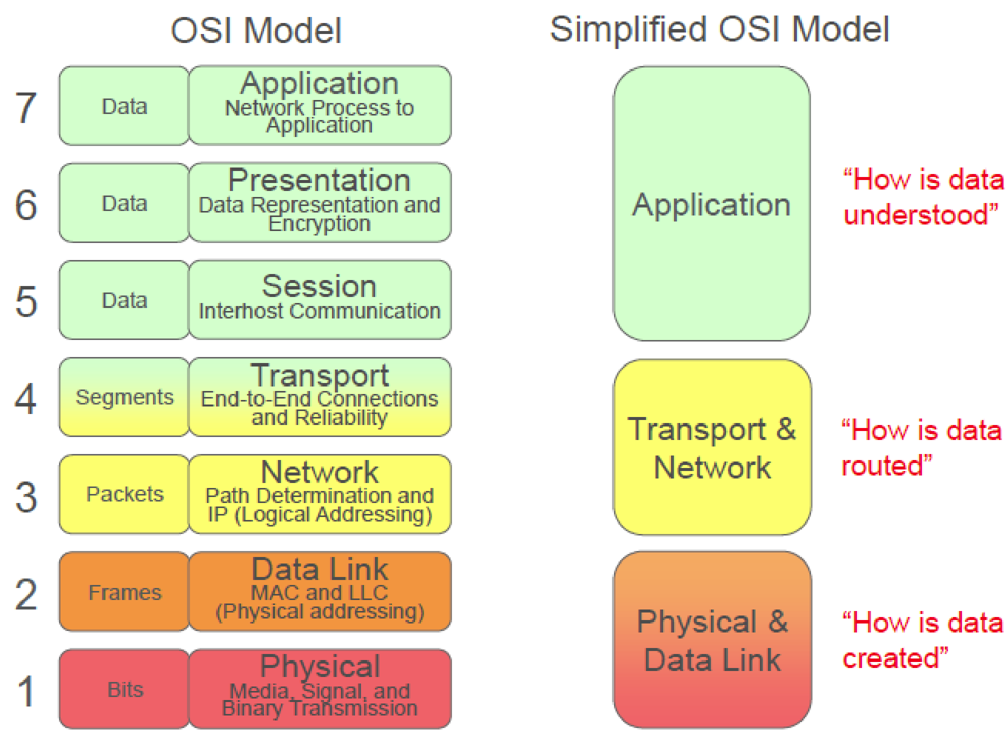


Figure 4.3 The Open System Interconnection (OSI) model shows how applications can communicate over a network. The reference model defines a networking framework to implement protocols in seven layers. The purpose of the OSI reference model is to guide developers so digital communication products and software programs they create will interoperate.

Source: Michael Poplawski, DOE SSL Market Development Workshop, Detroit, MI, November 2014 [69]

Standardized communication protocols can help increase interoperability and offer simpler system integration. Such standards can lead to more choices for customers among competing vendors, reducing investment risks for those customers because they may be freed from future dependence on a single vendor. Standardized communication protocols also can benefit the vendors because they support market growth, which benefits all players in the market. Several groups are working to establish common specifications and standards that support improved interoperability, including the ZigBee Alliance, the Thread Group, and the Open Connectivity Foundation. DOE intends to help industry consortia unlock the full potential of future systems. While interoperability may be perceived to be less important for relatively small, self-contained lighting systems (e.g., those servicing a single conference room or building floor), the challenges will increase over time as more systems become interconnected in support of initiatives such as net-zero building, smart-city, smart-grid, and intelligent transportation.

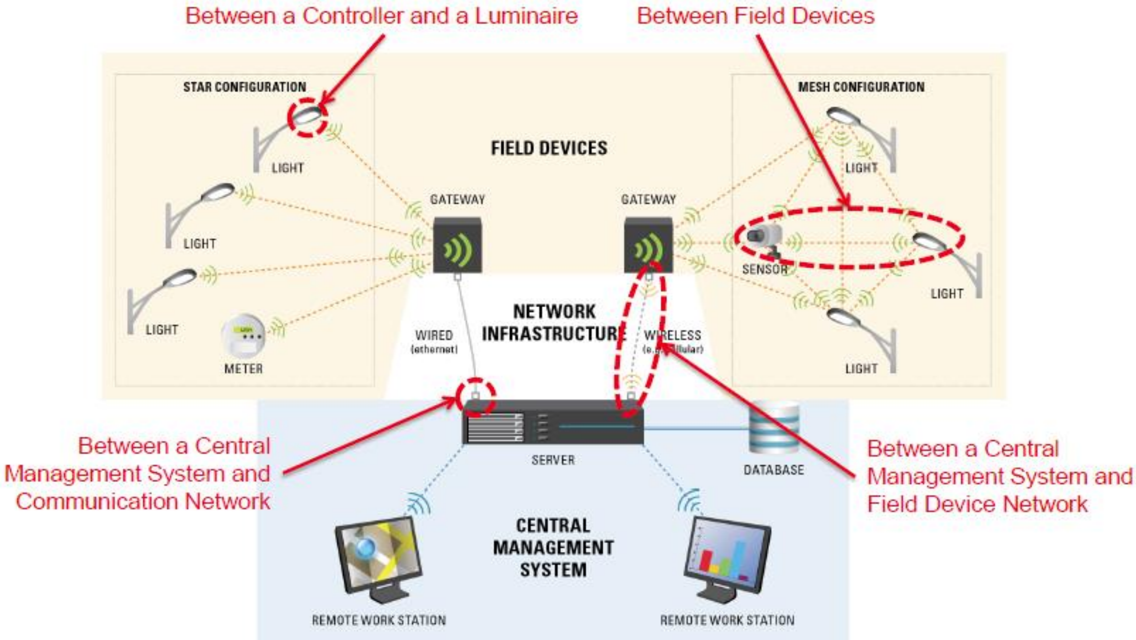


Figure 4.4 Lights, Sensors, Meters, Gateways, and Management Systems Working Together
Source: Michael Poplawski, DOE SSL Market Development Workshop, Detroit, MI, November 2014 [69]

Interoperability also remains a key hurdle for home energy management systems, along with the cost of those systems. Home management integration through systems like Wink, Belkin's WeMo, and Apple's Homekit allow consumers to control most home devices using one simple interface. For example, the Wink Hub allows a diverse collection of smart products to speak the same wireless language so that they can be easily controlled from a single Wink software application. The Wink app allows users to monitor and control energy use for the devices within their home. Many of the other home integration systems available behave in a similar manner. Most connected lighting products require a bridge or hub to connecting with a local Wi-Fi network (e.g., Philips Hue, GE Link, Cree Connected, OSRAM Lightify lamps). Figure 4.5 shows some of the products available for use with home energy management platforms. Interoperability among home automation systems could simplify the use and promote the acceptance of advanced lighting controls and home energy management systems.[n]

---

[n]Please refer to the following websites for more information on the mentioned products:
Wink: http://www.wink.com/
Belkin's WeMo: http://www.belkin.com/us/Products/home-automation/c/wemo-home-automation/
Philips Hue: http://www2.meethue.com/en-us/
GE Link: http://gelinkbulbs.com/
OSRAM Lightify: http://www.osram.com/osram_com/tools-and-services/tools/lightify---smart-connected-light/

(a) (b)

Figure 4.5 Residential Smart Lighting Products: Cree Connected and GE Link Lamps with Wink Hub and App

Source: Wink [70]

4.4 Connected Lighting Applications

4.4.1 Energy Monitoring

One of the key reasons electric utilities and energy service companies (ESCOs) have not invested more in lighting controls is uncertainty about the level of energy savings that will be achieved. Utilities know the savings can be highly variable and depend on a number of factors, including occupation levels and control system overrides by occupants. To reduce uncertainty, utilities and ESCOs sometimes resort to manual measurement and verification of lighting energy savings. This can push project costs much higher and sometimes undermine their cost effectiveness.

Connected lighting products can reduce the cost of energy savings measurement if those products have the capability to self-measure and report energy use. After the initial installation of energy measurement equipment, all the labor required to install and remove that equipment, and to analyze the collected data would be rendered unnecessary. The additional hardware cost could be modest, especially in the long run as required components are miniaturized and integrated into existing printed circuit boards in the luminaires. With this capability in place, utilities could offer incentives to customers based on actual savings instead of estimated savings. ESCOs could recover payments from their customers based on actual savings. Both ESCOs and utilities could offer a more convincing business case to their customers, and incur substantially lower cost for collecting and analyzing energy use data from lighting control projects.

Cree Connected: http://creebulb.com/products/standard-a-type/connected-60-watt-replacement-soft-white-led-bulb

The availability of energy use data from luminaires with integrated energy measurement and reporting capability creates opportunities for other energy-management processes. DOE is interested in the opportunity to facilitate and develop transactive energy markets with such data; a variety of market actors, including building owners looking to realize the value of available—and perhaps marketable—building-energy services also may be interested. DOE is working with industry partners to help identify and evaluate ways to leverage the broad availability of energy use data, and to identify cost-effective techniques for measuring the energy consumption of installed lighting systems.

4.4.2 Non-Lighting Related Data Analytics

Lighting is a ubiquitous powered infrastructure that can eventually be replaced with networked SSL devices providing a backbone for a dense sensor array. In addition to a range of occupancy and daylight sensors, other types of sensors could be installed, including those to measure CO_2, imaging, vibration, sound, and barometric pressure. This allows for data collection and exchange in ways not previously possible, and allows building owners/operators to manage and understand their physical environment to enable greater productivity, efficiency, and security.

Smart Cities

To create a smart city, a dense sensor network must be deployed to provide data on variables such as air quality monitoring, weather warnings, video surveillance, parking space availability, and traffic patterns The installation of LED street lights provides cities with dramatic savings through increased energy efficiency, decreased maintenance needs, longer-rated lifetimes, and can be the platform used to integrate a sensor network to provide value-added features to the city, as illustrated in Figure 4.6. By adding wireless controls and leveraging data through an intelligent platform, LED street lights act as a wireless mesh communications network that would be cost prohibitive if developed separately. The street light poles are the ideal platform for adding environmental sensors and security infrastructure, such as a cameras or acoustic sensors to detect gun shots in real time and notify police. The data can be sent to a centralized control platform, which then can be used to create dashboards for city staff to provide information and control appropriate to their responsibilities.

Cities will save money because LED lighting is more energy efficient than the incumbent High Pressure Sodium (HPS) lighting, and because they can pay only for the energy each light uses instead of a flat-rate tariff. In addition, city officials will be able to program when street lights turn on and off or dim (e.g., having the street light at 100 percent brightness when it turns dark and gradually dim to 50 percent in the middle of the night and return to full brightness in the early morning for commuters) allowing for further energy savings. The connected street lights also provide the city the location of each light pole to better manage the assets, particularly when there are failures.

Figure 4.6 Services that can be Provided to a City when Utilizing LED Lighting Street Lights Integrated with Sensors

Source: Himamshu Prasad, DOE SSL R&D Workshop, Raleigh, NC, February 2016 [71]

While the addition of sensors does add some cost to the final street light fixtures, the standard 7-pin American National Standards Institute (ANSI) receptacle allows manufacturers an easy way to add on a sensor suite (see Figure 4.7). A wireless node, like the GE Lighting LightGrid wireless node, can be added to the street light receptacle and provide valuable features including [71, 72]:

- Accurate, utility-grade energy metering per pole–you pay for what is used.
- GPS chip embedded into node–always know the exact location of controllers and fixtures.
- Node automatically connects to network and acquires location in just minutes, reducing commissioning time.
- One-piece control–no special electronics necessary in the fixture. Node simply connects to external socket, so it can be added easily at any time.
- Operates with programmed schedules in case of network outage

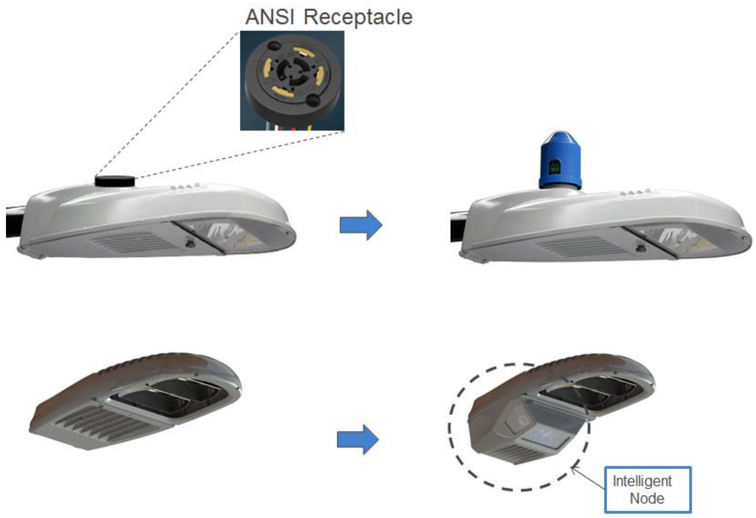


Figure 4.7 LED Lighting Street Light Fixtures Showing the Location of Integrated Sensors
Source: Himamshu Prasad, DOE SSL R&D Workshop, Raleigh, NC, February 2016 **[71]**

Indoor Positioning

LED lighting is being used successfully as a platform for indoor positioning in retail and other heavy traffic buildings by using visible light communication (VLC) to provide personalized location-based services for occupants via a mobile app. VLC is a technology in which information can be transmitted by switching, or modulating, LEDs on and off far faster than the eye can detect. This allows data to be transmitted wirelessly to receiving devices within range of the light emitted by the transmitting luminaires. VLC technology sends out a unique code that can be detected with any smartphone camera. The control software and Cloud solution identifies the code and exactly determines the position of the smartphone on the shop floor. In addition to VLC, which provides the real-time and accurate (within 10 to 15 cm) positioning, the luminaire contains Bluetooth Low Energy (BLE) beacons to track the customer path while the phone is stowed away (unable to use VLC).

Several lighting manufacturers have lighting products that incorporate VLC and BLE beacon technology into luminaires for use by retailers. Retailers can then use the luminaires for highly accurate indoor location services, complete with the ability to transmit location-specific data to shoppers using smartphones, such as discount coupons or product locations within the store (illustrated in Figure 4.8). The customer benefits through the receipt of targeted information or product promotions, and the retailer benefits from knowledge of customer flow and product interest. The ability to develop a source of recurring revenue from this feature changes the economics of LED adoption for the retailer by accelerating the return on investment.

In addition to app-based services for customer use, beacons embedded in LED luminaires allow for indoor analytics that can measure people passing by and entering your store or building. These location-based analytics allow you to visualize how many people in your buildings are first timers, repeat customers, and how long they are staying. The use of the beacons to locate smartphones through BLE or

Wi-Fi signal pings provides valuable information about traffic flow and dwell time in certain locations. The benefits to this granularity in building traffic can help businesses understand how to:

- Identify peak traffic hours
- Adjust staffing needs
- Maximize the value of repeat customers
- Draw customers inside the doors

Indoor positioning capabilities, together with the ability to provide mapping for surrounding outdoor spaces, create new opportunities for data analytics that can lead to operational efficiencies, enhanced safety, and increased revenues in spaces such as airports, shopping malls, logistics centers, universities and healthcare facilities.

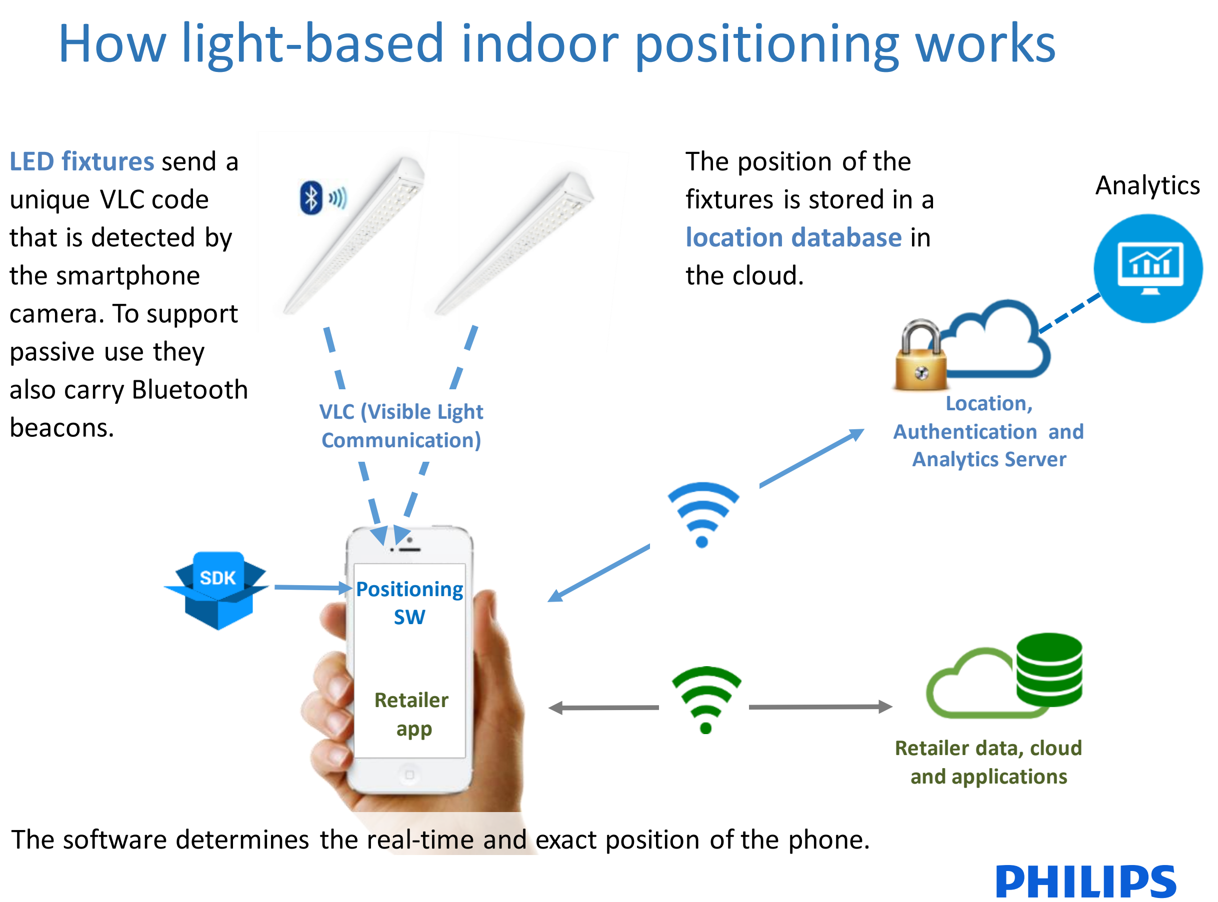


Figure 4.8 Indoor Positioning Concepts use VLC to Communicate with the Camera in a Smartphone to Provide the Desired Information to the Customer

Source: Philips Lighting, 2016 [73]

Broadband Communications Using VLC

The opportunity to provide new sources of broadband communication using VLC may be important in the future to help cope with the continuing rise of global mobile data traffic, which grew 74% in 2015. Cisco projects that global mobile data traffic will increase nearly eightfold between 2015 and 2020, growing at a compound annual growth rate (CAGR) of 53% from 2015 to 2020, as shown in Figure 4.9 [74]. The increasing number of wireless devices that are accessing mobile networks worldwide is one of the primary contributors to global mobile traffic growth.

R&D is being performed in the area of VLC to enhance communication bandwidth (Li-Fi), though products providing this feature are not currently available. VLC requires improvements to enable faster data transmission speeds to address one of the challenges for data transfer with lighting. More research is required to improve the modulation speeds of the LEDs; this would increase transmission speed and make this added communication functionality valuable. Increasing transmission speed may require the exploration of laser diodes (LD) or superluminescent diodes (SLDs) for lighting with their faster modulation speeds. Other system-level challenges include developing the ability to handoff the Li-Fi signal as users move between luminaires, as line of sight is required for VLC, and requiring that the luminaires have wired connections to a high-speed data network.

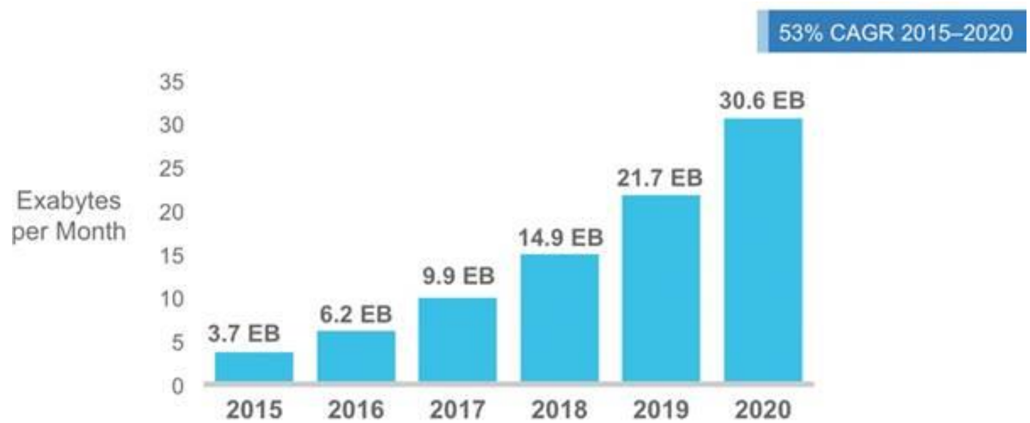


Figure 4.9 Cisco Forecasts 24.3 Exabytes per Month of Mobile Data Traffic by 2020
Source: Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update 2015–2020 White Paper, February 2016 [74]

4.5 Security

As more devices are becoming part of a connected world, the benefits come with security risks, as demonstrated by a few publicized cases in which firewalls have been breached by hacking into lighting products [75]. An Internet-connected lighting system can provide hackers entry points to everything behind the network firewall, e.g., a home computer, a retailer's payment terminals, or a government office’s sensitive database.

It is imperative that manufacturers integrate security into their product and software development lifecycle right from the start. Testing has found that even the most basic security practices were often not followed, including the lack of encryption and authentication, the use of clear-text protocols to transmit sensitive information (e.g., passwords), and the use of default passwords in customer environments [75]. Securing user data and privacy, ensuring availability, and protecting network-connected devices against unauthorized access will be critical for companies wanting to gain and maintain trust with smart-lighting buyers.

4.6 Conclusion

DOE intends to help develop connected SSL system technology primarily because it enables even deeper energy savings than those achievable by converting from conventional to SSL sources. Those deeper energy savings are made possible not only from the advanced lighting control potential of connected systems, but also from other end uses such as heating, ventilation, and air conditioning (HVAC) systems, transportation energy (from outdoor connected lighting systems), and others that will likely emerge as the incremental cost of providing that energy management capability falls.

Connected lighting systems promise to provide value far beyond energy savings, such as the location services for retailers described above. Those additional services have the potential to add value, revenue streams, and functions that may partly or even completely offset the cost of providing improved energy management services, making the energy management services low cost or potentially free, depending on how costs of additional functionality are allocated among potential services.

DOE is working with industry partners to help accelerate the development of connected lighting systems that 1) allow luminaire systems to self-measure and report energy use, 2) have a high degree of application-level interoperability, and; 3) are easier to configure, commission, and maintain than is common in current lighting systems. As part of that focused effort, DOE is conducting a series of connected lighting workshops, focused on facilitating and encouraging collaborative industry efforts in these areas. Those workshops will also be used to help identify high-priority R&D investments needed by both the public and private sectors.

5.0 LED Technology and Manufacturing Status, Opportunities, and Challenges

LED lighting technology has improved dramatically over the past 10 years. Improvements in technology have enabled LEDs to achieve among the highest efficiencies of available white light sources. Improvements in manufacturing have enabled LED products to achieve a low enough cost that there has been measurable LED adoption in all general illumination applications. Despite this progress, further improvements are possible and desirable. The technology can be improved in efficiency and in other features, such as color quality, light distribution, form factor, and building integration. The manufacturing technology for LED lighting can also be improved to reduce cost and increase market penetration, resulting in the greatest possible energy savings for the nation.

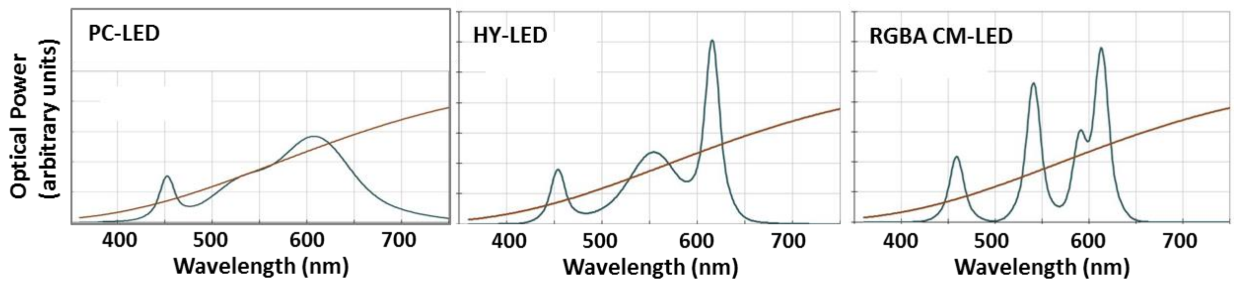
The following sections explore the current status, improvement opportunities, and challenges for LED technology. The key challenges currently facing LED technology also represent some of the greatest opportunities for improvement. The following sections identify eight key opportunities/challenges. The sections cover both the LED package, which creates the white light, and the LED luminaire, which houses the LED package and provides the appropriate interface between the electrical supply, building integration, thermal handling, and optical distribution.

5.1 LED Package Technology

This section describes three commonly considered architectures for creating white light. Simulated optical power spectra for the three architectures are shown in Figure 5.1. The phosphor-converted LED (pc-LED) is based on a blue LED to pump green and red wavelength optical downconverters (typically phosphors), thus producing white light. The hybrid LED (hy-LED) is based on a blue LED used to pump a green wavelength downconverter, then the blue and green light is mixed with light from a red LED to again produce white light. The red, green, blue, and amber (RGBA) color-mixed LED (cm-LED) is based on four primary LEDs, blue, green, amber, and red to produce white light.

Throughout this section, quantitative analyses of the three architectures are described by separating their overall efficiencies into sub-efficiencies associated with the various source colors, and then re-assembling them into white light using an optical modeling worksheet.[o] The analyses reveal the relative impacts of various sub-efficiency losses imposed on the different architectures, and the corresponding opportunities for targeted improvements. These sub-efficiency breakouts and efficiency roll-ups are detailed in Table 5.1 and Table 5.2.

[o] Simulator developed by Yoshi Ohno at the National Institute of Standards and Technology (NIST) (version 7.5).



Note: In all cases, the peak wavelengths and relative intensities are those which maximize luminous efficacy of radiation (LER) for a 3000 kelvin (K) (warm white) CCT, a "standard" color rendering index (CRI) R_a of 80 and a CRI associated with the ninth, deep-red Munsell color sample $R_9 > 0$. The spectral widths of the various source colors correspond to the current state-of-the-art. Overlaid on each spectrum is the spectrum from an incandescent black-body source at 3000K.

Figure 5.1 Typical Simulated Optical Power Spectra for the Three White-Light LED Package Architectures Considered

For all three white-light architectures, four important performance characteristics, when optimized (especially simultaneously), can introduce efficiency penalties: drive current density, operating temperature, CCT, and color rendering. The tradeoffs for each, as well as the values chosen for the following analyses, are described below:

1. Drive current density (35 amperes per square centimeter; A/cm^2). Drive current determines the amount of luminous flux being generated in the package. "Hero" commercial LED packages can achieve luminous efficacies of 200 lm/W, but only by operating at lower current densities, which results in less overall luminous flux being generated in the package, and thus having a higher cost per lumen. Packages driven at a higher current density, produce more lumens; however, due to a phenomenon known as efficiency droop (which will be discussed later), the efficiency of blue LEDs decreases at higher current densities, as shown in Figure 5.2(a). For normalization purposes, all analyses in this section are for packages driven at 35 A/cm^2.
2. Junction temperature (at room temperature, 25 degrees Celsius; °C). This is the temperatures during which operation occur at the junction between the p- and n-type semiconductors that form the diode. This junction temperature, T_j, affects the efficiency of the device. As shown in Figure 5.2(b), the relative lumen output (and therefore efficiency) decreases with increasing junction temperature. This phenomenon, known as thermal droop, is likely to grow in importance, and will be discussed in Section 5.2. For consistency with previous years' data and targets, the following analyses emphasize operation under standard room-temperature conditions (T_j equal to 25°C). However, because LED packages are often driven "hard" (35 A/cm^2 and higher), they also often run "hot" (T_j greater than 25°C). Therefore, their hot performance is often of greater interest than their room-temperature performance. This also is why many LED manufacturers test LEDs at 85°C. The junction temperature is affected by the package design, including thermal handling materials, drive current, and ambient temperature.

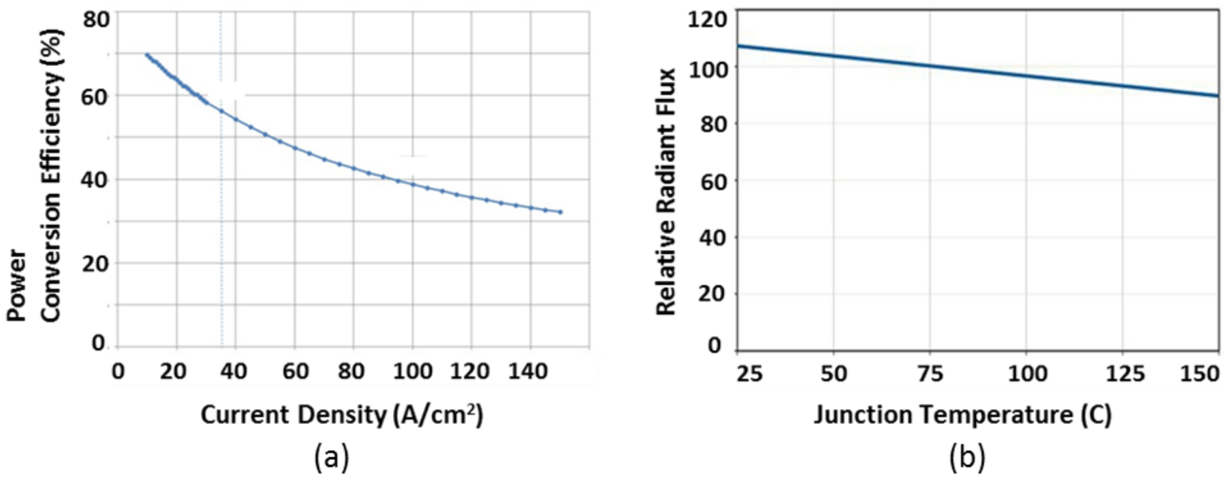


Figure 5.2 Two Types of Efficiency Droop: (a) Current Efficiency Droop, and (b) Thermal Efficiency Droop

Source: Cree XLamp XT-E Datasheet **[76]**

3. Correlated Color Temperature (Warm White, 3000K). Achieving higher efficiencies has thus far been more challenging for warm white LEDs than for cool white packages due to the relative inefficiency of red LEDs and red downconverters compared to blue LEDs. However, advancements driven by the push to increase the efficiency of warm white LEDs will also likely benefit cool white LEDs. Though warm white is currently more "challenged" than cool white, the maximum luminous efficacies of radiation achievable for warm is somewhat higher than that for cool white. As can be seen in the left panel of Figure 5.3(a), maximum luminous efficacies of radiation for color rendering index (CRI) 80 are slightly higher for warm (about 414 lm/W at 3000K) than for cool (about 390 lm/W at 5700K) white. This is because the human eye is more sensitive to red than to blue light.

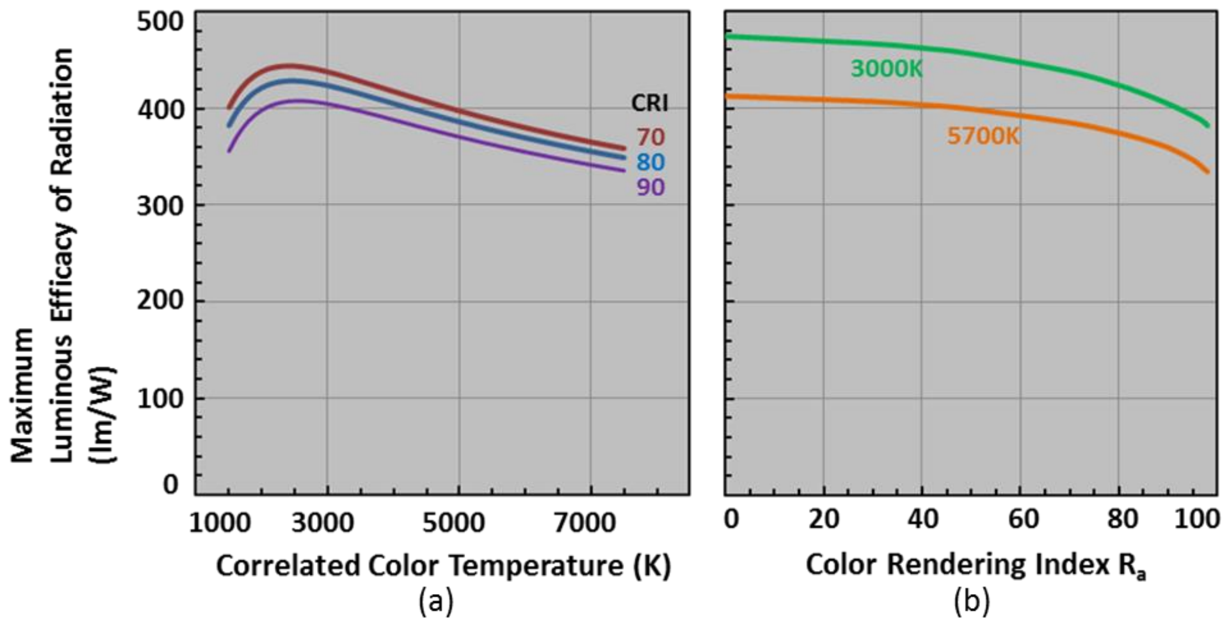


Figure 5.3 Theoretical Limits to White Light Luminous Efficacies of Radiation vs (a) CCT for a Given CRI, and (b) CRI for a Given CCT

Source: Hung and Tsao, Maximum White Luminous Efficacy of Radiation Versus CRI and Color Temperature: Exact Results and a Useful Analytic Expression, June 2013 [77]

4. Color rendering (Ra equal to 80, R9 greater than 0). There is an inverse relationship between luminous efficacy and color rendering quality. As seen in Figure 5.3(b), increasing CRI from 80 to 90 decreases the maximum achievable luminous efficacy by 10%. Practical data suggests the drop to be significantly higher in the pc-LED architecture, in the range of 15 to 25 percent, due to deficiencies in the red phosphors. To satisfy the majority of applications for white light, relatively high color rendering quality, i.e., a “standard” CRI, R_a of 80 and an R_9 value greater than zero is desired.[p] However, some sectors of the market increasingly demand even higher color rendering quality. Furthermore, the meaning of color rendering quality is itself an active area of study. It is likely that new measures will someday replace or at least augment the standard CRI in ways which depend on the particular illumination application. For example, the

[p] The standard CRI (R_a) is a measure of the ability of a source to accurately render a set of eight standard color samples R_1 to R_8 (CIE 1995), but fails to measure the ability to render saturated colors, especially red which is represented by color sample R_9. A value for R_9 is therefore often included with CRI to quantify the ability of a source to render red colors. For example, the ENERGY STAR specifications calls for R_9 greater than or equal to 0, but some specifications bodies are starting to consider higher values with the California Energy Commission voluntary specifications calling for R_9 greater than or equal to 50.

Illumination Engineering Society of North America (IES) recently articulated TM-30,[q] a new method for evaluating color rending that includes both a “fidelity index” and a “gamut index.”

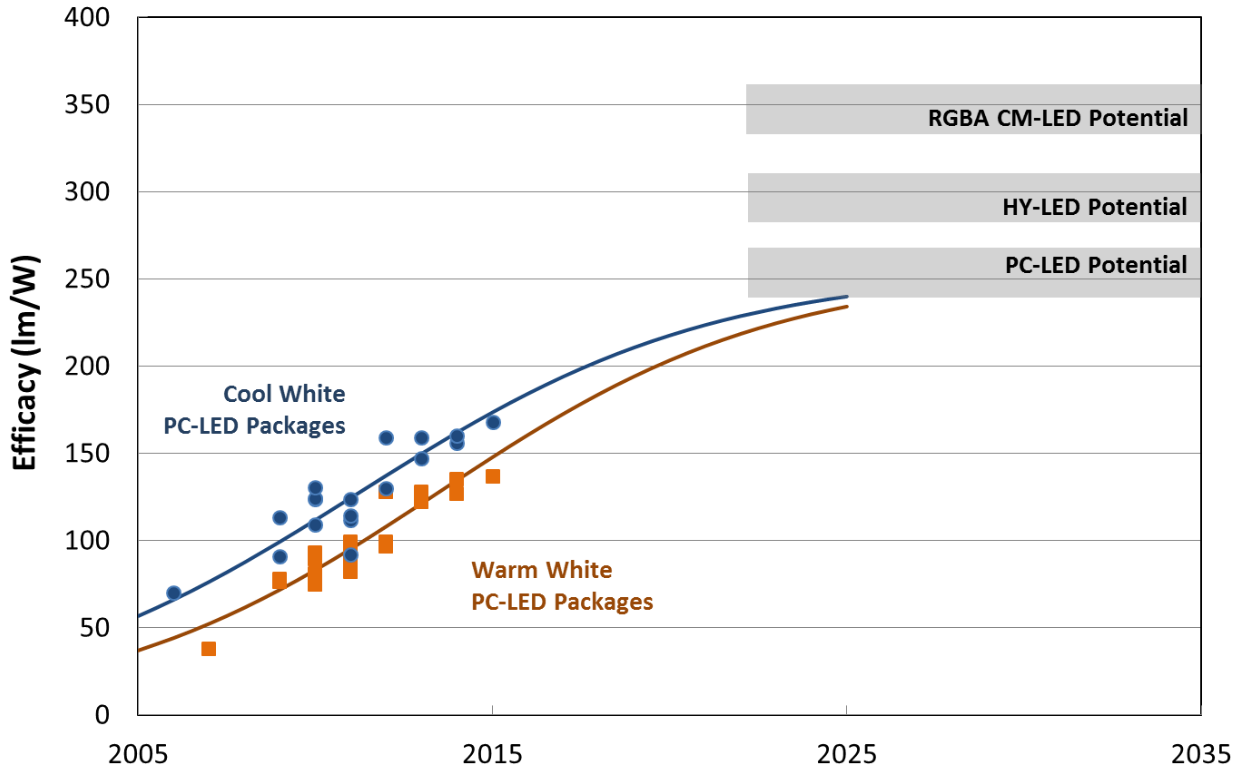
5.1.1 Pc-LED Architecture: Current Status

The pc-LED architecture was the first and is by far the dominant white light architecture. It has three major advantages over the other architectures: simplicity (only one LED to “drive”), temperature robustness (the indium gallium nitride, InGaN, blue LED and phosphor downconverters can operate at relatively high temperatures), and color stability (the fractions of red, green, and blue source colors is determined during manufacture by the phosphor optical density and is relatively stable over time).

Figure 5.4 shows a history of the luminous efficacy of pc-LEDs since the DOE SSL Program began and the progress that has been made. In just 10 years, luminous efficacies have increased by a factor of more than three, from less than 50 lm/W to approximately 150 lm/W. The principle reason has been improvement in blue LED efficiency; improvements also have been made in phosphors (efficiency and wavelength match to the human eye response) and package (optical scattering/absorption) efficiency.

---

[q] For more information on TM-30, please see: https://www.ies.org/store/product/ies-method-for-evaluating-light-source-color-rendition-3368.cfm

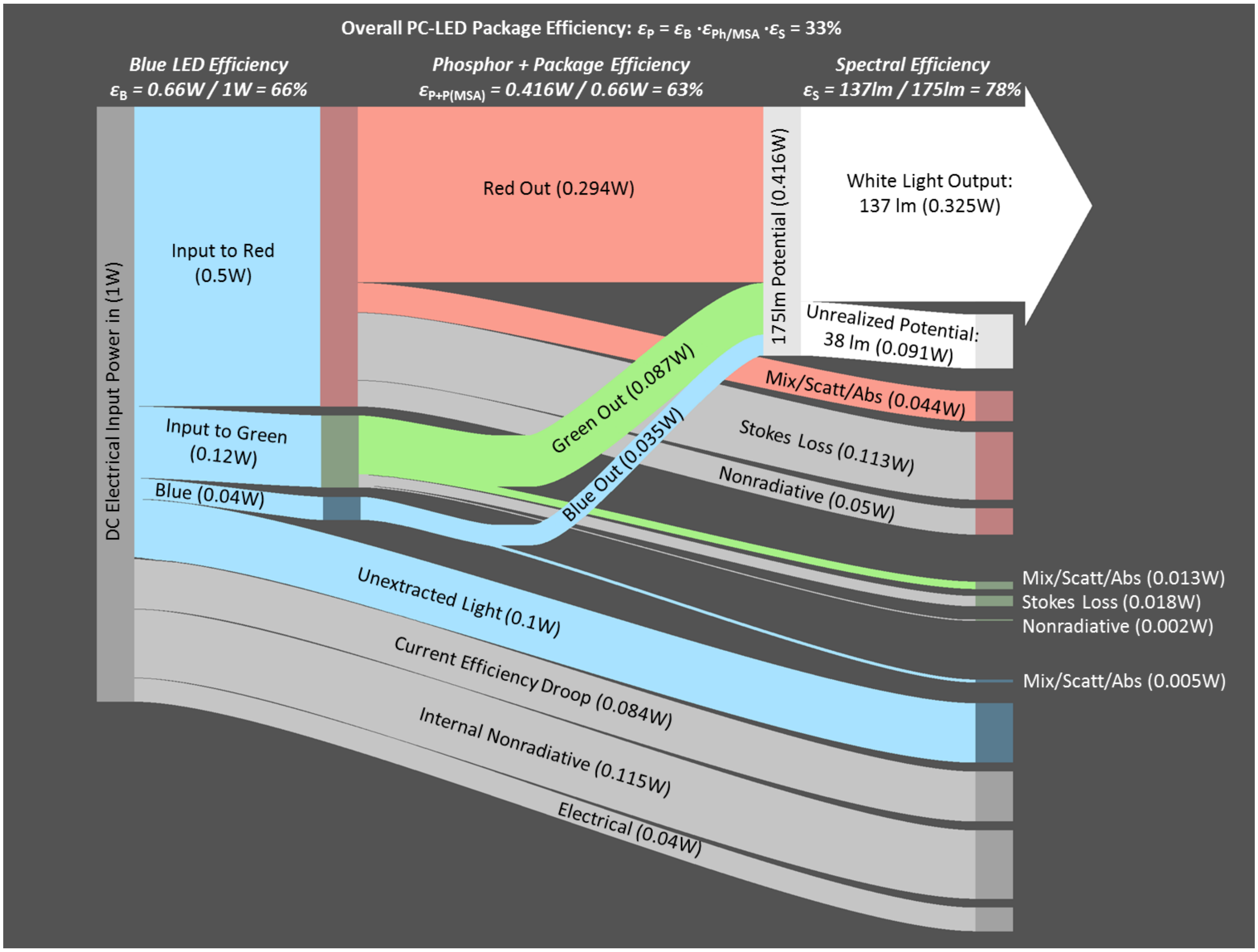


Note: Blue = cool white (5700K) data (circles) and logistic fit (line); orange = warm white (3000K) data (squares) and logistic fit (line). Late-2015 measured commercial products reach approximately 160 lm/W for cool white and approximately 140 lm/W for warm white. Approximate long-term-future potential efficacies of three white-light architectures (pc-LED, hy-LED, RGBA cm-LED) are shown as grey bars.

Figure 5.4: Efficacies of Commercial LED Packages Measured at 25°C and 35 A/cm^2 Input Current Density

Despite these improvements, there is much further to go. As illustrated by the lower gray band in Figure 5.4, luminous efficacies of approximately 255 lm/W are practically possible for pc-LEDs, a factor 1.6 times beyond the current state-of-the-art. To help visualize where this factor might come from, Figure 5.5 shows an estimated electricity-to-visible-light power-flow diagram for a current LED warm white light state-of-the-art commercial pc-LED package, in which a hypothetical 1 W (0.35 A x 2.85 V) is injected into the blue LED package at the left of the diagram, and 137 lumens of white light emerges from the pc-LED package at the right.

The blue LED converts the 1 W of electrical power with an efficiency of 66% into 0.66 W of blue optical power. En route, the blue LED loses 34% or 0.34 W of that electrical power to a combination of electrical resistance losses, internal quantum efficiency losses due to non-radiative recombination of injected electrons and holes at low current density, efficiency droop due to operation at higher (35 A/cm^2) current density, and losses due to incomplete extraction of blue light from the high-index InGaN semiconductor material.



Note: The diagram gives estimates for how 1 W = 0.35 A x 2.85 V of DC power is distributed into various useful and non-useful (loss) streams en route to being converted into white light. The colors of the various streams indicate the type of power they contain: gray for electronic excitations, colored for light at various RGB wavelengths, and white for white light formed from a combination of colors. For each loss stream we indicate both its absolute power as well as the percentage it represents of its immediately preceding parent stream.

Figure 5.5: Electricity-to-Visible-Light Power-Flow Diagram for a Late-2015 State-of-the-Art Warm White Commercial pc-LED Package

Source: Tsao, Coltrin, Crawford, and Simmons, Solid-State Lighting: An Integrated Human Factors, Technology, and Economic Perspective, July 2010 [78]

The green and red phosphors convert the 0.66 W of blue optical power with an efficiency of 63% into 0.416 W of blue (0.035 W), green (0.087 W), and red (0.294 W) optical power. En route, the phosphors lose 37% or 0.244 W of the initial blue optical power to a combination of internal quantum efficiency losses due to non-radiative recombination of electrons and holes excited in the phosphors, a fundamental Stokes deficit due to the lower energies of green and red versus blue photons, and a mixing/scattering/absorption loss as the green, blue, and red photons mix, scatter in, and occasionally get absorbed within the LED package.

Finally, the 0.416 W of white optical power, distributed spectrally in a 20 nanometer (nm) full width half maximum (FWHM) blue LED band, a 100 nm FWHM green phosphor band, and an 80 nm red phosphor band, yields a lumen output of 137 lm. The maximum luminous efficacy of radiation (LER) of white optical power at this CRI (80) and CCT (3,000K), when optimally distributed into three or four narrower (less than 20 nm) bands in the blue, green and red, is approximately 414 lm/W. Thus, 0.416 W of white optical power, if spectrally redistributed, could potentially give 175 lumens (0.416 W x 414 lm/W). The spectral efficiency of the LED package is thus 78% (137 out of a maximum of 175 lumens)

Taken together, the current overall LED warm white, state-of-the-art, commercial package efficiency is 33%, and is equal to the product of the blue LED efficiency (66%), phosphor and mixing/scattering/absorption efficiency (63%), and white light spectral efficiency (78%).

These estimates of sub-efficiency breakdowns and overall efficiency roll-ups are for warm white. Historical and current commercial pc-LED efficacies are somewhat higher for cool white because they require a lower optical power fraction of red light, and red light contributes more losses in the pc-LED architecture than either blue or green. The most important loss contribution is its Stokes efficiency loss (25% for the red, in contrast to 15% for the green and 0% for the blue). The second most important loss contribution is the 15% to the white light spectral efficiency loss, because the current 80 nm FWHM-wide red phosphor emission linewidth causes a significant spillover of light into the deeper red, where the human eye is less sensitive. This will be discussed in more detail in Section 5.1.2.

5.1.2 Pc-LED Architecture: Opportunities and Challenges

As discussed above, the current state-of-the art commercial pc-LED, with a luminous efficacy of approximately 137 lm/W, is about 33% efficient. Because of the fundamental Stokes efficiency loss associated with this architecture, 100% efficiency is not possible. As indicated in Table 5.1 and Table 5.2, even if all other losses were eliminated, the current pc-LED with its current spectral distribution of optical power can at most have a luminous efficacy of approximately 220 lm/W (LER × Stokes losses). This can be improved through improved spectral distribution of optical power, as discussed in more detail below, but it is not likely that all other losses will be eliminated. Thus we consider a luminous efficacy of 255 lm/W, or an efficiency of 61%, to be the “upper pc-LED potential,” and is indicated as such in Figure 5.4 by both the gray bar and the value that the logistic fit to the historical data has been set to approach.

Note that this upper pc-LED potential can be considered to be approximately equal for warm and cool white. This is because warm white requires a higher optical power fraction of red than blue light, which this leads to two offsetting effects. On the one hand, the human eye is more sensitive to red than to blue light, so warm white light will have an intrinsically higher spectral efficiency than cool white light. On the other hand, in the pc-LED architecture, red light has a higher Stokes deficit than blue light, so warm white light will have an intrinsically lower phosphor plus mixing/scattering/absorption efficiency than cool white light. These effects offset each other, with the net result being approximately similar potential efficacies.

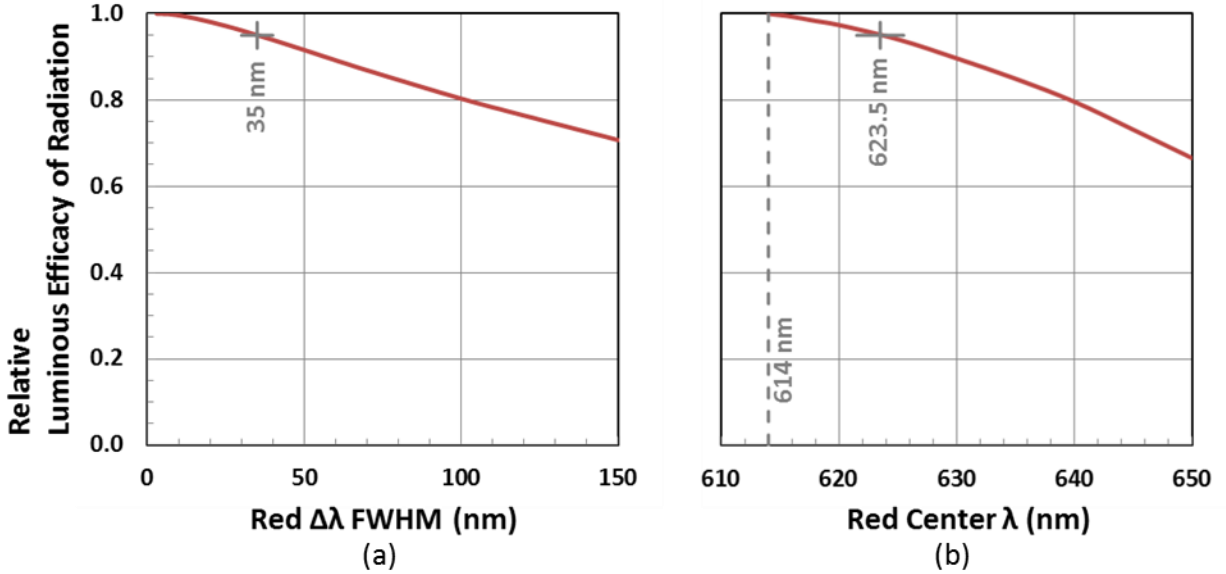
For both warm and cool white, there is significant opportunity: 255 lm/W is considerably higher than the current state-of-the-art for both warm white (137 lm/W) and cool white (168 lm/W). To achieve such a high luminous efficacy, a number of improvements will be required, ranging from continuing to improve the internal quantum efficiencies of the green and red phosphors, modestly narrowing the linewidth of the green phosphor emission to 50 nm FWHM or so, and improving the electrical efficiency of the blue LED. Three particularly important opportunities (and challenges) can be identified, as shown in Figure 5.5, Table 5.1, and Table 5.2.

Opportunity/Challenge 1: *Light extraction and mixing/scattering/absorption efficiency improvement.*

As can be seen from Figure 5.5, and from Table 5.1 and Table 5.2, a significant fraction (approximately 13%) of blue LED light is not extracted from the blue LED, and an equally significant fraction (approximately 13%) of white (blue, green, and red) light is not extracted from the white light package due to mixing/scattering/absorption losses. Taken together, minimizing these two loss channels represents a major opportunity for efficiency improvement. For both loss channels, the fundamental challenge is the high refractive indexes of the InGaN semiconductor that emits blue light and of the phosphors and encapsulants that absorb the blue light and mix/scatter the subsequent white light. The combination of high refractive indexes and scattering cause light to be trapped inside the white light package, and the long residence time of the light ultimately leads to optical absorption. Some of that absorption (e.g., blue light by the blue LED, or blue/green/red light by the green/red phosphors) might be recycled by photon re-emission, but most is lost to parasitic absorbers (e.g., metal contacts, interface states, heavily doped radiatively dark semiconductor layers). One challenge is to develop ways in which light can be made to escape from both the blue LED and white light package much faster (and the trapping time made much shorter). Examples of possible solutions include lower refractive index materials, novel micro- and nano-optical shapes or geometries, or coherent or partially coherent directed beams. Another challenge is to develop architectures and materials which minimize parasitic absorbers, or at least the degree to which light interacts with parasitic absorbers.

Opportunity/Challenge 2: *Red downconverter linewidth reduction.*

As mentioned earlier, the current 100 nm FWHM wide red phosphor emission linewidth causes a significant spillover of light into the deeper red, where the human eye is less sensitive, and is a significant contributor to the spectral inefficiency of current pc-LED white light. As can be seen in Figure 5.6(a), relative LER is higher with narrower red linewidth, increasing by 15%, from 80% to 95%, as the linewidth decreases from the current 100 nm FWHM to 35 nm FWHM. It is important to note that the improvement continues as linewidth continues to narrow to even less than 35 nm, with no penalty in color rendering quality. The challenge is thus to develop new red downconverters – phosphors, quantum dots, etc. – with narrower emission linewidths, while maintaining high (greater than 90%) internal radiative quantum efficiency. For on-chip (rather than remote) phosphor applications, robustness at high (85°C) operating temperatures and high impinging optical flux (1 watts per square millimeter, W/mm^2) saturation are also critical. Finally, as narrower linewidth red wavelength downconverters are explored, their center emission wavelength is also important. As can be seen in Figure 5.6(b), relative LER is higher the closer the center emission wavelength is to 614 nm. A center wavelength of 623.5 nm would incur a 5% efficiency penalty, and a center wavelength of 630 nm would incur a 10% efficiency penalty.



Note: Relative white light LER (a) as the FWHM linewidth of the red phosphor increases, for a given red center wavelength of λ = 614 nm, and (b) as the red center wavelength increases, for a given FWHM linewidth of Δλ = 7 nm. In both cases, the blue and green linewidths were fixed at 20 nm and 50 nm FWHM, but their center wavelengths were allowed to vary so as to optimize LER while maintaining R_a = 80 and R_9 > 0. The 95% efficiency points are indicated: FWHM of 35 nm and center wavelength of 623.5 nm.

Figure 5.6: Relative White-Light Luminous Efficacy of Radiation

***Opportunity/Challenge 3**: Blue LED efficiency droop.*

As can be seen from Figure 5.2, Figure 5.5, Table 5.1, and Table 5.2, the efficiency of the blue LED has improved enormously, but it is still highest at low current densities. The current "best" research has seen LED packages exceed 80% efficiency, but only at relatively low current densities. At the higher current densities desirable for low cost of light, higher market penetration, and ultimately the highest national energy savings, efficiencies decrease. This so-called "efficiency droop" from about 10 A/cm^2 to 35 A/cm^2 is about 10%, and to 100 A/cm^2 is about 15%. The challenge will be to circumvent the key physical mechanism responsible for efficiency droop, Auger recombination. Auger recombination is a non-radiative carrier recombination process which increases nonlinearly with carrier density and hence current density. Possible approaches to circumvent Auger recombination losses include: increasing the rate of competing radiative recombination (either through composition/geometry engineering or through use of alternative recombination mechanisms such as stimulated emission in laser diodes) or decreasing carrier densities (either through band-structure/transport engineering or through alternative geometries such as stacked active regions connected via tunnel junctions). The key to any of these approaches is to understand and control the complex epitaxial materials synthesis process so as to maintain the material quality that has been painstakingly engineered into current LED structures [79].

5.1.3 Emerging hy-LED Architecture: Status, Opportunities, and Challenges

The hybrid, hy-LED, architecture is the combination of a blue LED, a green phosphor, and a red LED to produce white light. This is a non-standard but emerging white light architecture. For example, in the Cree TrueWhite® and Osram Brilliant Mix technologies, greenish-white light (deliberately shifted off the black body curve toward the green) from a pc-LED is mixed with a pure red component from a red LED.

This architecture has a significant efficiency advantage over the more-standard pc-LED architecture because the red LED incurs no Stokes deficit in generating red light, and red LEDs have intrinsically narrow linewidths with little spillover into the deep red where the human eye is relatively insensitive. A luminous efficacy of about 280 lm/W, or an efficiency of around 68%, is considered to be the hy-LED "upper potential," as indicated by the middle grey bar in Figure 5.4. In contrast, the pc-LED "upper potential" is only 255 lm/W, and could be closer to 220 lm/W if narrower red phosphor linewidths are not achieved.

However, this architecture also has two major disadvantages, both associated with the current aluminum indium gallium phosphide (AlInGaP) technology used for the red LED. First, the thermal efficiency droop associated with these AlInGaP-based red LEDs is much greater than that associated with InGaN-based blue LEDs. Their very different thermal behavior requires a control system to maintain a consistent color point, which adds complexity and cost. It is expected that tunable-CCT sources, which are of increasing interest for human-centric lighting, will drive down the cost of such control systems, possibly minimizing this disadvantage in the future. Second, as illustrated in the bottom panel of Figure 5.7, AlInGaP-based red LED efficiencies decrease the shorter their red wavelengths. At 614 nm, which can be considered the ideal red as it is just long enough to provide good color rendering quality but just short enough for good sensitivity by the human eye (reasonably high LER), state-of-the-art research LED external quantum efficiencies are only about 25%.Thus, this architecture faces a number of challenges, two of which are the same as those for the pc-LED architecture: light extraction and mixing/scattering/absorption efficiency improvement and blue LED efficiency droop. But most importantly, it faces the challenge of improving the red LED.

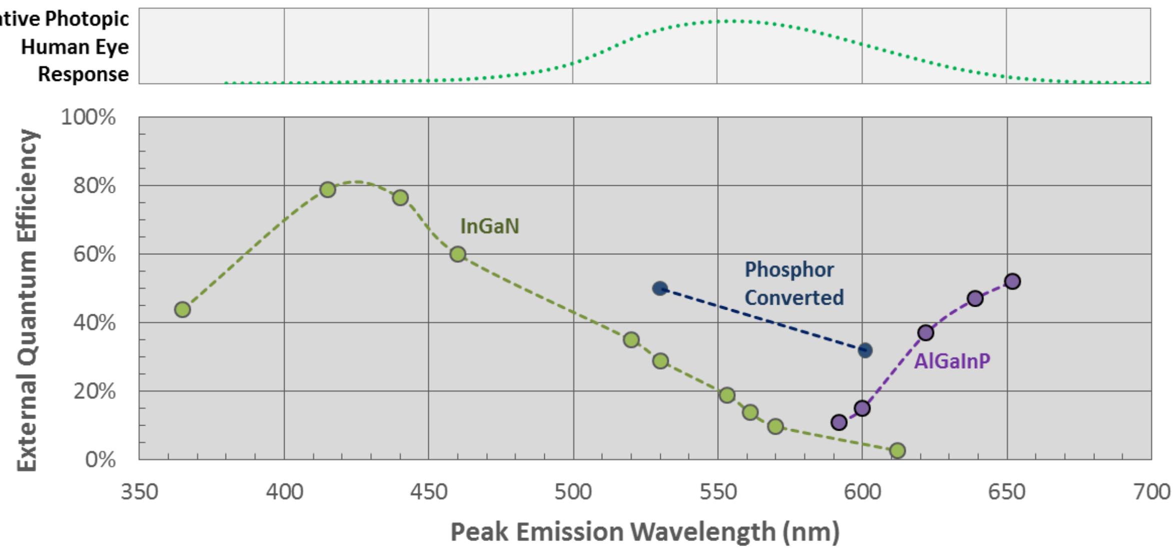


Figure 5.7 (Top) Photopic Human Eye Response vs Wavelength, and (Bottom) External Quantum Efficiencies of "Best Research" LEDs vs Wavelength.

Source: Pattison, Tsao, and Krames, Acta Horticulturae, "Light-Emitting-Diode Technology Status and Directions: Opportunities for Horticultural Lighting", May 2016 [80]

Opportunity/Challenge 4: *Red LED efficiency improvement.*

This is an important but tough challenge. Replacing even an ideal narrow linewidth red phosphor in a pc-LED architecture with a high-efficiency red LED at 614 nm in a hy-LED architecture would enable approximately 10% improvement, and replacing a non-ideal wide-linewidth red phosphor in a pc-LED architecture would enable approximately 25% improvement. The key challenge is to overcome what appear to be fundamental limits associated with AlInGaP materials: an unfavorable band structure in the shallow red both for carrier transport/confinement and radiative carrier recombination (due to a direct to indirect bandgap crossover). A novel variant of AlInGaP, or perhaps a different material system entirely (e.g., InGaN), may provide a solution. The full exploitation of composition and band-structure engineering in semiconductor materials is often limited by strain issues associated with lattice mismatches to common substrates; however, recently, there have been research breakthroughs in overcoming these issues including metamorphic epitaxy (in which strain-induced defects are minimized through gradual shifting of lattice constants) and nano-compliancy (in which strain is accommodated through nano–geometries). SSL would benefit from more complete understanding of these research breakthroughs and their application to red LEDs. The development of novel substrates which are lattice-matched to material compositions of interest for 614 nm red LED emission may also reap benefits.

5.1.4 Hypothetical RGBA cm-LED Architecture: Opportunities and Challenges

The four-color RGBA cm-LED architecture, in which all colors are generated by direct LEDs, can be considered the ultimate embodiment for white light architecture. There would be no wavelength down-conversion, and therefore no phosphor conversion or Stokes losses. As indicated by the upper grey bar in Figure 5.4, its ultimate "upper potential" might be on the order of 330 lm/W, limited only by the anticipated 80 to 90% efficiencies of the LEDs themselves and for the losses when mixing of their pure source colors to create white light.

There are various cm-LED possibilities that can be considered: three-color RGB, four-color RGBA, and perhaps even five-color RYGBA. This section looks at four-color RGBA, because it gives higher ultimate efficiency, better color rendering, and more flexibility for chromaticity tuning and hence for "smart" lighting (and implications for human comfort, health, and productivity) than three color RGB. Five colors are not considered, as a fifth color adds only negligibly to efficiency, color rendering quality, and chromaticity tuning flexibility.

It is important to note that this architecture can be considered somewhat hypothetical. Though there are specialty products that make use of this architecture, the low efficiencies of green and amber LED sources and thermal stability of red and amber AlInGaP based LED sources limit their performance. In particular, the green and amber LEDs, with ideal wavelengths at approximately 540 nm and 575 nm respectively, are right in the middle of the so-called "green gap." As can be seen in Figure 5.7, efficiency reduces as the green emission wavelengths are approached, both from the short wavelength and long wavelength sides. While performance of InGaN-based blue and violet LEDs has advanced rapidly over the past couple of decades with internal quantum efficiencies at low current densities now approaching 95%, increasing the Indium composition to provide emission in the green spectral region results in a rapid reduction in efficiency. For example, shifting the wavelength from 450 nm (blue) to 500 nm (cyan) results in a halving of PCE; a further shift to 525 nm results in an additional halving.

Opportunity/Challenge 5: *Green/Amber LED efficiency improvement.*
The realization of efficient LEDs in the green gap (e.g., green and amber) is thus a key technical challenge, and solutions have proven elusive. There is mounting evidence that performance of green LEDs is limited by more severe current droop than blue LEDs and is also caused by Auger recombination. Therefore, fundamental research in droop mitigation strategies should benefit both blue and green LEDs [81]. Another issues to be resolved is the strain associated lattice mismatches between InGaN (with a high enough Indium fraction to emit in the green and amber) and common substrates. It may be possible to leverage research breakthroughs for InGaN red LEDs (e.g., metamorphic epitaxy and nano-compliancy). If InGaN could be made to emit efficiently in the red, green and amber performance should benefit as well. Moreover, there is evidence that the low efficiency of green LEDs is in large part because efficiency droop is more pronounced in the green than in the blue. Therefore, an improved understanding of droop and ways to circumvent it in the blue might have broader ramifications to the green as well.

A possible alternative for producing monochromatic red, amber, and green LEDs is to use a phosphor-converted approach, which takes advantage of the very high PCE of blue InGaN LEDs by fully converting the blue light to the desired color. This can result in an overall conversion efficiency that significantly exceeds that of a direct semiconductor emitter, essentially negating the Stokes loss disadvantage. A comparison for green and amber/red LEDs is included in Figure 5.7, and it shows that the efficiency of wavelength down-converted green and amber/red LEDs are currently significantly higher than those of direct green and amber/red LEDs, even after accounting for the additional Stokes losses associated with wavelength down-conversion. Thus, the development of efficient narrow band down-converter materials would be an important intermediate step towards a cm-LED approach to white lighting. Table 5.1 presents a summary of the different sub-efficiencies for blue, green, amber and red light sources (both phosphor converted and direct emitter if applicable).

Table 5.1 Present and Future Target Sub-Efficiencies for Blue, Green, Amber and Red Light Sources, Along with Estimated Package (Optical Mixing/Scattering/Absorption) Efficiency for White Light Package

Properties of colored sources and their mixing to produce white light				Units	Present	Future (Targets)			
					2015	2018	2020	2025	Goal
Blue Source	LED or LD	Efficiencies	Electrical efficiency		0.96	0.97	0.98	0.98	0.98
			Internal quantum efficiency at 0 A/cm2		0.88	0.91	0.94	0.97	0.98
			Efficiency droop at 35 A/cm2		0.90	0.93	0.96	0.98	0.99
			Extraction efficiency		0.87	0.89	0.90	0.92	0.95
			LED efficiency		0.66	0.73	0.80	0.86	0.90
		Spectral Properties	Wavelength (center)	nm	459	459	459	459	459
			Wavelength (FWHM)	nm	20	20	20	20	20
			Luminous efficacy of radiation	lm/W	43	43	43	43	43
Green Sources	LED or LD	Efficiencies	LED efficiency		0.24	0.33	0.39	0.50	0.86
		Spectral Properties	Wavelength (Center)	nm	530	535	540	540	540
			Wavelength (FWHM)	nm	20	20	20	20	20
			Luminous efficacy of radiation	lm/W	566	602	630	630	630
	Phosphor	Efficiencies	Internal quantum efficiency		0.98	0.98	0.98	0.98	0.98
			Stokes efficiency		0.85	0.85	0.85	0.85	0.85
			Phosphor efficiency		0.83	0.83	0.83	0.83	0.83
		Spectral Properties	Wavelength (center)	nm	540	540	540	540	540
			Wavelength (FWHM)	nm	100	80	70	50	50
			Luminous efficacy of radiation	lm/W	486	486	499	552	552
Amber Source	LED or LD	Efficiencies	LED efficiency		0.08	0.15	0.22	0.25	0.86
		Spectral Properties	Wavelength (Center)	nm	587	575	575	575	575
			Wavelength (FWHM)	nm	20	20	20	20	20
			Luminous efficacy of radiation	lm/W	534	611	611	611	611
Red Sources	LED or LD	Efficiencies	LED efficiency		0.44	0.50	0.60	0.65	0.86
		Spectral Properties	Wavelength (Center)	nm	615	615	615	615	615
			Wavelength (FWHM)	nm	20	20	20	20	20
			Luminous efficacy of radiation	lm/W	304	304	304	304	304
	Phosphor	Efficiencies	Internal quantum efficiency		0.90	0.93	0.95	0.95	0.95
			Stokes efficiency		0.75	0.75	0.75	0.75	0.75
			Phosphor efficiency		0.68	0.69	0.71	0.71	0.71
		Spectral Properties	Wavelength (center)	nm	612	615	615	615	615
			Wavelength (FWHM)	nm	80	60	30	30	30
			Luminous efficacy of radiation	lm/W	313	314	308	304	304
Package (optical mixing/scattering/absorption) efficiency					0.87	0.89	0.90	0.93	0.95

5.1.5 Overall Conclusions and Future Prospects

Comparing the pc-LED, hy-LED and cm-LED architectures, the following conclusions can be drawn:

- The pc-LED architecture has significant room for further improvement, from the current status of approximately 140 lm/W to a potential of 255 lm/W, that may be accomplished by improving optical light extraction and package efficiencies from approximately 75% to 95%, narrowing the red phosphor emission linewidth to about 35 nm FWHM, and reducing blue LED efficiency droop from 10 to 20% down to 5% (in the 35-100 A/cm^2 range).

- The hy-LED architecture has somewhat more room for improvement, from the current status of approximately 160 lm/W to a potential of 280 lm/W, but with additional difficult challenges: improving the efficiency (from approximately 20% to 80%) and thermal stability of the red LED at the 614 nm wavelength that is ideal for white lighting.
- The cm-LED architecture has the most room for improvement, from the current status of 90 lm/W to a potential of 330 lm/W, but with the addition of the most difficult challenge: improving the efficiency of the green, amber *and* red LEDs.

Table 5.2 Present and Future Target "Rolled Up" Efficiencies for White Light Packages for the Three White Light Architectures: pc-LED, hy-LED, RGBA cm-LED. The Rolled-Up Efficiencies are Based on the Sub-Efficiencies Listed in Table 5.1.

Properties and effiacies of white light produced by package				Units	Present 2015	Future (Targets) 2018	2020	2025	Goal
Warm White: CCT=3000, R_a~80, R_9>0	Phosphor Converted PC-LED	Source power fractions of white	Blue		0.08	0.09	0.10	0.12	0.12
			Green		0.21	0.36	0.45	0.42	0.42
			Red		0.71	0.55	0.45	0.47	0.47
		White Luminous Efficacies	Fundamental (Stokes+spectral losses)	lm/W	256	281	300	306	306
			LER (spectral losses)	lm/W	323	354	372	381	381
			Max LER (no losses)	lm/W	414	414	414	414	414
			Actual (source+Stokes+spectral losses)	lm/W	137	175	208	237	255
		White Efficiencies	Source (no Stokes)		0.53	0.62	0.69	0.77	0.83
			Stokes		0.79	0.79	0.81	0.80	0.80
			Spectral		0.78	0.85	0.90	0.92	0.92
			Actual		0.33	0.42	0.50	0.57	0.61
	Hybrid HY-LED	Source power fractions of white	Blue		0.09	0.09	0.09	0.12	0.12
			Green		0.49	0.49	0.48	0.42	0.42
			Red		0.42	0.42	0.43	0.47	0.47
		White Luminous Efficacies	Fundamental (Stokes+spectral losses)	lm/W	335	335	337	343	343
			LER (spectral losses)	lm/W	374	374	376	381	381
			Max LER (no losses)	lm/W	414	414	414	414	414
			Actual (source+Stokes+spectral losses)	lm/W	166	189	215	243	285
		White Efficiencies	Source (no Stokes)		0.49	0.56	0.64	0.71	0.83
			Stokes		0.90	0.90	0.90	0.90	0.90
			Spectral		0.90	0.90	0.91	0.92	0.92
			Actual		0.40	0.46	0.52	0.59	0.69
	Hypothetical Color Mixed RGBA CM-LED	Source power fractions of white	Blue		0.13	0.14	0.14	0.14	0.14
			Green		0.29	0.24	0.27	0.27	0.27
			Amber		0.20	0.20	0.15	0.15	0.15
			Red		0.38	0.42	0.44	0.44	0.44
		White Luminous Efficacies	Fundamental (Stokes+spectral losses)	lm/W	390	400	400	400	400
			LER (spectral losses)	lm/W	390	400	400	400	400
			Max LER (no losses)	lm/W	414	414	414	414	414
			Actual (source+Stokes+spectral losses)	lm/W	89	119	154	186	327
		White Efficiencies	Source (no Stokes)		0.23	0.30	0.39	0.46	0.82
			Stokes		1.00	1.00	1.00	1.00	1.00
			Spectral		0.94	0.97	0.97	0.97	0.97
			Actual		0.21	0.29	0.37	0.45	0.79

As the future unfolds, performance characteristics are anticipated to become more demanding, which will have implications on which white light architecture is preferred, and for the relative importance of different routes for improving efficiency.

First, baseline current densities of 35 A/cm^2 and operating temperatures of 25°C are somewhat arbitrary. In practice, the higher the operating temperature that can be tolerated, the higher the allowable current density, and the higher the current density, the lower the cost of light (with both of these relationships mediated by current efficiency and thermal efficiency droop). Operating current densities of 100 A/cm^2 and higher and operating temperatures of 85°C and higher, are both highly desirable. Indeed, many LED packages are already routinely measured at a junction temperature of 85°C to be closer to the final device operating temperature and, as illustrated in Figure 5.2(b) typically exhibit a 10 to 13% reduction in efficiency compared to a junction temperature of 25°C.

Second, as more is learned about the influence of light on humans and human productivity, various spectral characteristics of light may become more important. Higher color rendering quality as measured by CRI may become more important, and many applications already demand CRI 90 over CRI 80. Other spectral features, including those discussed above in conjunction with the new IES TM-80 guidelines, may need to be controlled. As mentioned earlier, increasing CRI from 80 to 90 at 3000K results in a reduction in efficacy for current pc-LEDs of between 15 and 25%, and other desired spectral shapes may require similar efficacy compromises.

Progress towards either high efficiency, high current density, or low cost will help to improve all of these attributes. Efficiency improvement is perhaps the most key, as it increases lumen output per package (and thus decreases cost per lumen) and decreases the waste heat that must be removed (which in turn decreases package cost and decreases cost per lumen indirectly). As current density increases so does lumen output per LED, and thus decreases cost per lumen. Achieving low cost will create margin for more complex device designs for higher efficiency or current density.

5.2 LED Luminaire Technology

The LED package is at the heart of the overall system that produces and delivers white light to the environment and then ultimately to the human user, but it is surrounded on either side (input and output) by other components which collectively make up the luminaire. In this section these other components are discussed, along with their impact on the efficiency of the overall white light production and delivery system.

5.2.1 Luminaire Light Production Efficiency: Progress, Opportunities, Challenges

The white light production efficiency of an LED luminaire can only be as high as the efficiency of the LED package that is at its heart. The other pieces of the luminaire – the power supply and electrical driver on the front end, the mechanical and thermal-management structure, and the optical diffusing and/or directing on the back end – can only contribute additional losses. Progress in (and future targets for) the various efficiencies associated with these pieces of the luminaire, i.e., the driver efficiency, the luminous efficacy of the LED package at room temperature (25°C), thermal efficiency droop due to higher operating temperature (85°C), and the fixture (optical) efficiency, are indicated in Table 5.3.

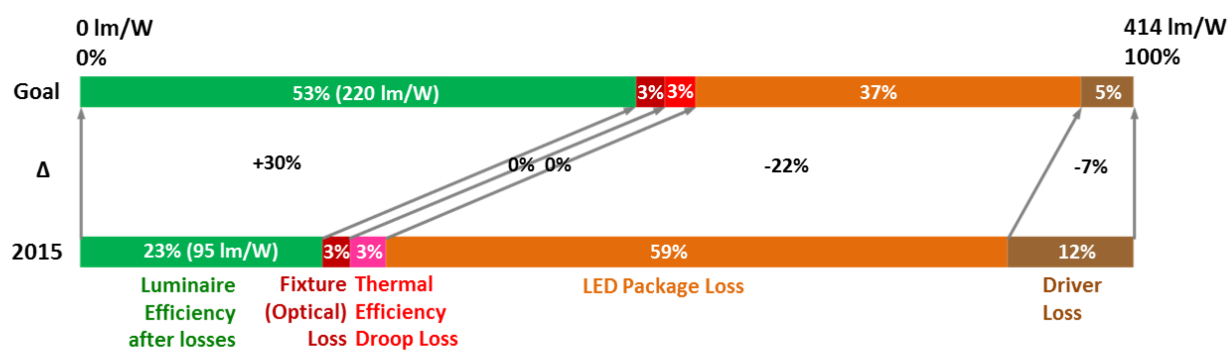
Table 5.3 Present and Future Target Luminaire Efficiencies. Package Luminous Efficacies are Based on the Rolled-Up Efficiencies Listed in Table 5.2.

Properties and effiacies of white light production and direction by luminaire, then of use by end user	Units	Present	Future (Targets)			
		2015	2018	2020	2025	Goal
Driver efficiency	%	0.88	0.91	0.93	0.95	0.95
Package efficacy (at 25°C)	lm/W	137	175	208	237	255
Thermal efficiency droop	%	0.88	0.91	0.93	0.95	0.95
Fixture (optical) efficiency	%	0.90	0.92	0.94	0.95	0.95
Luminaire Efficacy of White Light Production/Direction	lm/W	95	133	169	203	218

In this table, estimates of "best case," not average, efficiencies are listed, and, in any particular application, they may not be achievable. There is a wide range of lighting applications, and because the luminaire is the final custom element that tailors how the white light fits into the application, this results in a wide range of luminaire types. The brightness, size, direction, and diffuseness of the final beam; the aesthetics, shape, size, and cost of the fixture and overall luminaire; and the environment the luminaire must be compatible and integrate with are all considerations that lead to a much wider proliferation of luminaire types than of LED package types. In addition, many luminaires use LED packages operated at current densities below 35A/cm2, so the efficacy of the package can be higher than the levels described in the preceding two tables. All of these factors create a large range of varying efficiency levels that roll up into a large range of product performance levels.

Moreover, the market is also in the middle of an important transition from luminaires intended for use with lamps, to those designed around LED packages. A steady growth in the use of integrated LED luminaires can be anticipated, due to the efficiency and performance benefits that cannot be achieved in legacy lamp form factors.

The opportunities for improved efficiencies associated with luminaire components are indicated in Figure 5.8. Following the figure, two priority R&D opportunities are discussed, with an emphasis on integrated luminaires.



Note: From right to left, the percentage losses incurred from various channels in the conversion of electricity to visible light for commercial state-of-the-art luminaires, with the final percentage of the original electricity converted to visible light in green at the left. The 100% mark corresponds to an approximate theoretical maximum LER of 414 lm/W. The lower bar is current 2015, the upper bar is long-term goal, performance, the Δ's in the middle are the percentage changes due to potential improvements of the various channels. The improvement in the LED package is based on the rolled-up efficiencies listed in Table 5.2.

Figure 5.8 Losses Incurred in the Conversion of Electricity to Visible Light

Opportunity/Challenge 6: *Electrical Driver.*

On the front end is the power supply that converts AC line power to a voltage and current compatible with the LED package(s), and may incorporate control functions such as dimmability (for which there is an increasing demand). There are many driver configurations to accommodate different numbers of LED packages, varied circuit architectures, and various voltage levels of either AC or DC input. As seen in Table 5.3, "best case" driver efficiency is already reasonably high with potential to become even higher. Perhaps the weakest feature of drivers is not performance, but reliability. Driver reliability is the current weakest link amongst all of the components in the luminaire. A significant opportunity/challenge is to improve reliability of the driver, including fundamental reliability limitations of many of the subcomponents of this driver. There is also an opportunity to improve driver performance in terms of efficiency and flicker while the driver is operating at a dimmed setting and there is the further opportunity to embed additional control and communication functionality within the driver to enhance energy savings and functionality of the luminaire. An additional level of control could be the ability to better address and control individual strings of LEDs while maintaining a compact form factor and low cost.

On the back end of the light generation process is the mechanical, thermal management, and optical structures that are used to integrate LED packages into the larger luminaire. The optimized integration of the full luminaire, taking into consideration electrical, thermal, and optical integration, while also creating new value within a specific lighting application and saving energy, is a bigger picture opportunity/challenge. This opportunity/challenge encompasses many of the preceding topics and is called out as a priority research area and described in chapter 7.

With respect to thermal management, unlike traditional incandescent lamps, LED sources do not radiate heat and so heat generated by inefficiencies must be dissipated through conduction in the luminaire itself. The thermal management, the operating current(s) of the LED package(s), and the ambient temperature then determine the operating temperature(s) of the LED package(s). As illustrated in Figure 5.2(b), thermal efficiency droop represents the drop in efficiency of the LED as it is operated at an elevated temperature. Improved thermal handling and/or reduced operating current will result in a lower operating temperature of the LED and, in turn, higher LED efficiency. Luminaire developers have found that removing thermal interfaces within the luminaire thermal path can improve the thermal handling of the luminaire and improve LED efficiency.

With respect to optical efficiency, the optical system in the luminaire can make use of many permutations of lenses, reflectors, optical mixing chambers, remote phosphors, and diffusers, depending on the lighting application, the desired optical distribution, and the form factor of the lighting product. Well-designed luminaires in certain applications can experience less than 10% optical losses, and new approaches may reduce this further. In general, the fewer and smaller the LED packages, and the smaller the etendue, the more efficient the optical system can be. In the limit of laser diodes, optical systems can be envisioned which are extremely efficient, as well as novel (e.g., the possibility of ultra-thin edge-lit waveguide geometries).

Although much of the focus in luminaire development has been for pc-LED architectures, extremely good performance has been demonstrated for hy-LED architectures. In 2013, Philips announced the realization of a prototype 200 lm/W TLED lamp with CCT in the 3000 to 4500K range with CRI and R_9 greater than 80 and 20, respectively [82]; in 2014, Cree announced a 3,200 lumen concept luminaire delivering in excess of 200 lm/W at 80 CRI at thermal equilibrium while remaining within the ANSI color specification for 3000K [83]; and in 2014, OSRAM announced a prototype 3,900 lumen LED tube similar to Philips' but with an efficacy of 215 lm/W, or 205 lm/W when combined with a control unit, at 3000K and a CRI of 90 [84]. These R&D products meet the 2020 target shown in Table 5.2 and demonstrate that significantly better performance can be obtained through careful system optimization.

Opportunity/Challenge 7: *Integration of LED luminaire functionality.*
An emerging opportunity/challenge is the integration of existing and new luminaire functionality into smaller and lighter form factors, perhaps pushing some functionality down into the LED package. Sensors are one such functionality. With the advent of connected lighting, lighting fixtures may well become the most ubiquitous grid-connected “thing”, and the use of the IoT for environmental control (including lighting control) will require sensors of all types. Programmable directionality is another such functionality. As discussed in the next section, there is room for improvement with respect to how the light is used, and controlled placement of light would enable significant advance in that efficiency. Optical beam shaping is another functionality. Some street light designs have integrated specific lens functionality into the primary optic/encapsulant of the LED package, thereby removing the secondary optic and eliminating optical losses at the additional interfaces. The electrical driver is another such functionality, and there is even the possibility of monolithic integration of GaN-based drive electronics with GaN-based LEDs. Finally, simply making luminaires small may enable greater flexibility and density of luminaire placement, which in turn will enable lighting architects to more flexibly control lighting scenes and provide denser geographic coverage of sensors.

5.2.2 Light "End-Use" Efficiency: Looking Forward

After light is produced by the luminaire, light must be delivered to the environment and ultimately to the user. Whereas the previous section discussed the “production” efficiency, this section focuses on the "end-use" efficiency with which light is used, going beyond the "utilization" efficiency discussed in Section 2.2.

In an absolute sense, the “end-use” efficiency of artificial light is exceedingly low. In typical use, the fraction of photons leaving a lamp that finally strike the retina of a human eye is likely less than one millionth, even in an enclosed space such as an office. The loss factors include the less-than-100% reflectance of non-white objects being illuminated, the small entrance aperture and field of view of the human eye relative to the area and solid angle of the illuminated space, and the less-than-100% percentage of the time a room is occupied while it is illuminated.

It is not possible to eliminate all of these loss factors. However, through aggressive and sophisticated application of sensor-based real-time controls, they could possibly be reduced by as much as an order of magnitude. SSL, in particular, is characterized by fast switching speeds and the potential to focus and direct light while tuning the absolute and relative fluxes of its component colors. With this capability, one might imagine a sensor-based control system that tailors, in real-time the placement, spectral composition[r] and luminous efficacy of light to its use by humans. There is significant future opportunity

---

[r] For example, in the past when we have referred to spectral efficiency it has been in the sense of how effectively the emitted spectrum matches the human eye response while maintaining high color rendering quality of "typical" objects in the human environment. However, there has been discussion recently of new measures of color

in this area (e.g., sensors, micro-opto-electro-mechanical systems (MOEMS), human visual perception, lighting architectures and controls), and it may receive more attention in the coming decade. It is estimated that factors of 2x-3x improvements in use efficiency are possible, and these are reflected, in a speculative way, in the “end-use efficiency multiplier" future targets in Table 5.3.

Opportunity/Challenge 8: *Measurement of use efficiency.*
Before concrete, measurable progress in improving use efficiency can be made, first it must able to be measured. How to measure use efficiency is a big question with no current answers, but also it is not yet a question that the community has focused on. Do we need a new generation of sensors that can measure in real-time how much light the human eye sees and how much light a room’s luminaires are emitting, so that the ratio is proportional to use efficiency? Can we simply rely on an algorithm for lumens produced per square meter and room occupancy per square meter? The opportunity is significant, because once a measure, even if preliminary, has been established, lighting architects and engineers can begin more intelligently designing systems/components that enable improvements in use efficiency.

5.3 Manufacturing Status

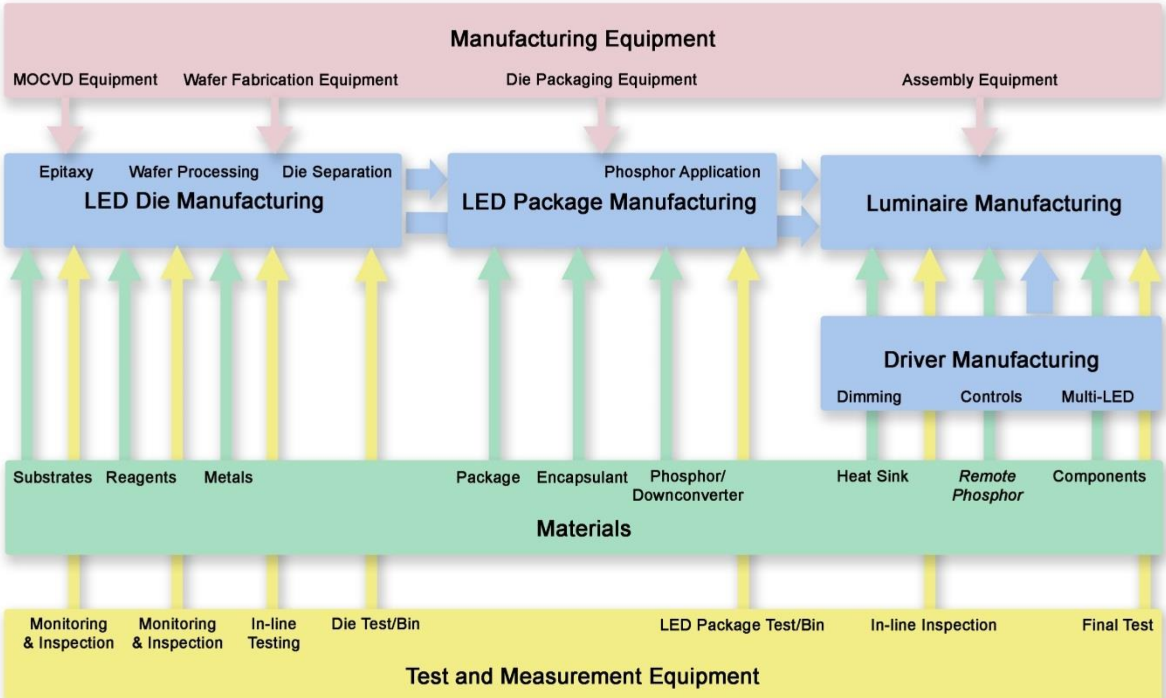
5.3.1 Supply Chain Outline

Understanding and managing the manufacturing supply chain is critical to the success of any manufacturing operation. In a general sense, the LED manufacturing processes can be defined by a sequence of relatively independent manufacturing steps. These manufacturing steps are supported by the supply of manufacturing equipment, materials, and testing equipment. The combination of the manufacturing processes, equipment, materials, and testing constitute the manufacturing supply chain.

The supply chain shown in Figure 5.9 represents the current situation for LED-based SSL manufacturing, but it should be recognized that the supply chain is ever-changing and will continue to evolve and mature. For example, a vertically integrated manufacturer might currently handle a number of these processes internally; however, as the manufacturing industry matures, it is common for the supply chain to become more disaggregated for optimum manufacturing efficiency. In addition, the manufacturing supply chain will be impacted by developments in technology and product design and can also be impacted by product distribution including geographical or regulatory considerations.

---

rendering quality in which one wishes to highlight particular objects in particular environments (green highway signs, surgical environments, etc.) without wasting light in undesirable or unnecessary wavelengths.



Note: The blue-shaded boxes and blue arrows describe the main manufacturing flow. The supporting elements of the supply chain are broken down into manufacturing equipment, materials, and test and measurement equipment. These supporting elements feed into the main manufacturing flow as indicated by the relevant arrows.

Figure 5.9 LED-Based SSL Manufacturing Supply Chain

The manufacturing process for LED-based luminaires begins with LED die manufacturing, consisting of growth of the LED wafer by metal organic chemical vapor deposition (MOCVD), processing of the LED wafer by mostly conventional semiconductor processes, and separation of the LED wafer into individual LED chips. The next step is typically to mount the LED die into LED packages, including the deposition of phosphor material to convert the blue LED emission to white light. Finally, the LED packages are integrated with a driver, heat sink, optical components, and mechanical elements to form the end luminaire or lamp product. The manufacturing process is constantly evolving as individual elements are refined or removed, new elements are developed, or new process sequences are introduced. Ultimately the optimum process flow for a particular product will depend on a detailed system level optimization.

5.3.2 LED Package Manufacturing

Manufacturing Methods

The LED die manufacturing process comprises epitaxial growth of the active device layers on the substrate, processing of the semiconductor wafer to define individual devices, dicing of the wafer to produce individual die, and mounting of the resulting die in packages that provide mechanical support along with thermal and electrical contacts.

The LED package no longer is the dominant cost element within the LED-based luminaire and represents a smaller fraction of the cost, from approximately 18% in a replacement lamp to 7% or less in LED indoor or outdoor fixture. Efforts to reduce costs while continuing to improve performance will require concerted action throughout the manufacturing supply chain. Such efforts will focus on higher quality and lower cost raw materials, improved epitaxial growth equipment and processes, optimized wafer processing equipment, and more efficient packaging methods, materials, and equipment.

There is a growing market demand for integrated light engines comprised of LEDs and the driver. The different integration levels are illustrated in Figure 5.10. Level 1 (L1) refers to the packaged LED; Level 2 (L2) refers to components such as LEDs or driver electronics mounted on a board; and Level 2+ (L2+) refers to various higher levels of integration such as LEDs with optical elements. L2 and L2+ integration is desirable for some luminaire manufacturers as it simplifies the value chain and their manufacturing process. Careful system optimization at L2 enables the ability to tailor the LED operating conditions, optimize the number of packages employed, and simplify the L2 configuration for lower manufacturing cost while retaining quality and reliability. This translates to reduced system size and/or cost, which is valued by customers.

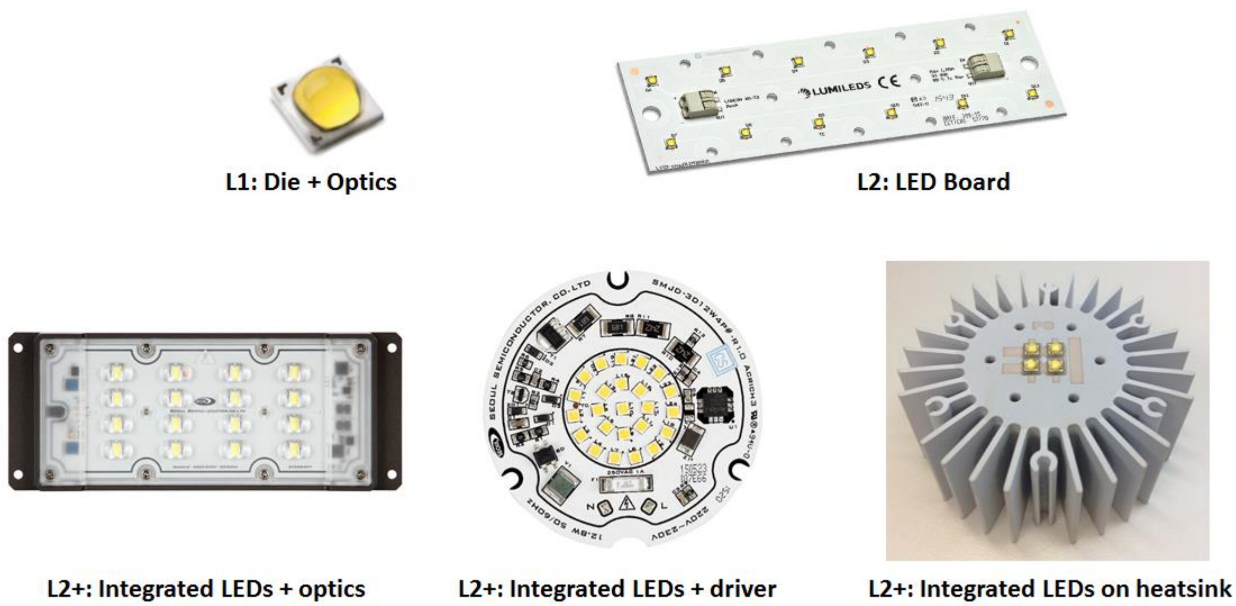


Figure 5.10 Integration Path for LED Components

Image Sources: a) Lumileds, Luxeon T datasheet, 2015 [85]*; b) Lumileds, Luxeon XR-TX Datasheet, 2016* [86]*; c) Seoul Semiconductor, Acrich2.5 Datasheet, 2015* [87]*; d) Seoul Semiconductor, Acrich3 Datasheet, 2016* [88]*; e) Frost & Sullivan, Circuit on Heat Sink, 2013* [89]

Package Diversity

The variety of LED packages for general illumination has exploded in recent years from a few types of 1 W class packages to a huge number of form factors, lumen levels, voltages, optical patterns, and physical dimensions. An LED manufacturer can have as many as 50 different package families, and within each family there are multiple variants based on lumen output, forward voltage, CCT, CRI, and binning tolerance. This package diversity has given luminaire manufacturers the freedom and flexibility to use LEDs best suited for the targeted lighting application and market.

Four main LED package platforms (shown in Figure 5.11) have emerged:

- High-power packages (1 to 5 W) typically used in products requiring small optical source size (e.g. directional lamps) or high reliability (e.g. street lights).
- Mid-power packages (0.1 to 0.5 W) typically used in products requiring omnidirectional emission (e.g. troffers, A-type lamps).
- Chip-on-board (COB) packages typically used in products needing high lumens from small optical source or extremely high lumen density (e.g. high-bay lighting).
- Chip scale packages (CSPs), also called package-free LEDs or white chips, have gained attention as a compact, low cost alternative to the high-power and mid-power platforms.

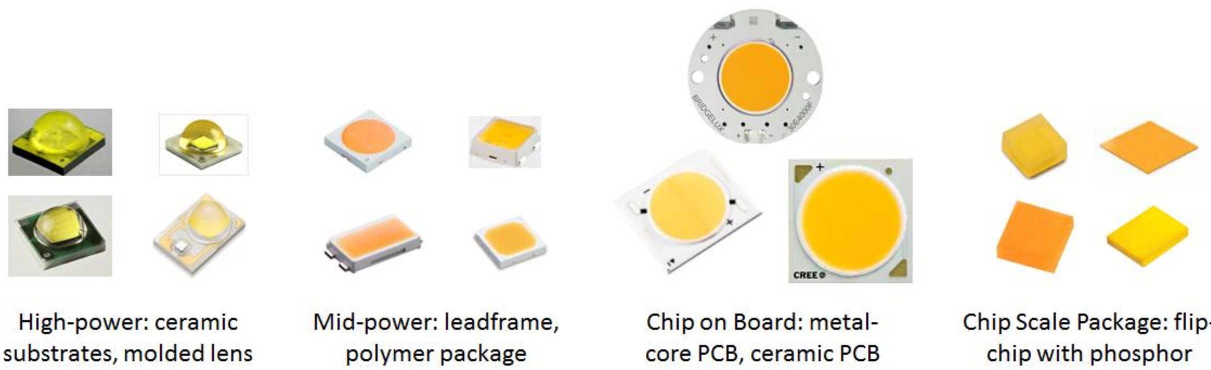


Figure 5.11 Examples of High-Power, Mid-Power, Chip-on-Board and Chip Scale LED Packages

High-power packages provide high efficacy, high luminous flux, and good reliability based on their thermal management and optical design. The design typically consists of a large 1 mm^2 die, or even multiple die for a high power array, mounted onto a ceramic substrate for thermal management. The phosphor is applied to the chip and then a hemispherical silicone lens is over-molded onto the package. In addition to the large die, some high-power package designs use numerous small die in series to create a high voltage package architecture that when grouped with a boost driver topology can yield system efficiency improvements.

Mid-power packages were originally used in display and backlighting applications, but found their way into general lighting applications in 2012 as chip performance improvements led to viable lumen levels for general illumination applications. Mid-power LEDs are low cost, plastic molded lead frame packages that typically contain one to three small LED die. The die are mounted on a silver (Ag)-coated metal lead frame surrounded by a plastic cavity. The cavity is filled with phosphor mixed in silicone to act as the down-converter and encapsulant. Mid-power LEDs have gained favor over high-power LEDs in a number of applications due to their low cost which improves the lm/$ for the system.

COB arrays typically use a large array of small die mounted onto a metal-core printed circuit board (MC-PCB) or a ceramic substrate. The LEDs are then covered with a phosphor mixed silicone. COB arrays provide high lumen output (up to 14,000 lumen) from a small optical source area and are typically used in high-bay lighting and low-bay lighting. With a good thermal substrate, these COB arrays can have the same color and lumen stability associated with high power packages as long as the operating temperature is kept within specification. Their ease of use in luminaire manufacturing appeals to a number of smaller luminaire manufacturers who do not have the surface mounting equipment to assemble discrete packages onto MC-PCBs.

CSP LEDs have gained prominence recently due to their lower cost from minimizing materials and manufacturing steps, as well as their small footprint allowing for tighter packing in a luminaire. The number of CSP product offerings continues to grow, as well as the number of manufacturers offering this LED product type. The majority of current CSP products use flip-chip die as a base, onto which the phosphor and encapsulant is applied, as illustrated in in Figure 5.12(a). Eliminating wire bonding and removing the need for lead frames or ceramic substrates, allows for a more compact size and reduced cost. The CSP manufacturers apply a conformal phosphor coating directly onto a blue flip-chip LED die, which provides luminous flux on five sides and at wider angles. Recent examples of CSP LED products include a variety of sizes to meet the different lighting application needs to replace the mid-power, high-power and small COB packages, as shown Figure 5.12(b).

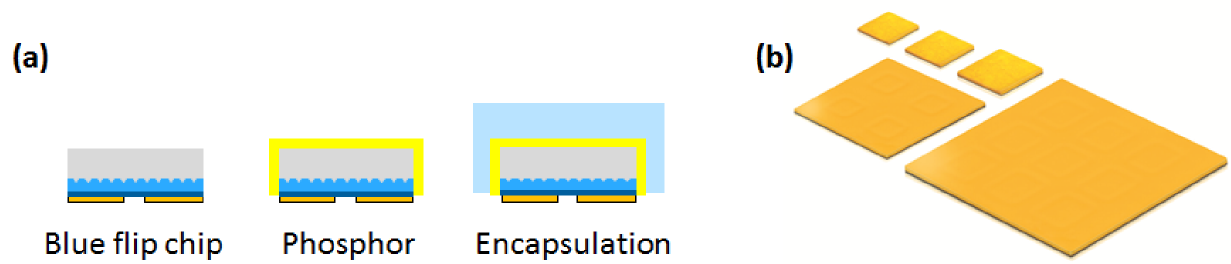


Figure 5.12 (a) CSP Manufacturing Approach and (b) Recent Example of the Scalability of Commercial CSPs.

Source: (a) Shatil Haque, DOE SSL R&D Workshop, Raleigh, NC, February 2016 [90]*, (b) Samsung Media Center, May 2016* [91]

While CSPs offer the potential for significant system cost savings, there are various performance tradeoffs to consider. There will be thermal impacts from eliminating the high conductivity ceramic substrate and optical losses associated with moving from a large dome primary lens to a conformal cubic encapsulant. In addition, other manufacturing challenges remain when integrating small CSPs onto Level 2 PCBs including:

- Higher precision manufacturing is required for alignment of much smaller CSP on PCB due to rotation and tilting.
- Control of radiation pattern can limit chip packing density and impacts secondary optics design.
- Shear force between CSP and PCB impacts the reliability of mechanical attach.
- Increased levels of electrostatic discharge (ESD) protection is required, because CSP devices do not have integrated Zener diodes for ESD protection.
- Handling of packages must be optimized in order to avoid destroying the phosphor layer, because direct handling of the phosphor layer is unavoidable.

- Accurate testing of the smaller CSP size create handling challenges in the test and sort equipment typically used for SMT lines.

LED Package Costs

The typical cost breakdown for a high-power and mid-power LED package is shown in Figure 5.13. The data for a high-power package assumes high-volume manufacturing of 1 mm^2 die on 100 mm diameter sapphire substrates and packaging of the die in ceramic packages to produce warm white pc-LED lighting sources. The data for a medium-power, warm white pc-LED package assumes a 0.5 mm^2 die packaged in a plastic leaded chip carrier package of similar dimensions. The cost breakdown for the high-power LED package is largely unchanged compared with 2015, although there is an overall cost reduction of around 20%, which is largely associated with reductions in raw materials costs and yield improvements. The die cost and package cost are much lower for the mid-power package, while the phosphor is still applied over a similar area; therefore, its relative importance to the overall cost increases. Typically, the mid-power package cost will be five to ten times less, depending on die area, and this is reflected in a similar price differential.

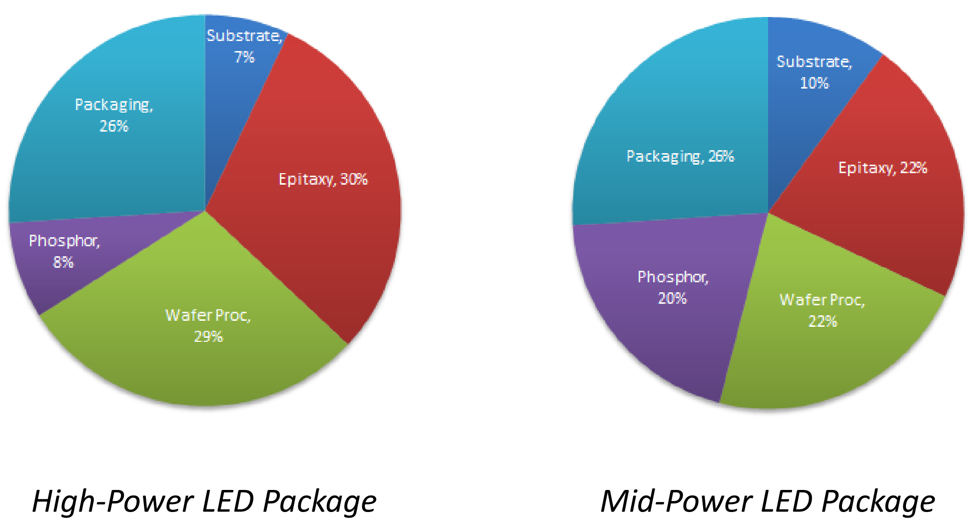


Figure 5.13 Typical Cost Breakdowns for High-Power and Mid-Power LED Packages
Source: Inputs from DOE SSL Roundtable and Workshop attendees

Figure 5.13 indicates that no single cost element dominates for high-power or mid-power LED packages. Packaging remains the largest cost element but wafer processing costs are similar and epitaxy costs are not far behind. These breakdowns suggest the need for a more holistic approach to cost reduction. Figure 5.14 shows how the high-power LED package cost may change over time as volumes continue to ramp, falling to about 65% of 2016 values by 2020. It is anticipated that the relative contribution from substrate, epitaxy, and wafer processing will decrease as wafer size increase over this period while the relative contribution from packaging and phosphor content will rise.

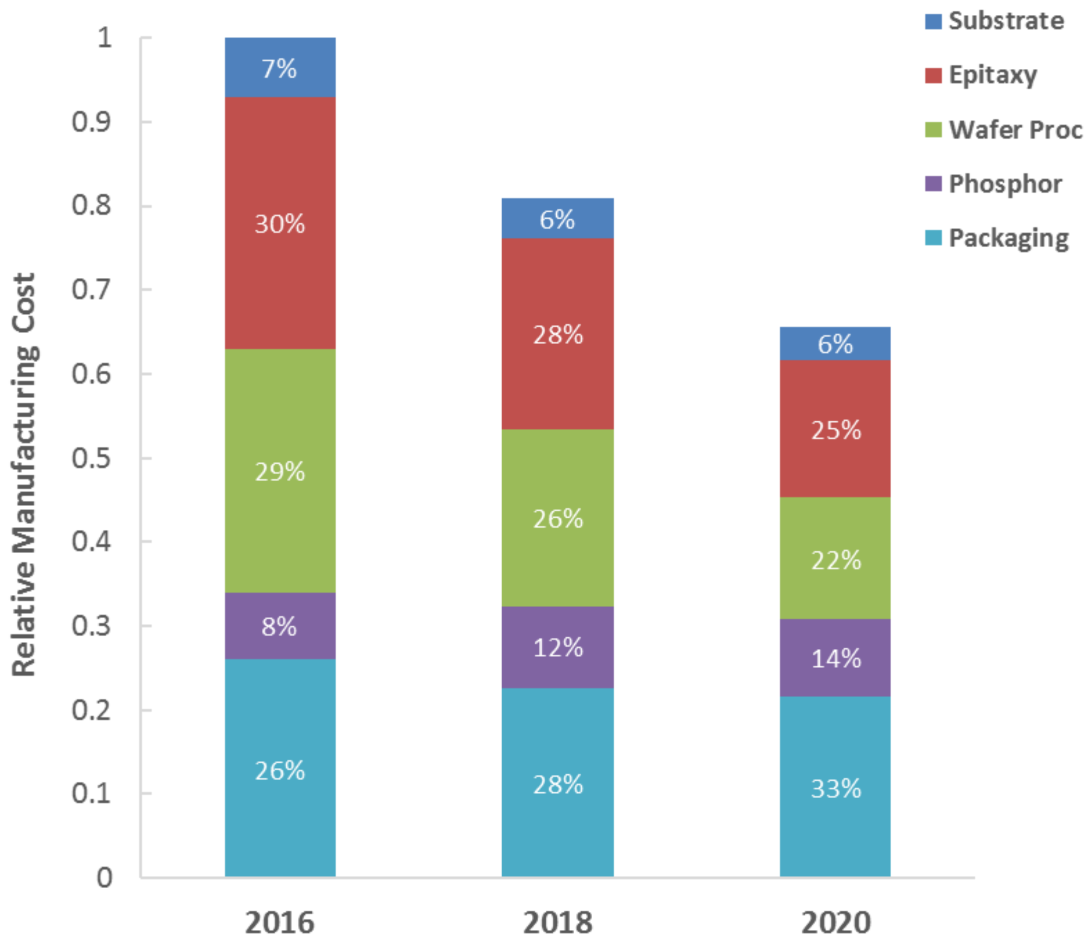


Figure 5.14 Projected High Power LED Package Cost Reduction
Source: Inputs from DOE SSL Roundtable and Workshop attendees

There is plenty of room for innovation in this area, and DOE anticipates many different approaches to cost reduction, including the following:

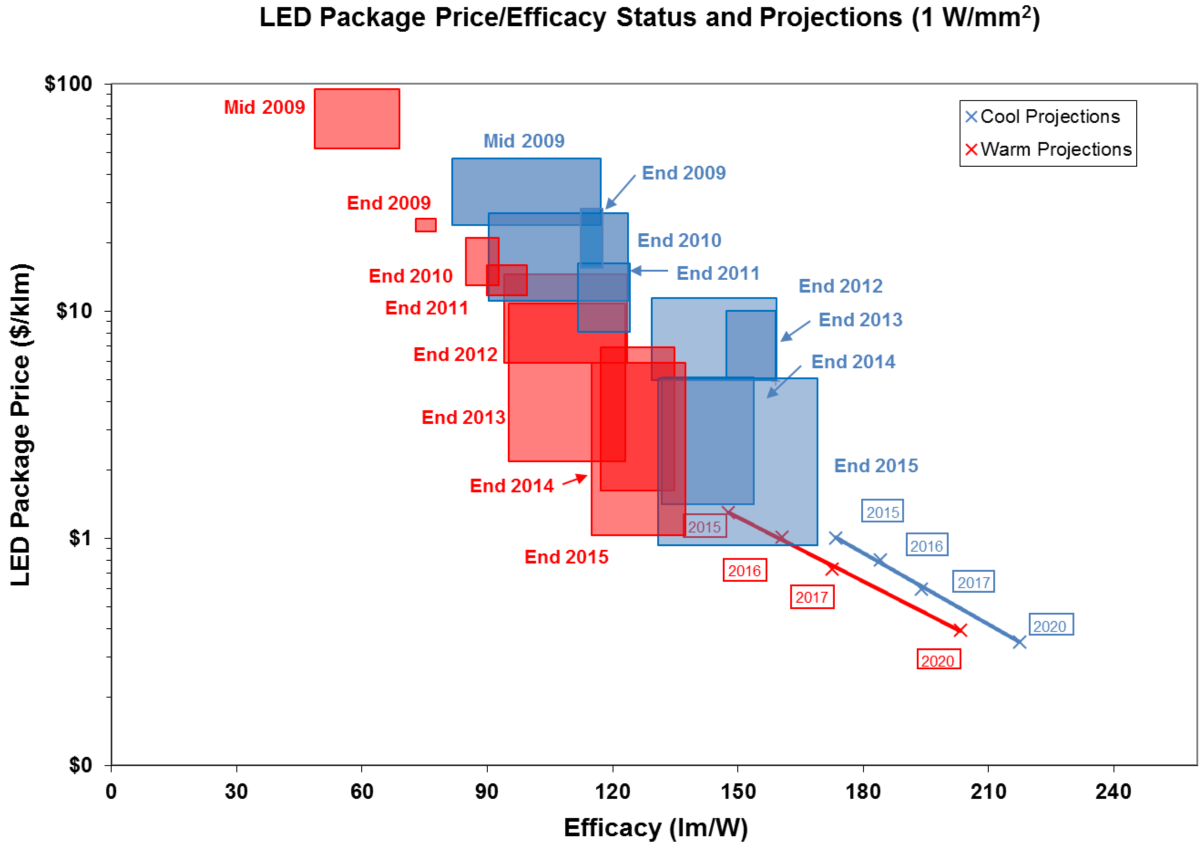
- Increased equipment throughput
- Increased automation
- Improved testing and inspection
- Improved upstream process control
- Improved binning yield
- Optimized packages (e.g., simplified designs, lower cost materials, and multi-chips)
- Higher levels of component integration (hybrid or monolithic)
- Chip-scale and wafer-scale packaging

5.3.3 Commercial Considerations

LED Package Prices

In the past, LED package prices have tended to dominate the cost breakdown for an LED-based lamp or luminaire; however, rapid price reductions have occurred over the past few years, along with the introduction of plastic packaging materials and chip scale packaging methods.

The price estimates in this section represent typical retail prices for LED packages purchased in quantities of 1,000 from major commercial distributors such as Digi-Key, AVNET, Newport, and Future Electronics. Each LED manufacturer produces a number of variants for each package design covering a range of color temperatures and lumen output levels. The selected data is based on available datasheets and represents devices in the highest flux bins where this is reported (taking the average value within that bin) or typical flux values for the total available distribution. Chosen devices fall within specified ranges of CCT and CRI. In all cases, the price, expressed in units of U.S. dollars per kilolumen ($/klm), and efficacy have been determined at a fixed current density of 35 A/cm^2 and a junction temperature of 25°C, unless otherwise indicated. Newly introduced packages are generally measured at 85°C and have been normalized to a temperature of 25°C using data provided by the manufacturers.



Notes: Cool white packages assume CCT=5700K and CRI=70 and warm white packages assume CCT=3000K and CR=80. Additionally, rectangles represent region mapped by maximum efficacy and lowest price for each time period; however, the maximum efficacy may not be available for purchase at the lowest price.

Figure 5.15 Price-Efficacy Tradeoff for LED Packages at 1 W/mm^2 (equiv. 35 A/cm^2) and 25°C.

The evolution of LED package efficacy and price is illustrated in Figure 5.15. Each time period is characterized by a rectangle with an area bound by the highest efficacy and lowest price products. Efficacies as high as 168 lm/W (cool white) and 137 lm/W (warm white) have been reported during 2015 as well as prices as low as $0.9/klm (cool white) and $1.0/klm (warm white). The rapid drop in prices is associated with the introduction of mid-power LED packages and changes to the normalization procedure which enables such packages to be tracked. The price-efficacy projections are also included in Figure 5.15 for comparison purposes and are summarized in Table 5.4. The price projections have been adjusted to account for the lower prices associated with mid-power package designs. Similarly, the efficacy projections have been adjusted to reflect the slower than projected progress, especially for cool white products.

Table 5.4 Summary of LED Package Price and Performance Projections (1 W/mm^2 and 25°C)

Metric	2014	2015	2017	2020	Goal
Cool White Efficacy (lm/W)	158	168	194	218	255
Cool White Price ($/klm)	1.4	0.9	0.6	0.35	0.3
Warm White Efficacy (lm/W)	131	137	164	208	255
Warm White Price ($/klm)	1.7	1.0	0.7	0.36	0.3

As mentioned above, changes have been made to the normalization procedure. Packages are now being normalized to a power density of 1 W/mm^2 instead of a current density of 35 A/cm^2. For a typical high power LED packages, these two values are essentially equivalent and therefore historical data can be retained. In order to track the performance of low and mid power packages, it is planned to introduce a second criterion of 0.3 W/mm^2 such that these packages are measured closer to their optimum operating conditions. By normalizing to power density, different package configurations can be easily accommodated since it is only necessary to measure input current, input voltage, and lumen output to calculate the efficacy and price per kilolumen once the total internal die area is known. Most major manufacturers have indicated that they will be prepared to share die area information with DOE for this purpose. Data will continue to be reported at 25°C as well as at 85°C if this is the specified test temperature for the package. Only packages that meet the CCT/CRI combinations of 5700K/70, 3000K/80, and 3000K/90 will be selected.

5.3.4 LED Luminaire Manufacturing

Manufacturing Methods

Manufacturing of an LED luminaire involves combining the LEDs with mechanical and thermal components (e.g., the heat sink), optical components to tailor the light distribution, and LED driver electronics. LED die or packages are a critical component of all LED-based luminaires, and luminaire manufacturing revolves around integrating the LED source with the other luminaire components to achieve the required form factor and the optimum balance between cost, performance, product consistency, and reliability. The balance of these features and necessary tradeoffs, depends on the lighting application, the customer profile, the incumbent lighting performance and cost. For example, a 6” downlight for the residential market can provide 67 lm/W, whereas a higher-end commercial downlight from the same manufacturer can reach 100 lm/W at the same color temperature and CRI. The difference in these two models is a factor of design choices for the product requirements for those applications. A lower cost downlight will have fewer LEDs, which in turn are driven at higher currents to achieve the lumen output required, thus pushing the efficacy lower due to current density droop at higher drive currents.

Reducing the number of LEDs can lower costs at the expense of efficacy but there are further consequences to consider: higher drive currents lead to higher temperatures in the package, which leads to earlier lumen degradation and color shift thus affecting the luminaires reliability performance and warranty life. This just involves one tradeoff with the LED source design. Further subsystem design choices such as heatsink, driver and optics designs lead to additional tradeoffs. Understanding all the nuanced performance tradeoffs and impacts on product design and manufacturing costs, determines the efficacy, CCT, CRI, warranty life and cost point that different luminaire products are brought to market. Figure 5.16 illustrates these trade-offs for various A-type LED lamps. The quality features such as high CRI, dimmability and longer L70 lifetimes all come at a higher cost. For lamps that have the lower first cost will not be dimmable or have longer life-times or high CRI. This illustrates why there is no one size fits all lighting product. The value of efficiency, color quality or lifetime vary for different customers and impact what they are willing to spend for those benefits.

Figure 5.16 Comparison of Quality Tradeoffs for Various A-Type LED Lamps

The fact that some form factors have lower efficacy than others does not necessarily indicate that certain LED lighting product classes cannot be made as efficient or reliable as other LED lighting products, but instead could reflect a specific tradeoff the manufacturer selected for the end-use case. There are certain cases, such as etendue limited lighting designs required for narrow spot lights, that can have efficacy limitations compared to large area light sources such as troffers (due to the small source size required to achieve small spot sizes) but it is not fundamental in many designs.

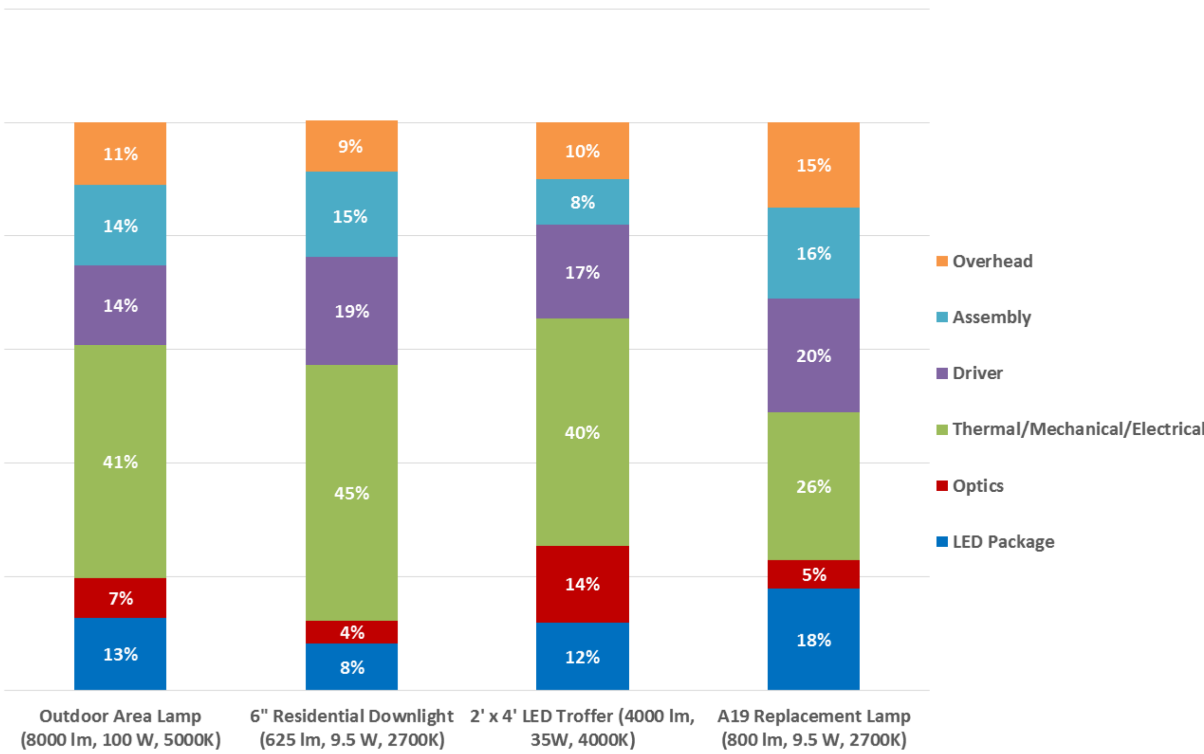
LED-based replacement lamps and LED luminaires have a similar level of integration but lamps use a standard electrical interface for use within conventional lighting fixtures. Manufacturing of LED-based lighting products shares little in common with conventional lighting products since conventional lighting technologies tend to be based around the fixture-plus-lamp paradigm, with the manufacturing of each part handled completely separately, and often by separate companies. The integrated nature of an LED-based lighting product, where fixture, light engine, and driver electronics are typically combined in a single unit, significantly complicates the manufacturing process. Luminaire manufacturers have successfully addressed the challenge by introducing manufacturing technologies more commonly seen in the consumer electronics industry, simplifying the materials and manufacturing processes, introducing system-level design optimization methodologies (including Design For Manufacturing and Design For Assembly), and developing improved testing capabilities.

LED Luminaire Costs

The typical cost breakdown for a lamp or luminaire will vary depending on the application. Figure 5.17 shows a comparison of the cost breakdown for an outdoor area lamp, indoor residential downlight, an

LED troffer, and A19 replacement lamp (and has been revised from previous years based on inputs from the community). This comparison reveals that the relative costs for different form factors can vary considerably. A noticeable trend in recent years is how fast the relative LED package cost is dropping in both the luminaires and the lamps.

Overhead costs also represent a real cost element, especially for LED A19 lamps, and should be included in the cost charts along with the bill of materials. The overhead included in the cost charts refers to manufacturing engineering, product development, documentation, packaging, in-line and compliance testing, shipping, and distribution. The retail price will include an additional channel margin of approximately 30%.



Note: This represents a typical manufacturing cost breakdown; though different luminaire manufacturers will have varying cost breakdowns depending on their business models.

Figure 5.17 Comparison of Cost Breakdown for Different Lighting Applications in 2016

Source: DOE SSL Roundtable and Workshop attendees and industrial partners

Early on in the development of LED lamps and luminaires, the cost of the LED packages dominated the total product cost, but this is no longer the case. For most luminaire products, the dominant subsystem cost has become thermal/mechanical/electrical, which represents the housing, heat sinking elements, electrical connectors, and mechanical fasteners. Moving forward, the cost of LED packages will continue to drop rapidly and so future cost reduction will be achieved more by focusing on optimization of the complete system rather than focusing on any specific cost element.

For a specific product, it is useful to consider how the cost breakdown might change as a function of time. Figure 5.18 shows how the relative manufacturing cost for a common LED A19 60 W equivalent replacement lamp is expected to change between 2015 and 2020. The major change in the cost breakdown relates to the cost of the LED package, which is anticipated to fall from around 23% of the lamp cost in 2015 to around 10% by 2020. As noted above, and shown in Figure 5.17, relative costs vary widely among specific luminaire and lamp types, so it is not possible to project a generic luminaire cost breakdown. While a straight cost down process is one approach to bringing down cost, system redesigns are a more common way to make greater jumps in cost reduction by changing the amount and type of components in a system. This system redesign approach also impacts the relative subsystem cost over time since a different design approaches to achieving good optical, electrical and thermal performance will impact the component costs and therefore their ratios. Manufacturers continue to seek manufacturing approaches that can enable cost reduction without degrading system performance in terms of efficacy, lifetime, color quality, etc.

The key cost drivers for each major element of the LED supply chain are summarized in Table 5.5.

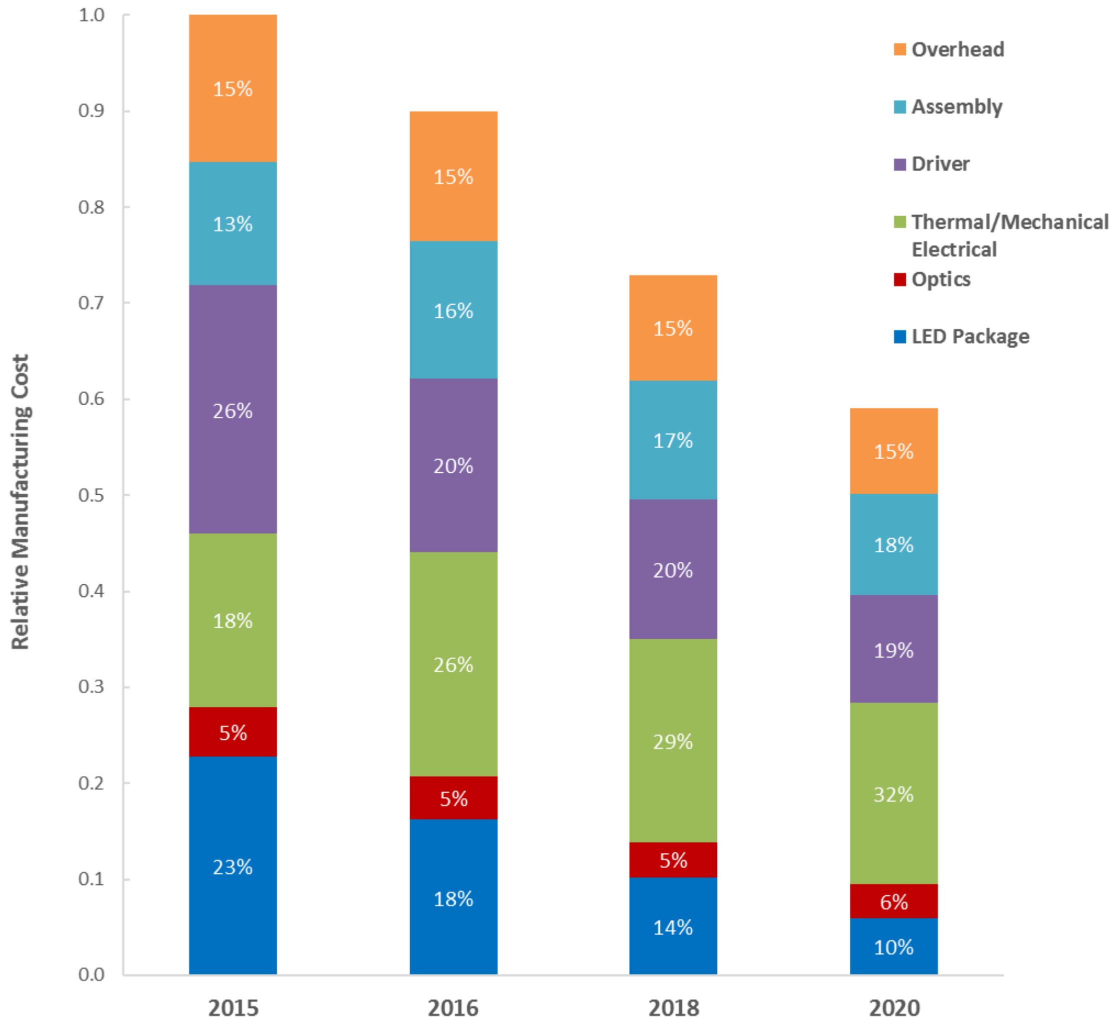


Figure 5.18 Cost Breakdown Projection for a Typical A19 Replacement Lamp
Source: DOE SSL Roundtable and Workshop attendees

Table 5.5 The LED Supply Chain: Key Cost Drivers

Supply Chain		Cost Drivers		
Equipment Suppliers	Epitaxial growth	• Uniformity • Throughput	• Reagent usage efficiency	• In situ monitoring/ Process control
	Wafer processing	• Throughput	• Automation	• Yield
	LED packaging	• Throughput	• Flexibility (packaging materials and package types)	
	Luminaire assembly	• Throughput	• Automation	• Chip scale packaging
	Test and inspection	• Throughput	• Accuracy	• Reproducibility
Materials Suppliers	Substrates	• Diameter	• Quality	• Standardization
	Chemical reagents	• Quality/Purity	• Bulk delivery systems	• In-line purification
	Packaging	• Standardization	• Plastic Packages	• Package Shrinks
	Phosphor	• Quality/Efficiency • Consistency	• Stability (thermal and optical flux)	• Reliability
	Encapsulation	• Quality	• Reliability	• Stability (thermal and optical flux)
Die Manufacturing		• In-line inspection/ Process Control	• Yield • Testing	• Throughput • Capital costs
Package Manufacturing		• Modularization • In-line inspection/ Process control	• Labor content • Testing • Standardization	• Yield • Throughput
Luminaire Manufacturing		• Automation/Labor content • In-line inspection/ Process control	• Testing (performance and compliance)	• Modularization • Throughput

5.3.5 Reliability and Color Shift

Lumen Maintenance

LED packages rarely fail catastrophically, necessitating consideration of parametric failures such as degradation or shifts in luminous flux, luminous intensity distribution, CCT, CRI, or efficacy. Of these, lumen depreciation has received the most attention, since it was previously thought that the degradation of lumen output of the LED source itself would be the prime determinant of lifetime for the completed product. While this is understood to no longer be the case, lumen maintenance is still used as a proxy for LED lamp or luminaire lifetime ratings, largely due to the availability of standardized methods for measuring and projecting LED package lumen depreciation.

The useful life of an LED package is often cited as the point in time at which the lumen output has declined to 70% of its starting value or L_{70}. In 2008, IES published IES LM-80, which is an approved method for measuring the lumen maintenance of solid-state (LED) light sources, arrays, and modules [92]. This procedure requires measurements of lumen output and chromaticity for a representative sample of products to be taken at least every 1,000 hours, for a minimum of 6,000 hours.

Many researchers have put a great deal of effort into devising a way to project the time at which L_{70} will be reached for an LED package in a luminaire, and IES has documented a forecasting procedure, IES TM-21 [93]. This technical memorandum stipulates that any projection may not exceed a set multiple of the actual hours of LM-80 testing data taken, which helps avoid exaggerated claims. It should be noted that LM-80 measurements are taken with the LED packages operating continuously in a temperature-controlled environment, where the solder point and ambient air temperature are at equilibrium. This does not necessarily reflect real-world operating conditions, so there may not be a perfect match between predictions based on laboratory test results and practical experiences with lamps and luminaires in the field. Nevertheless, lumen maintenance projections can help sophisticated users compare products, as long as their limitations are properly understood.

The impact of LED package design and materials of construction on performance, color quality, lumen maintenance and color shift, have been investigated for a variety of LED packages under the DOE Core Technology Research Program awarded to RTI International. The goal of this program is to determine failure modes for LED packages and develop software approaches to model failure rates in an effort to correlate package behavior to system reliability results. In performing this analysis, a methodology was developed to analyze LM-80 data across multiple manufacturers to provide new insights into LED-level factors impacting lifetime. The analysis provided a detailed look at lumen maintenance and color shift behavior for a range of LED packages with different designs and materials of construction from multiple manufacturers and found that the materials of construction have a direct impact on long-term performance of LEDs.

Different LED package platforms (detailed in Section 5.3.2) have different intrinsic characteristics based on materials of construction and manufacturing processes. Mid-power LEDs generally exhibit more rapid lumen degradation than high-power LEDs. This faster decay of luminous flux is largely due to degradation of the plastic resin body used in the mid-power LED compared to the more stable ceramic substrate used in the high-power LED. The plastic material most commonly employed in mid-power LED packages is polyphthalamide (PPA), a thermoplastic resin. At high temperatures and long operating times, the materials in the package can discolor, crack, or delaminate, leading to lumen depreciation and color shift as seen in Figure 5.19.

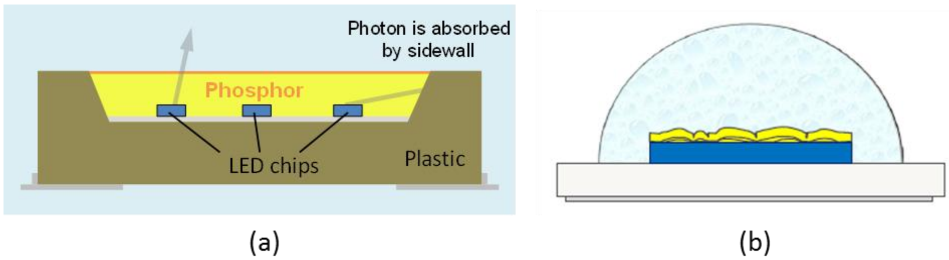


Figure 5.19 LED Package Schematics Showing (a) Sidewall Discoloration and (b) Phosphor Delamination

Source: Monica Hansen, Strategies in Light, Las Vegas, NV, February 2015 [94]

Different grades of plastic resin have different lumen degradation behavior as seen in Figure 5.20. Improved plastic resins such as epoxy molding compound (EMC) can reduce the thermal constraints associated with conventional mid-power commodity packages. Mid-power LEDs based on EMC resin are more resistant to degradation than PPA and compatible with higher operating temperatures. Figure 5.20 compares the lumen degradation performance of typical mid-power packages using PPA and EMC plastic resins to typical high power packages using ceramic substrates.

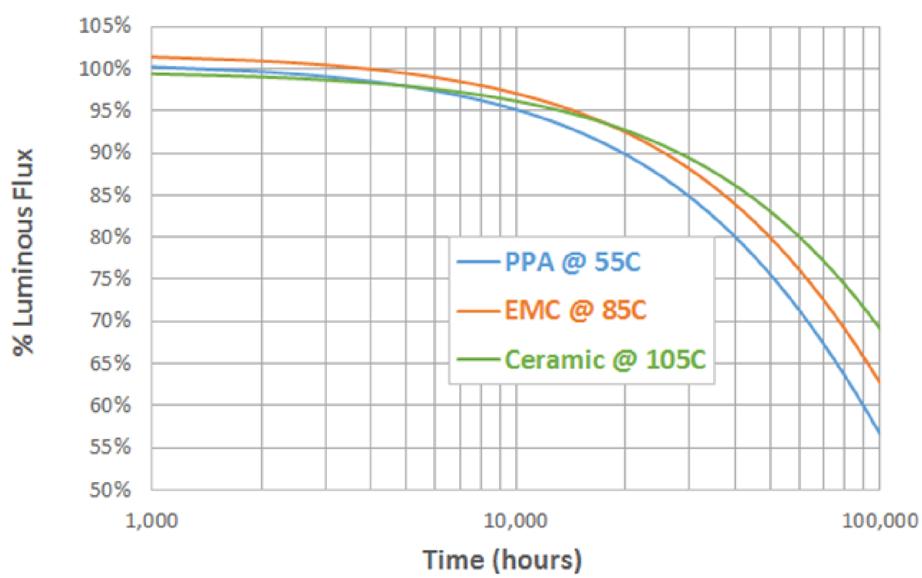


Figure 5.20 Lumen Degradation Performance of Typical Mid-Power Packages (PPA and EMC Plastic Resins) and High Power Packages (Ceramic Substrates).

Source: Monica Hansen, Strategies in Light, Las Vegas, NV, February 2015 [94]

Color Shift

While lumen maintenance is important, other forms of parametric failure for LED packages must not be overlooked. Color shift, for example, may be more detrimental than lumen depreciation for some applications; however, this is more difficult to predict. To date, color shift is best quantified using Δu'v', which describes the magnitude of chromaticity shift in the CIE 1976 chromaticity diagram (u', v'). Δu'v' encompasses shifts in CCT and D_{uv} (distance from the blackbody locus in u-v colorspace), but does not capture the direction of the shift, only the magnitude. The point at which a color shift becomes noticeable depends on the application. If the color change occurs slowly over a very long period (e.g., 25,000 hours) it may not be objectionable, provided all of the light sources shift by the same magnitude and in the same direction. Unfortunately, there is currently no available standard method for projecting color stability using LM-80 measurements.

Factors impacting color point stability in LEDs include aging-induced changes in the phosphor, emitter, and encapsulant materials. Emitters can exhibit decreases in radiant flux over time; phosphors can experience decreases in quantum efficiency or shifts in emission spectrum due to oxidation; and encapsulants can exhibit cracking, oxidation and yellowing, or changes in index of refraction. Higher temperatures will accelerate these degradation mechanisms leading to greater color shift, as demonstrated in Figure 5.21, but the magnitude of the color shift as a function of temperature will vary with packaging materials and manufacturing processes.

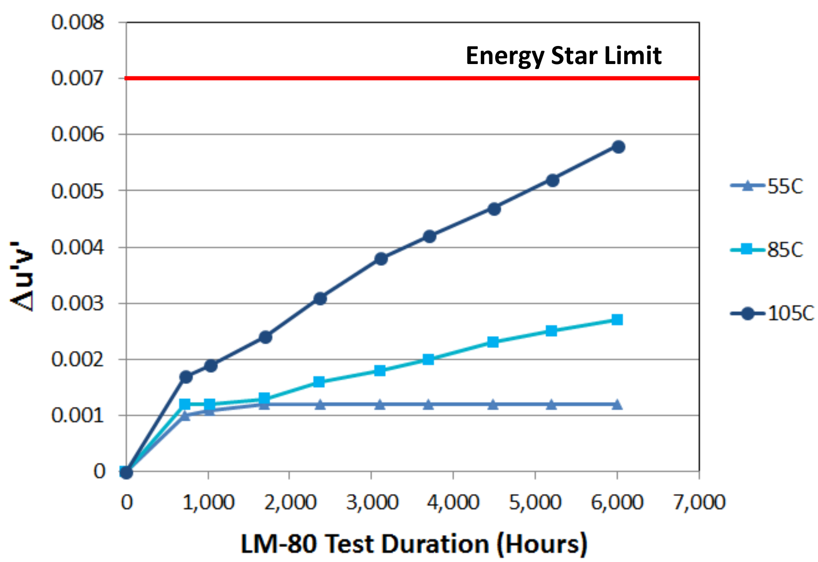


Figure 5.21 Color Shift of LED Package as a Function of Temperature
Source: Monica Hansen, Strategies in Light, Santa Carla, CA, March 2016 [95]

The resulting direction of color shift depends on the dominant degradation mechanisms occurring in the package, which in turn depends on the packages materials and methods of construction. The color shifts can be towards the yellow, blue, or green colors as illustrated using the CIE 1976 chromaticity diagram in Figure 5.22.

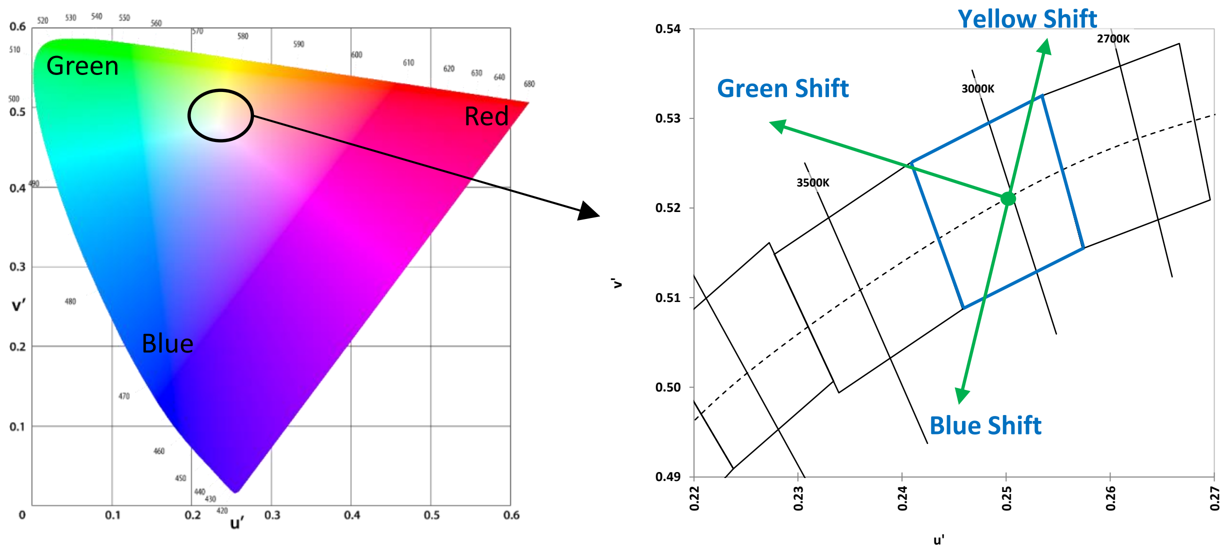


Figure 5.22 1976 CIE Chromaticity Diagram Illustration the Common Directions of Color Shift in LED Packages

Source: Monica Hansen, Strategies in Light, Santa Carla, CA, March 2016 [95]

Phosphor cracking and delamination can occur (as shown in Figure 5.19b), and can lead to a yellow shift in the spectrum due to an increase in the distance the blue photons travel through the phosphor. This steady yellow shift, seen in Figure 5.23, in the package is the terminal color shift mechanism for high-power packages. Discoloration of the plastic resin in the mid-power LED package (illustrated in Figure 5.19a), not only causes reduced lumen output due to absorption of light by the package sidewalls, but also leads to color shift. The photons that hit the package sidewall travel a longer path length through the phosphor and end up having a warmer color temperature compared to the photons that leave through the top surface of the LED without a reflection. As the sidewall becomes discolored, the photons creating the warmer white color component are increasingly absorbed, resulting in a blue color shift as photons taking the shorter path length (cooler white) begin to dominate.

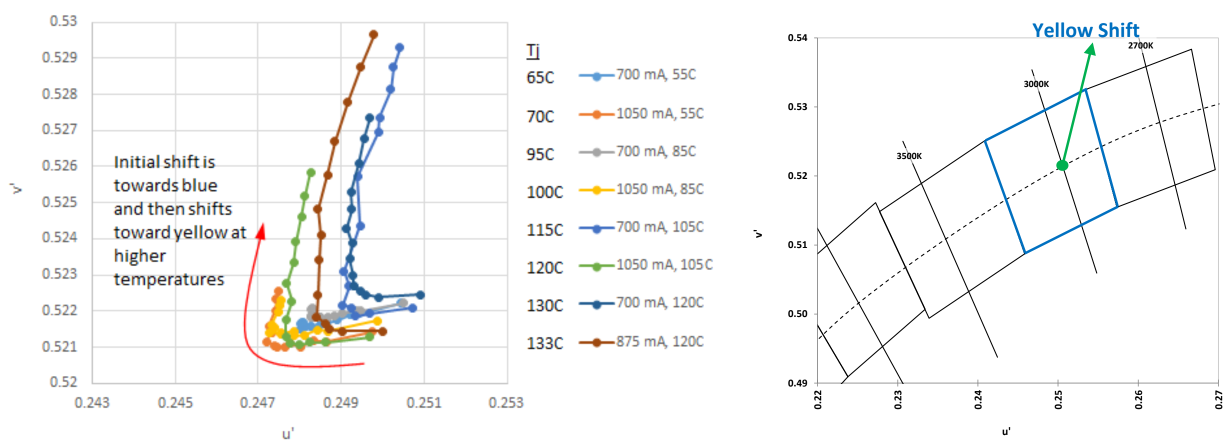


Figure 5.23 The Color Shift of a Representative High Power Package Indicating a Steady Yellow Shift

Source: Monica Hansen, Strategies in Light, Santa Carla, CA, March 2016 [95]

Experimental studies utilizing accelerated life tests (ALT) performed by RTI International have also provided insights into the impact of LED package materials on color point stability. Wet high temperature operating life (WHTOL) testing has been performed on individual high-power LEDs at 85/85 temperature/relative humidity settings. A color shift was seen in the warm white LEDs after 3500 hours ALT, which is attributed to a significant change in the characteristics of the emission spectrum in the red/orange region, with the main peak shifting from approximately 610 nm to 580 nm as seen in Figure 5.24. The study concluded that the spectral shift was due to degradation of the red phosphor in the presence of oxygen in the moisture present in WHTOL testing, causing the red emission wavelength peak to shift shorter. The shortened red emission ultimately caused color shift of the warm white LED emission towards the green spectral region.

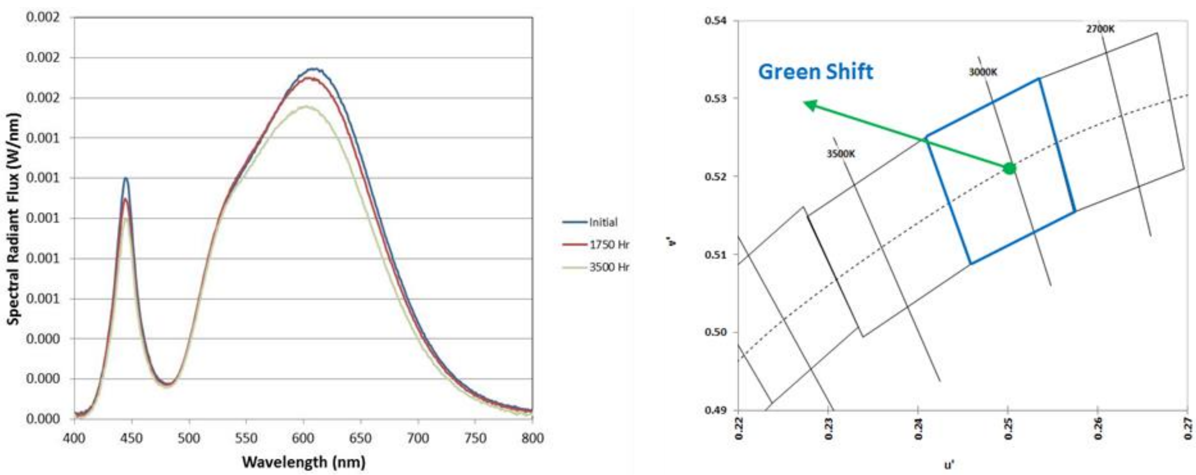


Figure 5.24 Accelerated Testing At 75°C and 75% Relative Humidity Shows a Shift in Red Phosphor Wavelength from 610 nm to 580 nm After 3500 hrs Resulting in an Overall Green Shift

Source: Monica Hansen, Strategies in Light, Las Vegas, NV, February 2015 [94]

Luminaire Reliability

For all lighting technologies, the end of life is signaled by the loss of light, but this may be less evident for LED luminaires. LEDs can emit light for 50,000 hours or more, but the light output may continuously fade or the color may slowly shift, possibly to the point where low light output or an unacceptably large color change constitutes practical failure. This type of parametric failure depends on the system design and how it can reduce the impact of heat on LED sources and electronic components.

As integrated lamps and luminaires appeared on the market, it was at first assumed that one could project the LM-80 test data obtained on LED packages to describe the degradation characteristics of the integrated product. Now, after further research, it is understood that electronic or driver failures, or degradation of optical components, can often occur long before LED lumen depreciation results in failure. This makes useful life difficult to verify. The first challenge is determining how system failure is defined:

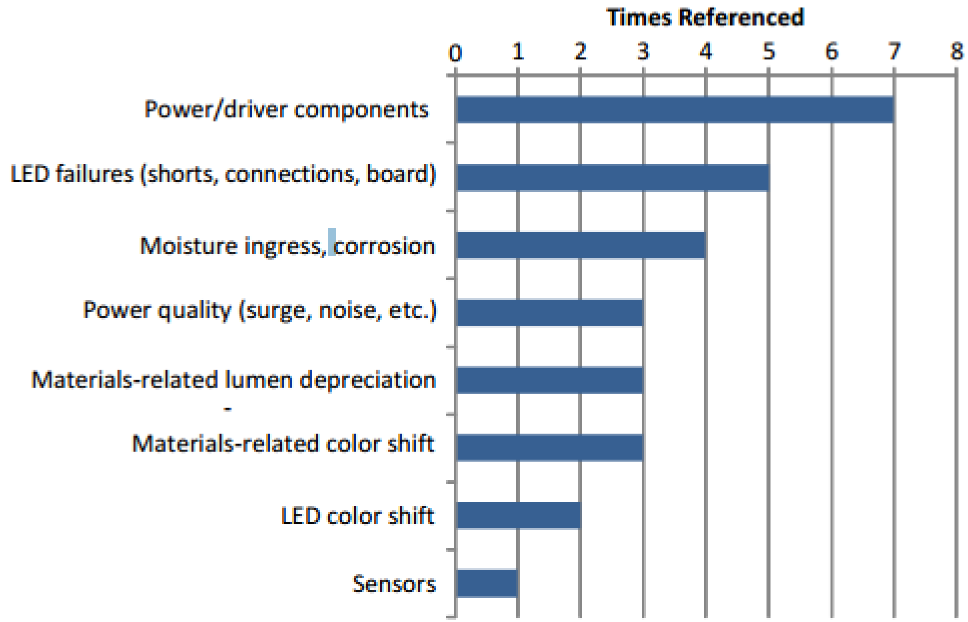
- Only if it generates a warranty claim?
- If it falls below DLC, Energy Star, or CA Title 24 requirements?
- Parametric performance drift?

- Increased ripple or flicker?
- If efficiency decreases?

In addition to defining failure, the cause of system failures – elevated temperatures, thermal cycling, surge events, repeat switching, etc. – needs to be determined. How can these system failures be mimicked in a “reasonable” amount of time to create failure distribution? Many manufacturers have developed proprietary means to estimate product life for their own designs using data on principal components such as the LED package, driver, and optical components, which allows an estimate of the overall luminaire performance. While such practices exist for specific product lines and applications, there is no industry-consensus protocol at this time.

The LSRC, in 2014, published "LED LUMINAIRE LIFETIME: Recommendations for Testing and Reporting (third edition)," in which they reviewed studies intended to identify potential failure modes and provide additional understanding of product life [96].

The results of some highly accelerated multi-variant tests and other available data were reviewed to learn which failures may be significant and how those failures might be accelerated. Some of the information on failure modes comes from a series of highly accelerated tests executed by RTI International on a limited number of product samples. Other information comes from the testing performed by the Pacific Northwest National Laboratory (PNNL) on the Philips L Prize-winning LED A-type lamp. Systematic field data is scarce (and tilted towards reported failures) but does provide some additional insight into those areas that should receive further attention. Other information was provided by members of the LSRC and helped inform the discussions about important failure mechanisms. The most frequently observed failure modes, according to the LSRC members, are summarized in Figure 5.25.



Note: "Times Referenced" means the number of respondents who cited this failure mode.

Figure 5.25 The Most Commonly Observed Failures from LSRC Member Survey

Source: Next Generation Lighting Industry Alliance LED Systems Reliability Consortium, September 2014 [96]

LED drivers and their components contribute to a significant portion of failures. The electrolytic capacitor has been commonly attributed as a leading cause of driver failures, though in recent years it has been seen that many different components within the driver fail. Figure 5.26 shows a survey of driver component failures for 6" LED downlights after accelerated testing, which indicates many different electronic components can fail in the driver.

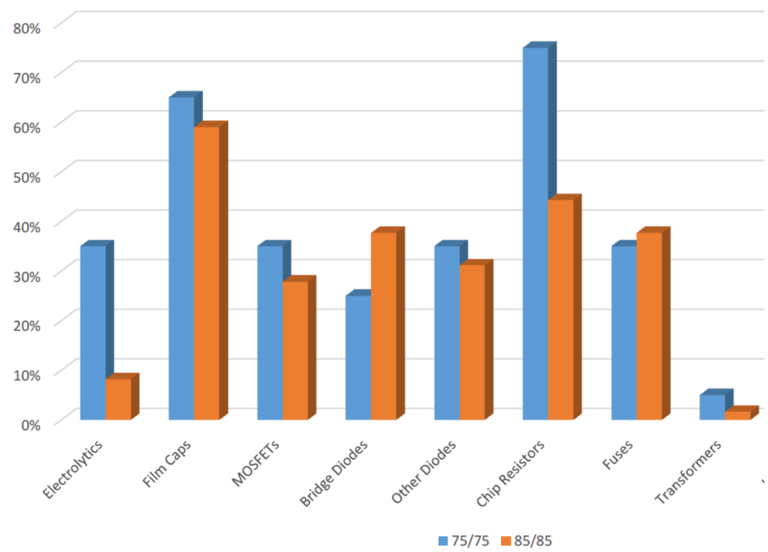


Figure 5.26 A Comparison of Driver Component Failures in 6 in. Downlights After Accelerated Testing at 75°C/75% Relative Humidity (Blue) and 85°C/85% Relative Humidity (Orange)
Source: Lynn Davis, RTI International, DOE SSL R&D Workshop, San Francisco, CA, January 2015 [97]

While color shift has not been identified as the largest reliability concern in this survey, it remains a real challenge since color shift mechanisms are unique to the LED lighting technology and do not have other industries to pull from for established procedures. Accelerated testing results, highlighted above, have increased concern about color shift in limiting the useful life of certain classes of products and applications where color is important. Accordingly, emphasis on understanding the causes for color shift and trying to find means to predict how it may affect performance is still needed.

6.0 OLED Technology Status

In the last few years, multiple high-performance panel products have become available. In 2014, breakthroughs included high-brightness panels based on multi-stacked OLED structures (from Philips), improved color quality and lifetime (from LG Chem), and the release of flexible panel samples (LG Chem) [98, 99]. Meanwhile, cost per kilolumen decreased dramatically to around $200/klm. While many technical advancements were made, 2015 was more of a year of business restructuring and consolidation. Following the 2014 Panasonic withdrawal from OLED lighting efforts, LG Display acquired the LG Chem OLED lighting business, and the Philips OLED lighting division was sold to OLEDWorks [100] [100, 101, 102]. Additionally, despite its 2014 release of the ORBEOS SDW-058+ panel with 65 lm/W (at 3,000 candelas per square meter, cd/m^2) and 15,000-hr lifetime (L_{70}), OSRAM has recently reinforced its focus on OLEDs for automotive lighting rather than general illumination applications [103, 104]. Other companies have experienced delays in production. Full-scale production at First O-Lite in Nanjing was delayed by a search for additional capital and identification of customers in China, and the Konica Minolta high-capacity production line in Tokyo has not reported product specs or significant sales. Though product performance (efficacy, lifetime, color) and cost metrics have not seen drastic improvements this past year, manufacturing yield and product reliability have made strides; OLED installations are now undergoing third-party testing to assess their performance. One such testing site is a Gateway demonstration at Aurora Lighting Design headquarters in Grayslake, IL [105].

While panel product technology remains largely the same, there has been considerable progress in core R&D, paving the way for future improvements. R&D efforts in OLED materials have led to advancements in such areas as thermally assisted delayed fluorescence, iridium-free emitters, and alternative transparent conductors. Internal light extraction approaches have been well engineered, and efforts to integrate these into panel products are underway. The use of bendable or flexible substrates (glass or plastic) is gaining interest, and barrier films to work with flexible structures are becoming more reliable.

Improvements in manufacturing have also been a focus in the past year. Efforts in this area are crucial to reducing the overall price of OLED panels to market-acceptable levels. In particular, luminaire manufacturers are relying on 10 fold yield improvements to reduce panel cost and improve panel reliability to meet customer expectations for product lifetime. Cost-effective short mitigation and particulate-reduction strategies are being explored, as are better thickness monitoring methods. Along with improvements in manufacturing methods, alternative OLED stacks that can simplify the manufacturing process by reducing the number of layers or making the process less sensitive to manufacturing conditions (e.g., more robust materials, simpler stacks, single white emitter devices) are being explored. Finally, there is rising interest in R2R deposition processes as a means to further cost reduction.

6.1 Technology Status

This section describes OLED panel and luminaire performance in terms of efficacy, lifetime, and color quality. A breakdown of each performance criteria is provided, and key technical challenges and goals are discussed. The performance goals are compared to recent data that illustrate the efficacy tradeoffs that are made to realize desirable lifetime, color quality, and unique form factors. Features that differentiate OLEDs from other efficient light sources are being developed and are continually expanding OLED product offerings. A snapshot of product availability and trends for upcoming luminaires are explored in the following sections as well.

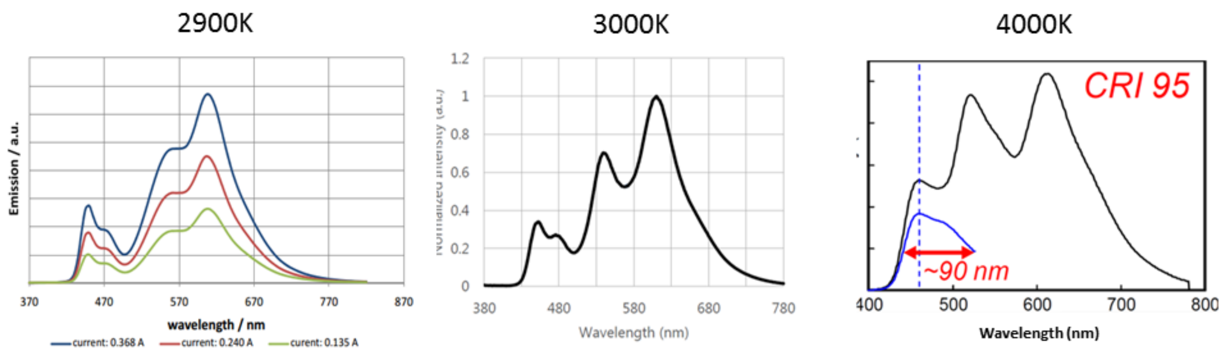
6.1.1 OLED Panel Efficacy

Panel efficacy has been static for the past few years. In 2014, Konica Minolta showed a 15 cm^2 panel with an efficacy of 139 lm/W at 1,000 cd/m^2 and 126 lm/W at 3,000 cd/m^2 [106]. The duration of lumen maintenance to 50% of the initial brightness (L_{50}) for the Konica Minolta panels is about 55,000 hours when operated at 1,000 cd/m^2. Panasonic has achieved 133 lm/W in a larger 100 cm^2 panel, with claimed lumen maintenance (L_{50}) of over 100,000 hours when operated at 1,000 cd/m^2 corresponding to an L_{70} lifetime of around 10,000 hours for a luminance of 3000 cd/m^2 [107]. However, no commercial panel product was available at the beginning of 2016 that surpassed the 60 lm/W efficacy first offered in 2013 by LG Chem. The delay is partly due to difficulties in the implementation of internal light extraction solutions. Panels are using external light extraction films that can improve the light extraction efficiency by a factor of approximately 1.6. Internal light extraction techniques that can push the extraction enhancement to 2.0 to 2.2x have been demonstrated in the laboratory, but integrating these into devices without adversely affecting yield and performance has proven to be a challenge. Efficacy improvement in commercial panels are expected to resume in 2016. LG Display has announced that high-efficacy panels with glass-based encapsulation and 2 mm thickness are now in mass production. These will deliver 90 lm/W with CCT at 2700K and 85 lm/W at 3000K or 4000K [108]. Thinner panels with thin film or metal foil encapsulation should be available in 2016 third quarter (Q3) delivering 70 to 75 lm/W. OLEDWorks is planning to introduce the Brite 2 FL300 family with 3000K high color quality (CRI greater than 90 and R9 greater than 50) with efficacy over 60 lm/W by the end of 2016 Q3 [109].

The following sections outline the factors that determine overall panel efficacy. The practical performance limits for OLED lighting panels are estimated, and milestones are set that take into account the tradeoffs among efficacy, color quality, and lifetime.

Spectral Efficiency

The white light emitted by OLEDs is generated by two or three different colored emitters. The relative densities of the emitters must be chosen to give good color quality and high efficacy, and uniformity of layer thickness must be precise for good color uniformity across the panel. Figure 6.1(a) and (b) show the spectra for two commercial panels from OLEDWorks (formerly Philips FL300) and LG Display (formerly LG Chem); Figure 6.1(c) shows one laboratory panel from Panasonic. The Panasonic panel has a blue emitter with a peak at 460 nm and a full-width half-maximum linewidth of 90 nm [110]. Similar to pc-LEDs, the relatively broad linewidth of red emission from OLEDs requires a tradeoff between color quality and efficacy. This comparison illustrates that there are tradeoffs in efficacy and color quality, often resulting in a penalty in LER of the order of 10% in assuring excellent color with vivid reds (high value of R_9). For OLEDs, the ideal LER is assumed to be 360 lm/W, so that the spectral efficiency of the examples shown in Figure 6.1 lies between 85% and 92%.



Philips: CRI 80; R9 0; LER 330 lm/W (a)

LG Chem: CRI 89; R9 31; LER 328 lm/W (b)

Panasonic: CRI 95; R9 77; LER 300 lm/W (c)

Figure 6.1 Spectra of Commercial and Laboratory OLED Panels

Sources: (a) OLEDWorks FL300 Data Sheet, 2016 [111]*; (b) LG Display OLED Light User Guide, 2015* [112]*; and (c) T. Komoda, "Overview of White OLED Technologies for Lighting Application", Printed Electronics USA, November 2014* [110]

Narrower red emitters could help to reduce the efficacy hit in high-color quality devices. Material developers are also considering tailoring the blue emission spectra to increase device efficacy. While "deep" blue emitters are necessary for display applications, these emitters tend to suffer from shorter lifetimes, and such a deep emission profile is not required for OLED lighting applications. The OLED lighting industry has exhibited a natural tendency to use what is available from the display industry, where R&D funding can support intensive materials tailoring, but it may be time to target efficacy gains specific to OLED lighting devices through spectral tuning of the emitters.

Electrical Efficiency

Electrical efficiency is the ratio of the average energy of the emitted photons to the energy needed to inject charge carriers into the device. The factor contains several components:

- Injection and ohmic losses as the current flows from the electrodes into the recombination region where the photons are created
- Ohmic losses as the charge is distributed over the panel area across the anode and cathode structures
- Stokes losses

The average photon energy varies slightly with the CCT and other details of the spectrum, but is around 2.25 electron volts (eV) for warm white light. Under ideal conditions, the minimum drive voltage required to enable the spectrum to be extended to approximately 450 nm in the blue region is approximately 2.8 volts (V). The drive voltage must also be sufficient to produce the desired current density, which is a few amperes per square centimeter for a single-stack device.

High electrical efficiencies of around 80% are observed with the use of stacked devices. However, there are tradeoffs in using structural design to alter the electrical efficiency. Tandem devices can result in improved electrical efficiency because the conductivity of the various organic materials can be adjusted so that the voltage drop across the lower energy emission layer(s) is less than that of the blue, thus minimizing Stokes losses. However, additional material interfaces can lead to voltage losses through the device. Careful design and material selection is necessary to realize improvements.

Data on the OLEDWorks FL300 panel, which has a six-stage structure with an emissive area of 105 cm^2, provides insight into the dependence of luminance on current and voltage. Figure 6.2(a) shows that the luminous flux varies linearly with current. Output of 10 kilolumens per square meter (klm/m^2) can be attained at a current below 0.12 A. Figure 6.2(b) shows this current can be reached at a drive voltage of 18.2 V, or just over 3 V per stage, giving an electrical efficiency of 74%.

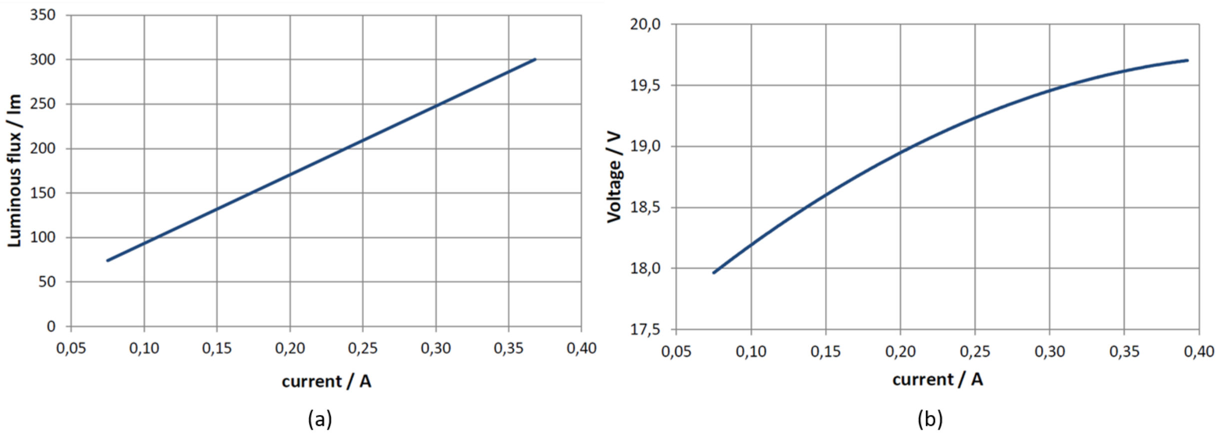


Figure 6.2 Dependence of (a) Luminous Flux and (b) Drive Voltage on Current
Source: OLEDWorks FL300 Datasheet, 2016 [111]

The FL300 is designed to operate at very high luminance of up to 8,300 cd/m^2, producing 300 lumen at a current of 0.368 A [111]. The increase from 100 lumen to 300 lumen leads to a 12% decrease in efficacy. The required drive voltage increases from 18.2 to 19.7 V, contributing 8% of the loss in efficacy. Thus, the efficiency in converting current into light drops by only 4% in these panels, which use fluorescent blue emitters.

Internal Quantum Efficiency

The internal quantum efficiency (IQE) of an OLED depends primarily on two factors. The first is the creation of a balanced flow of electrons and holes into the emission layer. The second is the fraction of recombining electron-hole pairs that lead to the production of visible photons. It is difficult to optimize both factors simultaneously when the emissive layer contains a single component, so typically a dopant to produce the photons is combined with a host that controls the charge transport.

The lack of emission from triplet states in fluorescent emitters usually limits the IQE to about 25% due to the ratio of singlet to triplet states. However, triplet-triplet annihilation can result in triplet fusion in which additional singlet excitons are formed such that IQE as high as 40% has been observed [113]. On the other hand, phosphorescent molecules have demonstrated near 100% IQE. The major problem in exploiting phosphorescent molecules is stability. Phosphorescent excitation energy is held for a much longer time than in fluorescent systems (typically microseconds rather than nanoseconds). This energy can be diverted to non-radiative processes that reduce the IQE and can cause damage to the system, resulting in shorter lifetimes and more rapid lumen degradation when operated at high luminance levels.

Following 15 years of research, the lifetime of red and green phosphorescent emitters has reached levels that are adequate for most applications. However, the lifetime of higher energy phosphorescent blue emitters is still of concern. Therefore, most panel manufacturers use hybrid systems in which stable blue fluorescent emitters with lower IQE are combined with red and green phosphorescent molecules.

Researchers at the University of Michigan and the University of Southern California are working on a unique approach to reduce the observed efficiency roll-off at high brightness. As mentioned above, phosphorescent droop is attributed to charge imbalances and exciton interactions (triplet-polaron annihilation and triplet-triplet annihilation). Such interactions generate a "hot" polaron state on the dopant or host which in turn, leads to degradation. By doping the emission region with a "manager" that can capture and deactivate these hot polarons, lifetime may be extended [114].

In fluorescent emitters with small singlet-triplet separations, thermally activated up-conversion of triplet to singlet states may yield delayed fluorescence resulting in high IQE (up to 100%), but it is too early to know whether this phenomenon can be practically exploited to give systems higher efficacy and longer lifetime. Kyushu University in Japan has been active in thermally activated delayed fluorescence (TADF) R&D. Researchers at Kyushu built extensively on the foundation of TADF over the past several years to demonstrate potential for OLED applications. Most recently, they demonstrated improvement in lifetime of green TADF emitters by as much as 8x, by incorporating thin 8-hydroxy-quinolinato lithium (Liq) layers on either side of the hole-blocking layer [115, 116]. These additional layers allow transport of electrons to the emitter while preventing holes from exiting the device before contributing to emission. Researchers at Seoul National University have shown lifetime improvements in blue TADF material called 9-((6-phenyl-1,3,5-triazine-2,4-diyl)bis(benzene-5,3,1-triyl))tetrakis(9Hcarbazole) (DDCzTrz), using a stable carbazole donor component and triazine acceptor component . With optimized charge balance at high doping concentrations, high quantum efficacies of up to 19% were reported [117]. Cynora, another company working with TADF materials, is focusing on copper-based emitters [118]. On a more academic level, the EU launched a project called "Phebe" to support the development and commercialization of TADF materials with TU Dresden taking the lead with emitter design and Novaled providing additional materials and stack architecture knowledge [119].

Efforts in alternative and improved phosphorescent materials also continue. While researching alternatives to iridium-based phosphorescent emitters, Arizona State University (ASU) has demonstrated that Pt-based emitters can be as stable as iridium-based emitters. ASU researchers are seeking to develop single emitter white devices using molecules with blue monomer emission and orange excimer emission in balanced ratios to achieve white light [120]. Such single emitter systems have the potential to simplify the manufacture of OLEDs, particularly in the case of solution-processed devices.

Extraction Efficiency

Extraction efficiency is the ratio of visible photons emitted from the panel to the photons generated in the emissive region. For basic OLED devices on planar glass substrates, only about 20% (17 to 25%) of the generated light is emitted from the panel. This is due to absorption and trapping of photons in the electrodes, transparent substrate, and inner layers resulting from mismatches in the index of refraction along the photon path (i.e., organic materials, anode, substrate, encapsulation layers, and air). The DOE target for light extraction efficiency is 70%, an extraction enhancement of 3 to 3.5x. The extraction efficiency of current products is only 30 to 35%, leaving ample room for improvement and energy efficiency gains.

There are several ways to increase light extraction:

1. **External extraction layers**

   External extraction layers (EEL) provide a textured external surface to scatter or direct the light out of the substrate, as seen in Figure 6.3. Though simply roughening the external surface can allow for significant light scattering, EELs usually consist of microlens arrays on the substrate, which can be formed by several well-tested techniques. The patterns can be periodic or irregular, but care has to be taken to avoid variations of color with emission angle when periodic structures are used. Surface modulations can be formed during production of the substrate or can be etched into the substrate after manufacture. The most common procedure is to add a structured polymer film that is matched in refractive index to the substrate, either by lamination or in-situ deposition.

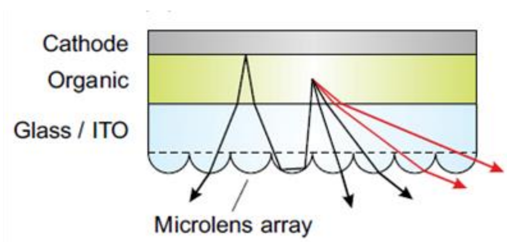


Figure 6.3 External Light Extraction Schematic

Source: Mark Thompson, University of Southern California, DOE SSL R&D Workshop, Raleigh, NC, February 2016 [114]

   External extraction films generally can be applied to the OLED substrate after device fabrication and encapsulation, thus minimally interfering with the delicate OLED stack. EELs are the predominant extraction method currently incorporated into products. Films for lamination are available from several vendors, and effectively extract light trapped in wave-guided modes in the substrate. Extraction enhancement realized by such films is in the range of 1.3 to 1.8x, typically around 1.6x.

2. **Internal extraction layers**

   Internal extraction layers (IELs) may consist of scattering centers (microspheres, zirconia particles, etc.) or periodic arrays at internal interfaces. IELs are promising because they have the potential to extract light trapped in organic layer/indium tin oxide (ITO) wave-guided modes as well as reduce the amount of light trapped in the substrate by bending the light towards the normal as seen in

Figure 6.4. IELs are usually inserted between the substrate and the first electrode as laminated films or formed in-situ. One major challenge is to ensure that the electrodes and organic layers can be deposited on top of the IEL, so surface roughness and chemical composition are critical. Often, issues arise when scatterers at the substrate/ITO interface roughen the deposition surface, which leads to electrical shorting in the OLED device. Alternatively, if the scatterers are embedded in a planarizing polymer matrix, the polymer material may not allow for high temperature deposition and anneals required for peak ITO performance.

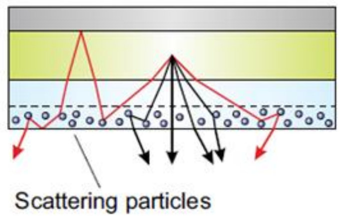


Figure 6.4 Internal Extraction Schematic

Source: Mark Thompson, University of Southern California, DOE SSL R&D Workshop, Raleigh, NC, February 2016 [114]

Microlens arrays that are suitable for insertion into OLEDs have been demonstrated by Panasonic and others, but have not yet been used in high-volume production [121, 122].

Scattering films, formed by the insertion of micro-particles into a host material with high refractive index contrast, are also proving harder to implement than was initially anticipated. Due to challenges with integration of the IELs into devices, these approaches have not yet been incorporated into panel products. However, the potential gains in efficacy are significant (2 to 3x), and this is the most pursued and likely path to light extraction in the next generation of devices.

3. **Reduce surface plasmonic losses**

The presence of emitting molecules very close to a metallic surface (typically the OLED cathode) can result in the excitation of surface plasmon polaritons (SPP). The most common way to reduce surface plasmon losses is to increase the distance between the emitter and the metal electrode. This minimizes the coupling to SPPs, which is a near-field effect [123, 124]. Thick electron transport layers (ETLs) have been engineered for use, but beyond a certain thickness, the thicker layers affect light transmission and voltage. An alternative approach is texturing at the cathode, which can be achieved by patterning at the cathode interface using a material, such as Novaled NET61, within the stack that leads to cathode corrugation [125, 126]. An alternative approach to texturing the cathode is by corrugations at the substrate level that translate through to the cathode via the conformal deposition of OLED layers [127, 128, 129]. Such corrugations allow for Bragg scattering of the surface plasmon resonance modes. Koo et al. reported 2.2x enhancement in current efficiency through corrugations formed through the use of buckle structures on the substrate [127]. However, it is difficult to separate out how much of the gains from texturing approaches are due to scattering of ITO/organic wave-guided modes versus SPP modes. Further, these approaches may compromise the performance of the OLED device due to the non-planar deposition surface. Non-uniform layer thickness and current distribution can cause issues with lifetime, yield, and color quality.

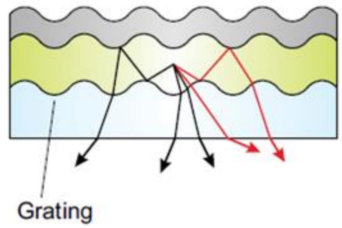


Figure 6.5 Surface Plasmon Decoupling Schematic

Source: Mark Thompson, University of Southern California, DOE SSL R&D Workshop, Raleigh, NC, February 2016 [114]

4. **Reduce Fresnel reflections**

Fresnel reflections may be reduced using graded refractive index schemes or high-index substrates. Index matching the layers in a device provides a very simple approach to high gains in light output. For instance, simply using a high-index substrate in combination with EEL can yield up to 3x extraction enhancement. The difficulty with this approach is the lack of cost-effective and mechanically robust high-index substrates (glass or plastic). An alternate approach is to use lower index organic stack materials. One study showed how the very low index aerogel hosts can yield devices with extraction efficiency of 70% [130].

Pixelligent is exploring an approach to combine the benefits of IELs in combination with a graded index layer to reduce Fresnel back scattering [131]. This technology is being developed with support from a DOE funding opportunity announcement (FOA) grant. The manufacturing problems associated with incorporating scatterers in high-n matrices are being investigated in a DOE-funded Small Business Innovation Research (SBIR) project [132].

5. **Use directionalized emitters**

Emitting molecules can be aligned so that the emitted light and transition dipole moment is desirably oriented. When molecules are oriented perpendicular to the substrate plane, the dipoles couple strongly to the plasmon modes and light is lost. Dopant dipole driven alignment, electrostatic dopant-host interactions, or new materials designs can be used to achieve order. This approach has been shown to be effective for polymer OLEDs, and recent data suggests that efficiency enhancements of up to 2x can be achieved by this method [120]. Figure 6.6 shows how light emission to air is higher with horizontally aligned dipoles as compared to vertically oriented emitters.

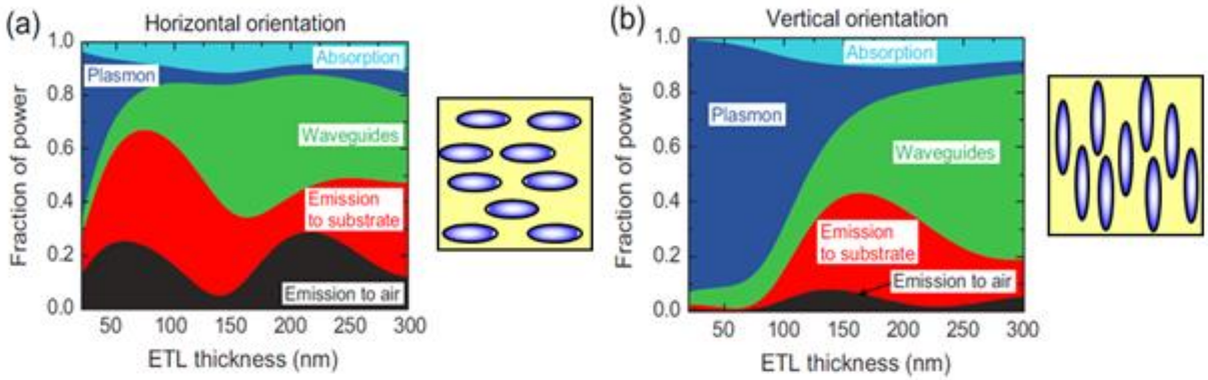


Figure 6.6 (a) Horizontally Oriented Emitters as Compared to (b) Vertically Oriented Emitters
Source: B. Scholz et al, Optics Express Journal Entry, 2012 **[133]**

Efficacy Breakdown and Goals

Table 6.1 provides estimates of the efficiency factors for four OLED devices, comparing the performance of currently available commercial panels and next generation panel products expected to ship this year. The first two columns refer to commercial panels from LG Display, and the second two columns represent OLEDWorks panels. Data are given for operation at a luminance of 3,000 cd/m^2. All are tandem stack devices, allowing for a good balance of brightness and lifetime. Manufacturers have carefully considered all the performance and cost tradeoffs in developing new products. Thus, the efficacy of commercial panels is improving without sacrificing color quality, stability, or cost-effective manufacture. LG's focus has been on high-efficacy panels, with a 50% increase in efficacy from 60 to 90 lm/W. OLEDWorks has simultaneously made drastic improvements in efficacy and color quality. OLEDWorks' Brite 2 panels have an impressive CRI greater than 90 and R9 value of 76 in preliminary product tests. They also exhibit an efficacy increase of 35% compared to Brite 1 panels, resulting in panels delivering 62 lm/W. As can be seen in Table 6.1, OLED devices are performing well in terms of color and lifetime. Luminous efficacy is also competitive, especially compared with conventional lighting, but there is a long way to go to optimize device efficiency. Likewise, cost remains a major challenge for OLED product adoption.

Table 6.1 Components of OLED Panel Efficacy

Source	LG	LG	OLEDWorks	OLEDWorks
Product	LL055RS1-62P1[1]	LL055RS1-92P1[1]	Brite 1[2]	Brite 2
Illuminance (lm/m^2)	10,000	10,000	10,000	10,000
LER (lm/W)	328	328	336	302
Electrical Efficiency (%)	80	80	73	70
Internal Quantum Efficiency (%)	65	65	62	62
Extraction Efficiency	35%	52%	31%	47%
Panel Efficiency (%)	18	27	14	21
Panel Efficacy (lm/W)	60	90	46	62
CCT (K)	2700	2700	2900	2956
CRI (R_a)	>87	>87	80	93
CRI (R_9)				76
Lifetime (L_{70}) (hrs)	40,000	40,000	>50,000	>50,000

Note: All data provided in communications with represented company.

1. A hybrid triple stack with fluorescent blue emitters and phosphorescent red and green; 2700K
2. A hybrid 6-stage stack with fluorescent blue emitters and phosphorescent red and green; 2700K A double stack with all phosphorescent emitters **[111]**

Figure 6.7 shows OLED loss channels, compares state-of-the-art performance to the program goal, and indicates how much improvement might be possible. The values for 2014 refer to the LG LL055RS1-62P1 panel with a triple stack, giving an efficacy of 60 lm/W for a current of 150 mA driven at 8.5 V across a panel with a luminous area of 81 cm^2 [108]. The goal corresponds to an LER of 360 lm/W and a panel efficacy of 190 lm/W.

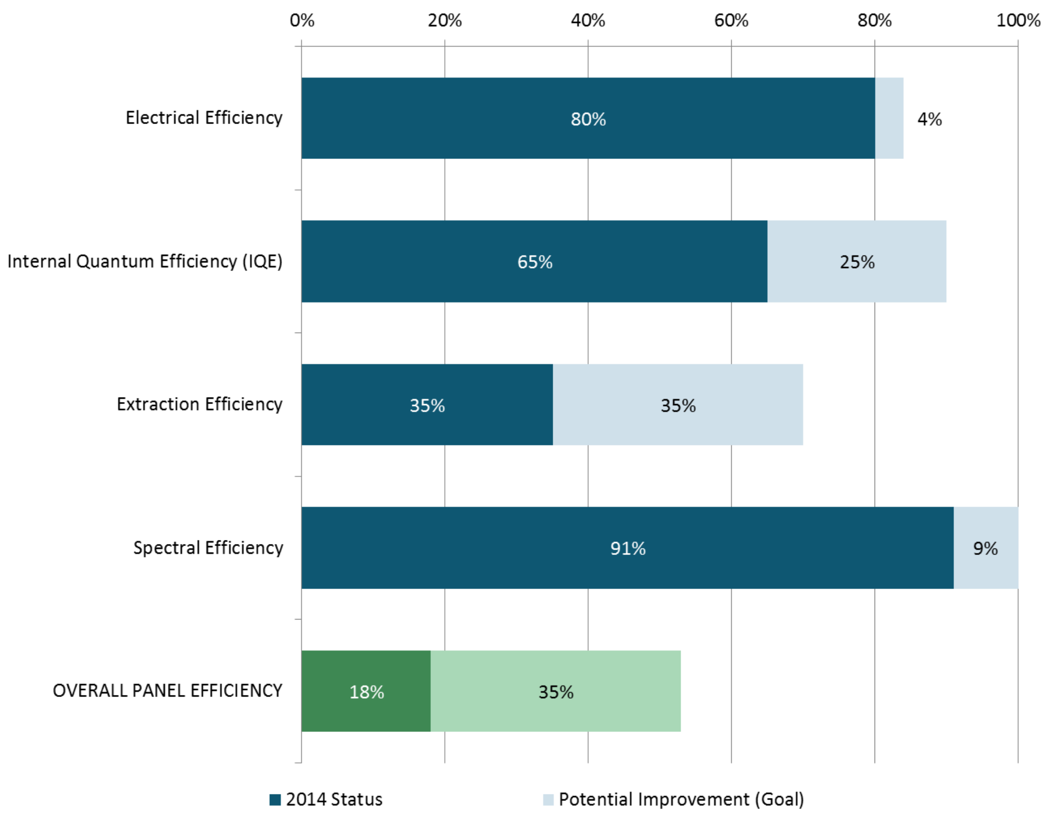


Figure 6.7 OLED Panel Loss Channels and Efficiencies

6.1.2 Panel Lifetime

There are several important metrics relating to panel lifetime. The lifetime of OLEDs is typically reported as a lumen maintenance value, L_p, representing the number of hours of operation during which a light source can maintain a percentage of its initial luminance. Lifetimes on par with LED packages (exhibiting L_{70} greater than 50,000 hours), are desired. Though lumen maintenance is taken as an analogue to lifetime, the operational lifetime is also affected by other failure mechanisms, including catastrophic failures, electrical failures, color shifts (to the point in which the color is no longer suitable for the specific application), and black spot formation. The shelf life of OLEDs is another important metric, which represents the length of time an OLED can be stored without affecting its performance for application. A shelf life of 10 years is expected under normal ambient conditions (temperature around 20°C, low humidity).

The lifetime of OLED devices is influenced by numerous factors including materials robustness (e.g., heat stability, host stability), device architecture, diffusion of materials in the active region, and the impermeability of the barrier materials that protect the device from water and oxygen. The main challenge to OLED lifetime is attributed to the blue emitter systems. The higher energies required by blue emitters cause bond breakage and defects due to local energy dissipation. This effect is exacerbated as the current density is increased to achieve higher luminance levels.

The following approaches are being investigated to extend operating lifetimes:

- Developing new materials that offer the prospect of improved stability (e.g., faster radiative decay rates, stronger bond strengths).
- Engineering devices to extend the recombination region, thus reducing exciton pile-up which reduces the two particle (exciton-exciton, exciton-polaron) interactions that lead to defects.
- Introducing excited state managers to rid the system of hot polarons that lead to molecular degradation of the host and emitter.
- Investigating longer wavelength blue emitters to avoid the higher energies required by deep blue emitters used in displays.
- Reducing the current density through the use of tandem devices and/or enhanced light outcoupling.

Reducing the current density has been the most successful route to lifetime improvements in OLED panels in the past few years. The major benefit of tandem devices and/or improved outcoupling is that the desired amount of light is obtained at lower current density, therefore slowing the rate of defect formation and lumen depreciation. For example, tandem architectures explain, in part, the high L_{70} values of 40,000 and 50,000 hours (based on an initial luminance of 3,000 cd/m^2) reported by LG Chem and OLEDWorks, respectively [111, 134]. Implementation of light-extraction techniques to reduce the current across the device is also effective and can work in concert with tandem devices for lifetime improvements. These approaches are particularly important as panel and luminaire manufacturers are targeting higher operating brightness. For instance, Acuity Brand's roadmap for OLED lighting targets luminous emittance of up to 4,000 cd/m^2 in 2018, and OLEDWorks is already providing panels that operate at 8,300 cd/m^2 with a lifetime of 10,000 hours [111, 135]. Tandem architectures allow many benefits, yet also require added complexity, which leads to lower yields and higher manufacturing costs.

6.1.3 Panel Color Quality

High color quality has been demonstrated in available OLED lighting products. LG Display's panels have a CRI greater than 87. For its 2700K panel, this high CRI is coupled with efficacy of 60 lm/W, and L_{70} at 40,000 hours from an initial luminance of 3000 cd/m^2 [108]. Progress also has been made on reducing panel-to-panel color variations to around ± 2 standard deviation color matching (SDCM) ellipses in luminaires with multiple panels.

Acuity Brands has reported that its market feedback suggests a need for better color quality for OLEDs to enable more high-end lighting applications and feature lighting [135]. OLED panel manufacturers have been responding, with most commercial panels demonstrating a CRI of at least 80 (e.g., OLEDWorks Brite FL300, MC Pioneer Velve). Some manufacturers, such as Lumiotec and LG Display, are targeting a higher CRI of 90 [136, 137]. R_9 values are also increasing and D_{uv} is decreasing. State-of-the-art devices today achieve CRIs of 88 to 90, with R_9 values of 20 to 30, and D_{uv} within 0.002. Target color specifications include CRI greater than 90, R_9 greater than 50, and low D_{uv}. Manufacturers are working toward these goals. OLEDWorks new Brite 2 panel is specified at CRI greater than 90 and R9 greater than 50 [138].

OLED companies are not yet describing color quantity in terms of the new TM-30 metrics of color fidelity and color gamut. However, Figure 6.8 shows that OLED and LED panels can yield similar values, 89 and 88, respectively, for the sources represented below.

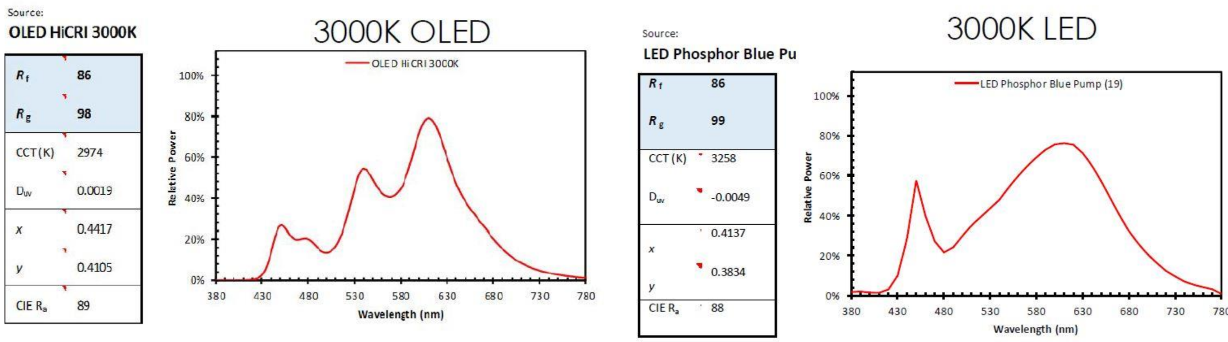


Figure 6.8 TM-30 Comparison of OLED and LED, 3000K

Source: Mike Lu, Acuity Brands, OLED Stakeholder Meeting, Pittsburgh, PA, September 2015 [139]

While high color quality is essential, it is very difficult to control. The exact ratios of light emitted by the various emissive components of the device, which is influenced by the layer thicknesses and dopant concentrations, determines the color of OLED devices. Therefore, precise compositions and uniform thicknesses over large areas are critical for high-quality devices. In the OLEDWorks FL300 panel, variations in color across a single panel are usually very small, with a Δu'v' less than 0.002. Color uniformity from one panel to the next is also important, particularly when several panels are placed in close proximity within a luminaire. For the FL300 panel, the specification in (u',v') space is u' = 0.255 $\pm$ 0.006, v' = 0.521 $\pm$ 0.005 [111]. The driving conditions of the device also influence the color and brightness, because different emitters require different voltages. Variations can occur between panels, but can also be observed within a single panel if the layer thickness, composition, or current varies across the width of the device (See Figure 6.9). The angle of emission can lead to more substantial color shift, which is also illustrated in Figure 6.9. Such variations are particularly sensitive to the existence of micro-cavity effects or of periodic structures used to enhance light extraction. Moreover, complications can arise with non-uniform degradation of the different color emitters over time resulting in a color shift with ageing.

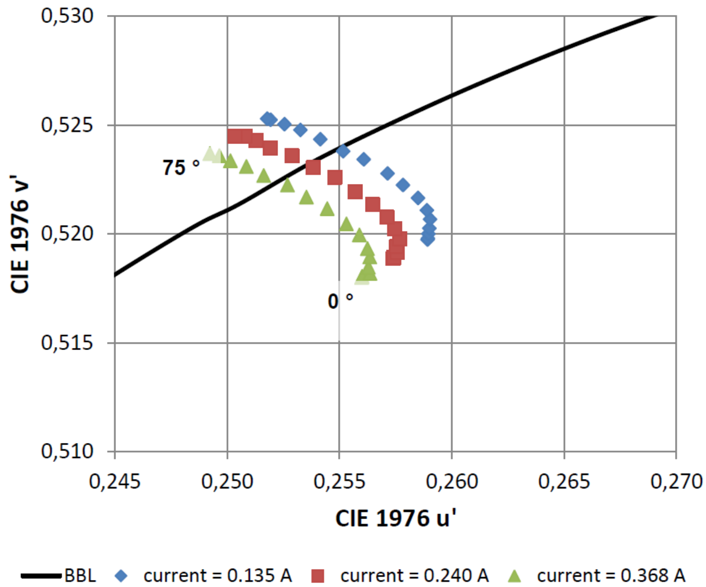


Figure 6.9 Variation of Color Point on CIE1976 (u',v') Diagram with Drive Current and Emission Angle
Source: OLEDWorks FL300 Datasheet, 2016 [111]

6.1.4 Form Factor

Along with performance improvements, OLED developers have been working to improve form factors through the use of lightweight, flexible, or bendable substrates (e.g., metal foil, polymer, ultra-thin glass). A key obstacle to the use of flexible/bendable substrates is the development of reliable barriers to prevent ingress of water and oxygen through plastic substrates and covers. The use of ultra-thin glass can provide a good, impermeable substrate, but there are concerns about handling issues and limited flexibility. A thin film encapsulant can be used in conjunction with ultra-thin glass substrates to minimize weight and thickness. An alternate approach is to use ultra-thin glass as both the substrate and encapsulant, although development of cost-effective, high performance sealing mechanisms is needed for this approach. Corning and OLEDWorks are partnering to implement Corning's Willow glass (50 and 100 micrometers, μm) as a substrate and encapsulant to create flexible and conformable panels. The substrate glass also includes Corning's light extraction technology [140].

Prototypes of ultra-light flexible panels have been displayed for many years, but are now coming to market. For example, Figure 6.10 shows pendants with flexible LG Display panels that were demonstrated at the Light and Building Show in Frankfurt, Germany, in 2016. A family of six flexible panels is now included in the catalog from LG Display, with thickness of 0.41 mm, efficacy of 50 to 55 lm/W at a luminous emittance of 10,000 lm/m^2, CCT between 2700K and 4000K, CRI of 87, and lifetime (L_{70}) of 20,000 hours [108]. These flexible panels on plastic substrates have replaced their former "bendable" panels on ultra-thin glass by allowing for greater design freedom, lower cost, and easier handling.

Figure 6.10 Pendants with Flexible OLED Panels from LG Display
Source: LG Display OLED Light Catalog, 2016 [108]

Konica Minolta is also producing white- and color -tunable flexible panels on its R2R line in Tokyo, as seen in Figure 6.11. These 0.35 mm-thin panels built on plastic substrates were showcased at Lighting Japan 2016.

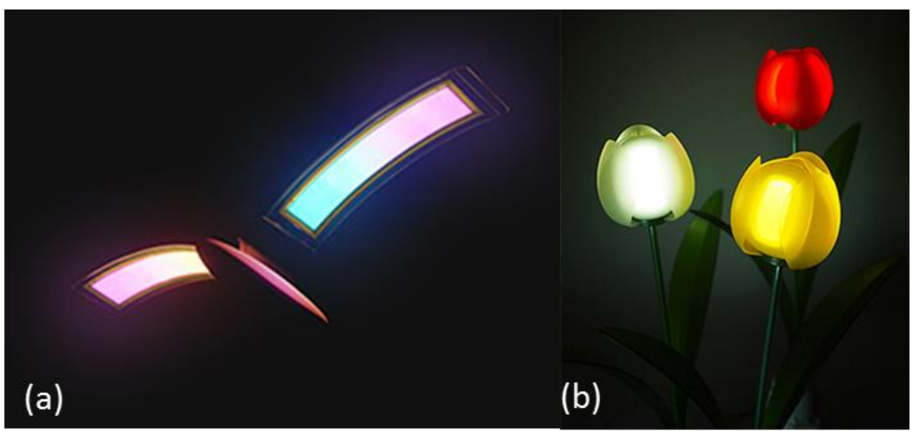


Figure 6.11 Konica Minolta "Habataki" and "Tulip" Comprised of Flexible, Lightweight OLED Panels
Source: Konica Minolta Webpage, 2016 [141]

Flexible and bendable substrates reduce design constraints. Ultimately, designers envision the use of such OLEDs in 3-dimensional (3-D) lighting surfaces, especially in architectural spaces with non-planar surfaces, and space-constrained areas such as vehicles, vertical surfaces, and task-specific lighting.

6.1.5 OLED Luminaire Efficiency

Efficacy

In luminaires that are now available commercially, the efficacy is affected by integration of the panel into the luminaire. Many prototype luminaires have been designed such that the only additional efficiency loss arises in the driver, leading to a reduction of around 15%. No exterior optics are added, so that the light distribution remains close to Lambertian. Though there are some luminaires that offer efficacy close to that of the panel (around 85% of panel efficacy), most commercially available luminaires deliver an efficacy of around 70% . A DOE Gateway Demonstrations showed that a 2014 installation of Acuity Brands Trilia luminaires had a system efficiency of 46 lm/W using panels rated to deliver 60 lm/W, thus representing cumulative losses of around 24% [105].

Improvements in luminaire design and drivers can help reduce losses. The projections in Table 6.2 assume that the efficiency of OLED drivers will improve along with that of LED drivers, but with a 2- year time lag because OLED-specific drivers are required for optimal operation. Off-the-shelf LED drivers have voltages that do not necessarily correspond to the voltages of the OLED panel or panel aggregates, thus compromising system efficiency. OLEDWorks is now offering specified drivers to complement its panel products to alleviate issues with installation [142]. At the 2016 DOE SSL R&D Workshop, the need for the development of such OLED light engines was emphasized. This approach, of designing the stack and drivers in concert, could help to get over electrical efficiency hurdles.

In addition to improvements in luminaire efficacy, the overall utilization efficiency of the OLED luminaire can be affected by the light distribution profile. The broad angular distribution of the light from an OLED can be used to good effect in several ways. The light from ceiling-mounted fixtures or high pendants provides a good balance between illumination of vertical and horizontal surfaces, which is important for viewing faces as well as wall decorations. If the efficacy can be raised to 100 lm/W or above, OLEDs can then compete on good terms with other sources of ambient light. For task lighting, OLEDs that are placed close to the work surface provide additional illumination without distracting shadows.

In future applications, beam-shaping may be required to focus the light where it is most needed or to avoid glare. It seems unlikely that this will be accomplished within the panel, so exterior optical elements may be needed in the luminaire. Though some light-shaping optics may be cost effective in high brightness OLED luminaires, in many applications the bare panel will remain sufficient, providing an advantage in reducing the cost-scaling factor in going from light source to luminaire.

The anticipated evolution of the efficiency breakdown in a typical luminaire efficiency is shown in Table 6.2. The degradation in projected optical efficiency beyond 2020 represents the optical losses associated with a more directed beam distribution, whereas up until 2020 no external beam distribution is assumed.

Table 6.2 Breakdown of OLED Luminaire Efficiency Projections

Metric	2015	2017	2020	2025	Goal
Panel Efficacy[1] (lm/W)	60	100	125	160	190
Optical Efficiency of Luminaire	100%	100%	100%	90%[2]	90%[2]
Efficiency of Driver	85%	85%	85%	90%	95%
Total Efficiency from Device to Luminaire	85%	85%	85%	81%	86%
Resulting Luminaire Efficacy[1] (lm/W)	51	85	106	130	162

Notes:
1. Efficacy projections assume CRI >80, CCT 3000 K
2. Losses representing possible use of beam shaping optics

Luminaire Design

The OLED community is identifying key differentiating features of OLED lighting that are expected to give OLEDs an advantage in the lighting industry, such as bendability, flexibility, and transparency. OLEDs also can offer color tunability, high efficacy, thin and lightweight designs, and diffuse lighting, distinguishing them from conventional lighting. From a product development standpoint, integration of differentiating features is key. Acceleration of luminaire development is anticipated as manufacturers settle on common panel sizes and electrical and mechanical connection schemes. The development of OLED light engines that supply the panel or group of panels with an appropriate, efficient driving mechanism for luminaire manufacturers to work with can also simplify luminaire integration, leading to acceleration of luminaire product development and deployment. LG and OLEDWorks are offering do-it-yourself kits for developers, such as the one shown in Figure 6.12.

Figure 6.12 LG Lighting DIY Kit
Source: LG Display, February 2015 [143]

Advancements in driver technology to improve the ease of panel installation are also desirable to accelerate the integration of OLEDs into lighting designs. Figure 6.13(a) shows an OLED track light developed by LG in which the OLED panels have an aluminum casing with easy-to-connect mounting brackets for attachment to the track. Each panel is cased and integrated with a DC-DC driver on the back, while an AC-DC driver supplies DC to the track rail. Figure 6.13(b) depicts the Versa lights from Astel Lighting, Slovenia, showing how modular tiling can be enabled.

Figure 6.13 User Customizable Lighting Using (a) LG Rail Module and (b) Astel Lighting "Versa"
Source: LG Display OLED Light Catalog, 2016 [108]; *Astel Lighting, 2016* [144]

The advancement and commercial availability of color-tunable, transparent, mirror-finish, or printed panels may further increase design possibilities for luminaire manufacturers. Color tunability can be achieved either by placing several emitters side by side, each with its own drive circuit, or by enabling voltage control of the charge generation layers in a stacked OLED. Laboratory demonstrations have been made by UDC/Acuity and the Fraunhofer Institute in Dresden among others, and prototype color-tunable panels have been offered by Konica Minolta; however, Pioneer currently offers the only commercially available color-tunable OLED panel on the market [145, 146, 147]. At Light and Building 2016, Pioneer exhibited these white- and RGB-tunable "Velve" panels. Their white-tunable panels (CCT tunable from 1200K to 6500K) have efficacy of up to 52 lm/W, CRI 87, maximum luminance of 2000 cd/m^2, and lumen maintenance, L_{70} of 80,000 hours (from maximum brightness) [148].

Transparent electrodes can be used for both cathode and anode, leading to devices that are transparent when turned off. Samsung has demonstrated that active matrix OLED displays can be fabricated with transmittance of 45%. Because the TFT backplane blocks significant amounts of light, it should be possible to achieve higher values in lighting applications. Values of more than 70% have been reported by UDC [149, 150]; in 2012, Osram announced its RTW-078 transparent panel with transmission value of 57% and luminous efficacy of 20 lm/W. Fraunhofer FEP has demonstrated transparent, flexible panels at LOPEC 2016, including the green-yellow "night fly" developed as part of Flex+ project, as seen in Figure 6.14. The low efficacy of transparent panels is partly due to the requirement of high transparency, which restricts the methods that can be used to enhance light extraction. The use of transparent cathodes also introduces challenges with scaling, as the conductivity of transparent cathodes is significantly less than metal cathodes. UBI Research has forecast that the market for transparent OLED display panels may rise to $5 billion by 2020, so the display industry may drive the development of solutions to these problems [151]. The primary market is expected to be the front panels for display cases in retail stores.

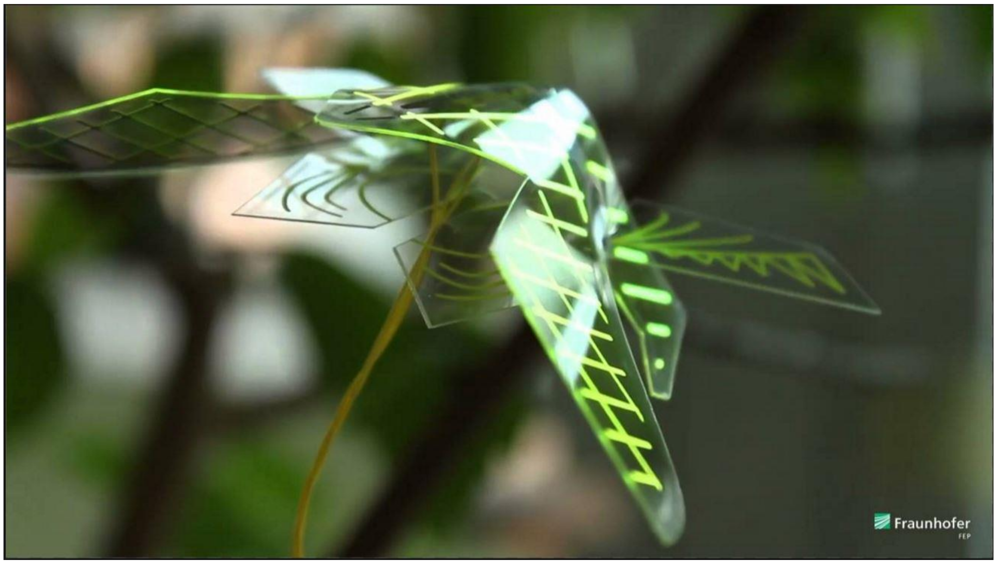


Figure 6.14 Fraunhofer FEP, “Night Fly”
Source: Fraunhofer FEP, “Full-Plastic OLED Lighting” Video, November 2015 [152]

Panels can be made with a mirror finish in the “off” state if the scattering light extraction layers are not used in the device. In this case, when the panel is not emitting light, the user can see through the transparent anode and OLED stack to the highly reflective cathode, which provides a mirror-state for the device as illustrated by LG Display panels in Figure 6.15.

Figure 6.15 LG Display Mirror OLED
Source: LG Display Catalogue [108]

The need for electrical connections and drivers sometimes constrains the freedom to introduce new form factors. However, LG Display has shown that the stylish advantages of OLEDs can be extended by surrounding the active panel by a transparent conducting border that carries the current into the emitting area, as shown in Figure 6.16.

Figure 6.16 Embedded OLED Panels with Current Supplied Though Transparent Conductors
Source: LG Display OLED Light Catalog, 2016 [108]

Printed devices are also of interest for applications where a logo, image, or segmentation of emissive areas is desired. Advancements in printed materials and manufacture are also being pursued in hopes that this approach will pave the way for low-cost, large-area devices. Sumitomo Chemical is offering for sale its printed OLED Cosmos tiles. They have shown the following performance parameters for white devices: CCT at 3100K; CRI at 72; efficacy of 56 lm/W, and lifetime L_{70} of 10,000 hours from initial brightness of 1,000 cd/m^2.

To promote the development of creative yet practical luminaires, OLEDWorks and Corning are sponsoring an OLED lighting design contest with a prize of $10,000 to the winning designs [153]. Meanwhile, the European Union has launched an open-access pilot line, PI-SCALE, to allow companies to produce flexible OLED designs for automotive, aerospace, and designer luminaire applications.[s]

6.1.6 OLED Product Availability

OLEDs are mostly being used in modular form, as arrays of small panels of area 100 cm^2 or less. These panels can be configured either in 2-dimensional (2-D) or 3-D forms, offering light sculptures as a new form of architectural lighting. Such sculptures can be used to form elaborate chandeliers and artistic room lighting. LG Display offers the largest lighting panel with an area of 1,000 cm^2 [108]. Eventually, lighting designers would like to see OLEDs in the form of large, customizable (any size, shape) sheets of light.

[s] For more information on PI-SCALE, please see: http://pi-scale.eu/

Today's OLEDs are not a practical option for the primary source of lighting in a room due to their limited light output and high cost. For now, many proponents are recommending their use in wall sconces and task lights, in conjunction with other sources of ambient lighting. Acuity Brands and others (e.g., Osram, WAC, Zumtobel) have demonstrated hybrid OLED-LED luminaires [15]. Such designs boost the light output and reduce cost per lumen while maintaining the aesthetic appeal of OLED luminaire designs, as discussed in Section 2.3.

The low brightness of OLEDs allows them to be placed close to the task surface to improve light utilization without being uncomfortable to the user. OLED desk lamp products from U.S. companies Workrite Ergonomics and OTI Lumionics came on the market in 2015. The Workrite Ergonomics lamp shown in Figure 6.17(a), named "The Natural," uses an LG Chem panel and delivers 442 lumens (at 32 lm/W) at the max brightness setting, at list price of $399 [154]. The OTI Lumionics "Aerelight" Figure 6.17(b) is another desk lamp operating at 7 W, with a list price of $299 [155].

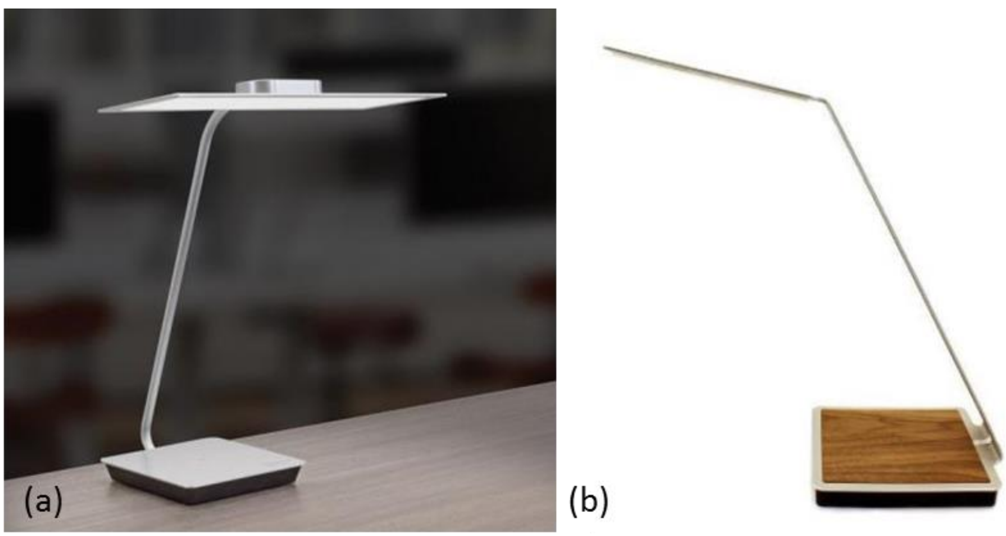


Figure 6.17 OLED Desklamps (a) Workrite Ergonomics, "The Natural," and (b) OTI Lumionics "Aerelight"
Source: (a) Darren Husley, Workrite Ergonomics [154] *and (b) Jacky Qiu, OTI Lumionics* [155]
DOE R&D Workshop, Raleigh, NC, February 2016

A developing market for OLEDs is automotive lighting. Applications for OLEDs in automotive lighting include rear lights, interior lighting, indicators, and accent lighting. The 2016 Audi TT RS coupe, a high-end, serially produced car has an OLED taillight (Figure 6.18a). An interesting feature of OLED lights is that the emissive area can be patterned. Osram has demonstrated this differentiating feature in OLED taillights [103]. Whereas LEDs require an optical system consisting of reflectors or lightguide structures to shape the light emitted by the point source LED, OLEDs are surface emitters that can be patterned and segmented allowing to shape the emissive area without an optical system. 3-D effects can be created out of 2-D lights by differing brightness levels. Further, using the ability to independently address light segments, OLEDs can be used to create interesting, dynamic rear lighting scenarios. Such an effect is demonstrated in the limited edition BMW M4 GTS coupe, which is now in production (Figure 6.18b).

(a) (b)

Figure 6.18 (a) Audi TT RS 2016 OLED Tail Light (b) BMW M4 Concept Iconic Lights OLED Tail Light

Source: (a) http://www.beelighting.co.uk/news/ (b) BMW Blog, 2015 [156]

Osram also has been investigating transparent and flexible panels for use in auto applications. With support from the German Federal Ministry of Education and Research's R2D2 project, Osram has worked with partners such as Audi and Hella to demonstrate the application of flexible OLEDs in taillights [157]. Figure 6.19 shows an example of Audi's flexible versus rigid red panels in an Audi Q7.

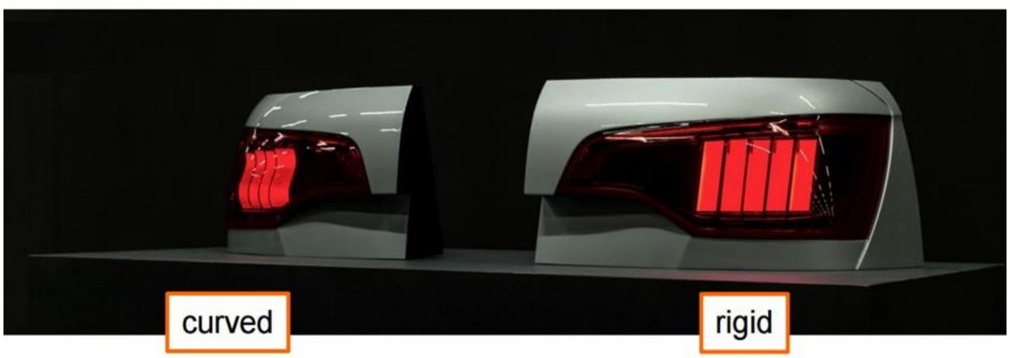


Figure 6.19 Audi Q7 Tail Light Demonstrator

Source: Thilo Reusch, OSRAM LED, DOE R&D Workshop, Raleigh, NC, February 2016 [103]

OLED Panels vs. Diffuse Light LED Panels

A key feature of OLED technology is the diffuse nature of the area light sources. However, mimicking OLEDs, LED products with large-area diffuse lighting are becoming more compelling. Several edge-lit and direct-lit products are available. Figure 6.20 shows some examples of LED panel products.

(a) (b) (c)

Figure 6.20 (a) GE Edge-Lit Panel (b) Maxlite Direct-Lit Luminaire (c) Cooledge Flexible Direct-Lit Technology

Source: (a) GE Lighting Overview Webpage, 2012 [158]*, (b) Maxlite Direct-Lit LED Data Sheet, 2015* [159]*, (c) Cooledge Flexible Direct-Lit Technology, 2016* [160]

With the high performance and low cost of LEDs, such products provide an attractive alternative to OLED luminaires. LED panels are around \$25 to \$40/klm, compared to \$120/klm and up for OLED panels. In addition to low cost, LEDs have established longevity, and some panel products have efficacies of more than 100 lm/W for 3500K products. The limitations of LEDs are mostly in aesthetics and form factor. For direct lit panels, a considerable distance between the emitters and diffusing optic is required to prevent viewing the individual point sources. In edge-lit panels, costs are higher and there are constraints on the area of the device in order to maintain brightness uniformity across the panel as luminance decreases away from the edge source. A further limitation is that waveguiding approaches would be difficult to implement in flexible panels. Thus, the extremely thin nature of OLEDs, combined with optional patterning, transparency, and flexibility allow for designs that cannot be attained with LED technology alone. As fabrication lines designed specifically for higher volumes begin to churn out volumes of OLED panels, it is hoped that costs will come down, allowing for competitive products (in price and performance) to reach the market.

6.2 OLED Manufacturing Status

The following section focuses on recent progress and major challenges facing OLED manufacturing. OLED manufacturing processes can be defined by a sequence of relatively independent manufacturing steps which are supported by the supply of manufacturing equipment, materials, and testing equipment. The combination of the manufacturing processes, equipment, materials, and testing constitute the OLED manufacturing supply chain, which is described in great detail in the 2014 SSL Manufacturing Roadmap.[t]

---

[t] Available at: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_mfg_roadmap_aug2014.pdf

Over the past 3 years, OLED manufacturing has evolved from an R&D activity, with test panels being delivered to lighting designers and custom buyers, to pilot production activity with lines designed for efficient manufacturing. These lines were developed by LG Chem in South Korea, Osram and Philips in Germany, First O-Lite in China, Konica Minolta in Japan, and OLEDWorks in the United States. These companies join Astron Fiamm (France) and Lumiotec and Kaneka (Japan), which have been making panels and selling luminaires for many years. Other companies, such as Panasonic, have decided to delay entry into commercial production, although they will continue their R&D efforts. Each manufacturer has its own set of manufacturing challenges and business decisions, but the major challenges appear to be cost reduction, panel consistency and reliability, and the production of large areas of material.

Most of these pilot production lines use traditional vapor deposition techniques to form the organic layers on glass substrates sized around 370 mm x 470 mm. The capacity of these lines can be estimated using production parameters for the Aachen line released by Philips in early 2015 [161]. Their process cycle time, often denoted by the German acronym TAKT, was 3 minutes and their yield of good panels was around 70%. Their substrate size is 400 mm x 500 mm. If we assume that 12 panels are created on each substrate and that the line can be run for 7,500 hours (allowing 1,260 hours for scheduled shut-downs, maintenance, and breakdowns), the annual capacity of this OLEDWorks line will be close to 1.3 million panels with active area around 100 mm x 100 mm.

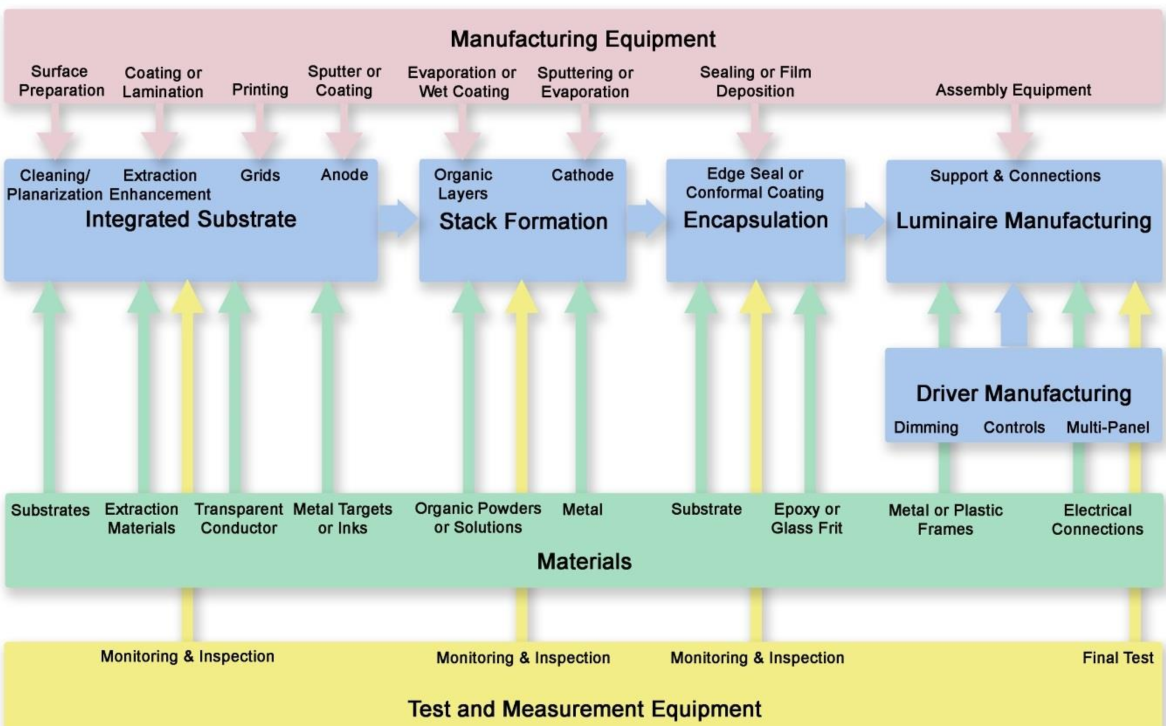
Konica Minolta has long been a proponent of R2R manufacturing on flexible substrates. In May 2014, announced a ¥10 billion (almost $100 million) investment in an R2R production plant with a capacity of 1 million panels per month. The schedule was to complete construction in the summer of 2014 and begin production in fall 2014 [162, 163]. In January 2015, Konica Minolta announced that high-volume production was underway, and that 15,000 OLED lights would be used to create 5,000 tulip shaped luminaires for the Kingdom of Light event at the Huis Ten Bosch amusement park in Japan [164]. However, no commercial sales had been announced by the end of the first quarter of 2016.

Limited panel production is also available from Kaneka and Mitsubishi-Pioneer in Japan, and from Visionox in China. In total, the global capacity in 2015 was about 100,000 m^2, sufficient to produce 10 million panels of size 100 mm x 100 mm. Assuming a price of $15 per panel would lead to estimations of total global revenues of $150 million. However, sales have been much less than this, suggesting that the available capacity is underutilized.

Acuity Brands and Neumuller have provided inspiring leadership in the Unites States and Europe, respectively, demonstrating the effective use of OLED technology for lighting. However, there are a number of issues that are delaying development, manufacturing, and adoption of OLED lighting technology. There are performance shortcomings of the OLED products with respect to LED lighting products. Advancements in LED technology have presented a moving target in terms of acceptable performance levels. Clearly, manufacturing issues of OLED panels can be inferred from the high level of claimed manufacturing capacity coupled with the high price and limited commercial production of OLED panels. OLED lighting products are also an unknown quantity to the consumer in terms of reliability, light output, color, and total performance. This consumer hesitancy is also occurring with LED lighting products, but LEDs have been able to replicate legacy lighting form factors at a more reasonable price point that has convinced consumers to take a chance on the energy savings. The fundamental technology of OLEDs does not allow for replication of common lamp types, so the OLED community has a more difficult task of educating consumers about new lighting form factors and the benefits of the technology. The limited number of product examples that are available for consumers to explore exacerbates this difficulty. The likely solutions require technological advancements in performance and manufacturing, manufacturers willing to take a chance on the technology, consumer education, and development of products that offer a compelling value proposition.

6.2.1 Supply Chain Outline

Although the number of companies involved in the manufacturing of OLED panels or luminaires is relatively small, they depend on a large number of suppliers of materials, equipment, and process techniques. The roles of the various suppliers are indicated in Figure 6.21. Appendix 0 contains additional information on companies involved in the OLED supply chain.



Note: The blue-shaded boxes and blue arrows describe the main manufacturing flow. The supporting elements of the supply chain are broken down into manufacturing equipment, materials, and test and measurement equipment. These supporting elements feed into the main manufacturing flow, as indicated by the relevant arrows.

Figure 6.21 OLED-Based SSL Manufacturing Supply Chain

6.2.2 Critical OLED Components

OLED manufacturing requires many processes as a result of the many components, or layers, required to produce white light. In addition to an overview of existing manufacturing capabilities, each component will be discussed in the following sections. It may be of use to those who are less familiar with OLED panels to refer to Figure 8.2, Components of an OLED Panel, in Appendix 8.1.

Substrate Selection and Preparation

The substrate used in most commercial OLED lighting panels is display-grade glass, such as the type produced in the fusion process by Corning. This leads to sheets of thickness less than 1 mm, with high transparency, very smooth surfaces, excellent thickness control (less than 20 µm variation) and waviness less than 1 µm [165]. The low coefficient of thermal expansion enables processing at high temperature with minimal registration and alignment problems. The thickness can be reduced to less than 100 µm, allowing for the fabrication of flexible panels and use in R2R process lines. Less expensive forms of glass, (e.g., soda-lime window glass) are being explored, but they are only commonly available in thicknesses over 1 mm. For all glass substrates, care must be taken to ensure that the surface is smooth, preferably with a peak-to-valley roughness of less than 10 nm.

The preferred plastic substrate for OLED displays is polyimide because of its tolerance to processing temperatures of up to 350°C. However, the cost of transparent polyimide with an effective moisture barrier layer is higher than that of display-grade glass. Less expensive alternatives are available, such as polyethylene terephthalate (PET) and polyethylene naphthalate (PEN). Although these are not compatible with the high processing temperatures used in making the thin film transistor backplanes for OLED displays, this is not required in lighting applications. However, surface roughness can be a serious problem with plastic materials not developed specifically for this application.

Metal foils can also be used as the substrate in R2R manufacturing and provide an effective barrier against moisture. They enable high-temperature processing and offer a thin, lightweight alternative to glass as a cover material. However, either the substrate or cover needs to be transparent and so metal foils cannot be used for both. Once again, surface roughness can be an issue as the peak-to-valley roughness of stainless-steel rolls can be as high as 1 µm. Therefore, surface roughness must be controlled, for example, by polishing or adding a planarization layer. Metal foils are well suited to flexible panels and devices, provided the bending does not lead to crinkling. Both stainless steel and aluminum foils have been used successfully in prototype OLEDs.

Regardless of the choice of substrate, surface contamination must be prevented and surface cleaning is critical. Fortunately, custom-designed equipment does not seem to be needed because suitable tools have already been developed for the semiconductor, flat-panel, and photovoltaic industries. Robotic handling is desirable at all stages of the manufacturing process. For web processing, the inner surface should preferably not come into contact with any tool.

Barrier Layers for Plastic Substrates

All plastic substrates are extremely porous to oxygen and water vapor, both of which must be kept away from the OLED active layers. Although perfect layers of hard inorganic materials can provide an adequate barrier, it is difficult to avoid the formation of pinholes during deposition. Effective barriers can be formed by creating multiple layers of dense silicon (or metal) nitrides or oxides interspersed with organic layers. The inorganic layers are typically formed by plasma enhanced chemical vapor deposition

(PECVD) or atomic layer deposition (ALD). The organic layers prevent the propagation of defects through the dense inorganic layers and may contain active moisture absorbers and oxygen scavengers. Figure 6.22 shows such structures developed at the Holst Centre that can be fabricated by R2R techniques.

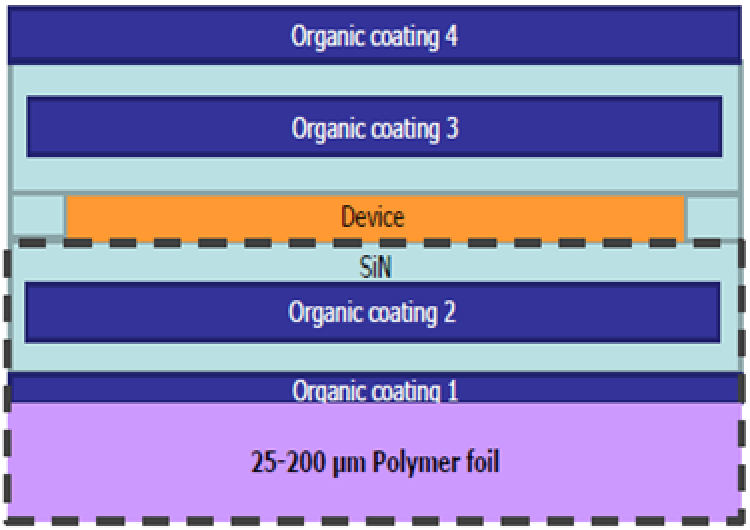


Figure 6.22 Multi-Layer Barrier Coating to Prevent Ingress of Moisture and Oxygen
Source: Pim Groen, Holst Centre, DOE SSL R&D Workshop, San Francisco, CA, January 2015 [166]

Estimates of the cost of producing multi-layer barrier films are in the range of $35/m^2 to $60/m^2, which is far above the long-term targets for OLED lighting. However, recent progress in the development of large-area inkjet printing equipment for organic layers by Kateeva and of improved PECVD or fast ALD deposition tools for inorganics offers the prospect of lower prices in the future [167, 168].

Applied Materials is the leading global developer of PECVD tools and has recently developed R2R equipment for fabricating flexible electronics in several application areas. Figure 6.23 shows why Applied Materials prefers PECVD with silicon nitride (SiNx) as the best choice for performance, cost, and mechanical robustness in the deposition of inorganic layers, especially on plastic substrates that cannot tolerate high temperature processing. Applied Materials has demonstrated R2R tools that can deposit up to five layers in a single pass on webs of 1.5 m wide. Great care has been taken to minimize particle contamination and deposition uniformity is better than ±2.5% [169].

Material	Deposition Method	Conformal Coating	Cost	Particle Size / Density	Resistance to Acids	Layer Density	Fracture Toughness
AlOx	PVD	No – line of sight deposition	High - low dep rate process	Microns/ high density	Low	3.2 g/cm^3	3.3-4.8 MPa m$^{0.5}$
SiOx	PECVD	Yes	Low – high dep rate process w/ HMDSO	Submicron / high density	High	2.2 g/cm^3	0.55-1.7 MPa m$^{0.5}$
SiNx	PECVD	Yes	Moderate – high dep rate process w/SiH_4	Submicron / low density	High	2.7 g/cm^3	4-6 MPa m$^{0.5}$

Figure 6.23 Deposition of Inorganic Layers for Barrier Films

Source: Neil Morrsion, Applied Materials, Flex Conference, Monterey, CA, March 2016 **[169]**

Atomic layer deposition (ALD) produces extremely hard films, but conventional ALD was a very slow process. Several manufacturers have developed fast ALD techniques, and Meyer Burger has demonstrated an R2R tool can deposit aluminum oxide (Al_2O_3) on PET at rates of more than 1 nm/s while operating at atmospheric pressure [170].

The cost of barrier layers could be reduced substantially by creating all-inorganic multilayers that can be deposited in a single machine. One way of doing this has been developed by the California company, PlasmaSi, which was recently acquired by Aixtron. Its OptoCap™ barrier is created by interleaving hard layers that are thin enough to bend with softer layers that decouple the hard layers and reduce the film stress, as shown in Figure 6.24. The structure is formed by multiple passes through a PECVD machine. An early version of this approach was introduced by Universal Display, who showed that varying layer density could be obtained by modifying the processing conditions and gas mixture during PECVD deposition from hexamethyldisiloxane (HMDSO) and oxygen [171].

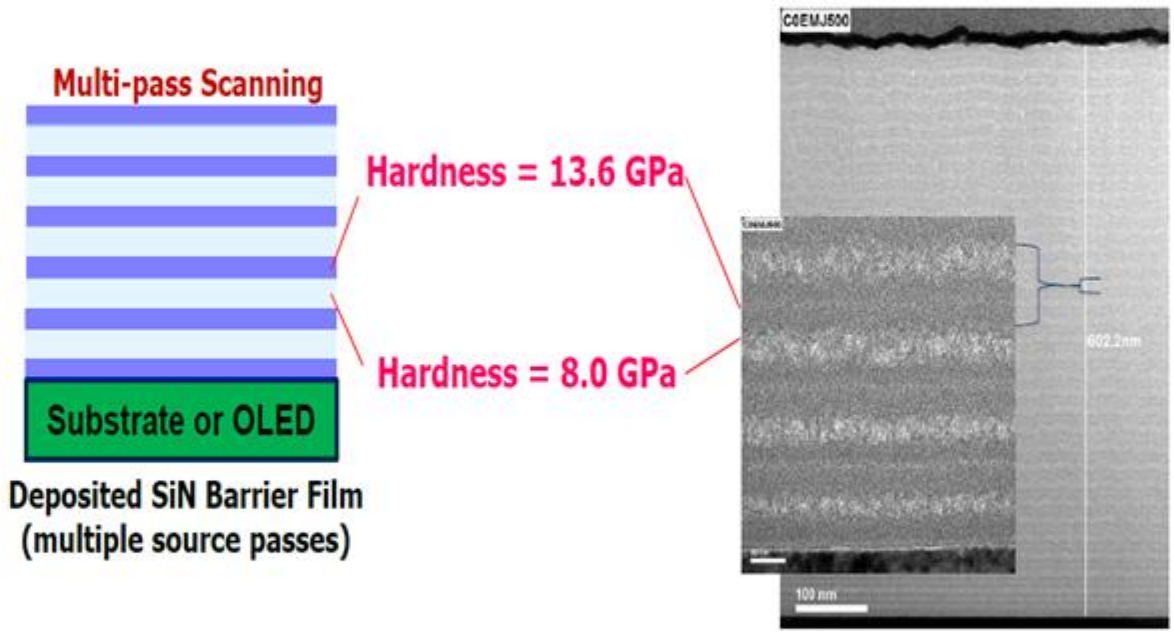


Figure 6.24 Multi-Stack Barriers with Alternating Inorganic Layers of Varying Hardness (Aixtron)
Source: Juergen Kreis, Aixtron, "Cost Efficient OLED Manufacturing," Smithers Apex OLED World Summit, October 2015 [172]

An Aixtron tool large enough for 200 mm x 200 mm substrates was ordered in 2015 by an Asian manufacturer for delivery in the first quarter of 2016 [173].

Applied Materials also has explored the use of soft inorganic layers as replacement for the organic buffers in multilayer barrier stacks. It has created plasma-polymerized HDMSO using mixtures of HDMSO and N_2O and have obtained promising results in three-stack structures of PEN [169].

A similar approach is used by Vitriflex, shown in Figure 6.25. Two forms of metal oxide layer are deposited alternately. The diffusive layers block the transmission of H_2O and O_2, while the amorphous material guards against the propagation of pinholes. The reactive layer traps any H_2O and O_2 that penetrates through the first layer. A hybrid polymer top seal is added to protect the barrier material. The barrier structures are formed by reactive sputtering in R2R equipment with web width up to 1.4 m [174].

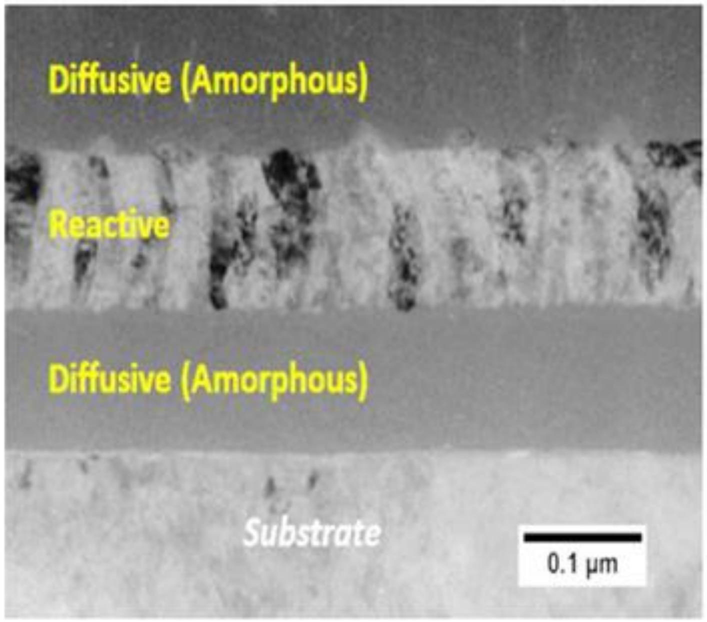


Figure 6.25 Multi-Stack Barriers with Alternating Inorganic Layers of Varying Hardness (Vitriflex)
Source: Ravi Prasad, Vitriflex, "Transparent Barrier Films," OLED Stakeholder meeting, Pittsburgh, September 2015 [174]

Extraction Enhancement Structures

As noted above, external extraction layers usually consist of microlens arrays on the substrate, which can be formed by several well-tested techniques. The patterns can be periodic or irregular, but require care to avoid variations of color with emission angle when periodic structures are used. Surface modulations can be formed during production of the substrate, or they can be etched into the substrate after manufacture. The most common procedure is to add a structured polymer film that is matched in refractive index to the substrate, either by lamination or in situ deposition. Films for lamination are available from several vendors.

Internal extraction layers are usually inserted between the substrate and the first electrode as laminated films or formed in situ. One major challenge is to ensure that the electrodes and organic layers can be deposited on top of the IEL, so surface roughness and chemical composition are critical. Microlens arrays that are suitable for insertion into OLEDs have been demonstrated by 3M, Panasonic, and others, but have not yet been used in high-volume production [175, 176]. Index-matching fluids and scattering films, formed by the insertion of micro-particles into a host material with high refractive index contrast, are now available in production volumes from Pixelligent and others [177, 178]. The manufacturing problems associated with this approach are being investigated at OLEDWorks in a DOE-funded project. The scattering film is deposited by slot-die coating and results in extraction enhancement of up to 2.18x [132].

Electrode Structures

Although there seems to be universal agreement that ITO is not the best transparent electrode for OLED lighting, especially in flexible panels, and many laboratory experiments have been performed to optimize and test alternatives, ITO is still used in all commercial panels. Recent results in SSL projects have confirmed that Ag nanowires have superior performance to ITO. For example, by embedding nanowires from Solvay in its proprietary polymer host, Sinovia has demonstrated sheet resistance of 3 $\Omega/\square$ (resistivity per unit area) and transparency of 76% [179]. However, because the thickness of the wires at 20 to 40nm is greater than the thickness of some organic layers, it remains to be shown if the organic stack can be deposited on top of the nanowire layer without causing shorting.

An alternative approach is to supplement a transparent conducting sheet with a metallic grid. The volume resistivity of bulk metals is very small, e.g., 1.6×10^{-8} Ωm (resistance of a given material) for Ag, 1.7×10^{-8} Ωm for Cu, and 2.8×10^{-8} Ωm for Al. Thus, a grid of Ag lines with a height of 1 µm that covers 10% of the panel area would provide an effective sheet resistance of 0.16 $\Omega/\square$. However, creating the metallic grid can be expensive. If the metal is deposited in bulk form, the gaps between the grid lines must be removed by etching, which exacerbates particulate control and results in most of the deposited material being wasted or recycled.

Printing of the metallic grid seems to offer a more promising approach for most manufacturers, but a significant penalty in electrical resistance can arise from the use of nano-particle metal inks. A survey from the Holst Centre indicated that the typical resistivity of printed Ag lines is 7 to 10 times that of bulk Ag, while inks under development might reduce the resistivity deficit to 3 to 4 times the bulk value [180]. The resistance of the printed lines depends critically on the curing method that is used. Using thermal curing, a resistivity of 3 to 4 times bulk can be obtained using conventional inks by operating at temperatures around 200°C. However, thermal curing is a relatively slow process, and attention is turning to photo curing. Novacentrix has achieved a resistivity of 2.8×10^{-8} Ωm on coated PET using nano-Ag inks developed by PChem [181]. This is only two times the bulk Ag and could be used to create a grid with effective sheet resistance of less than 1 $\Omega/\square$ while blocking only 5% of the light. Grid lines can be patterned directly with such inks by using screen printing, flexography, or inkjet printing.

The incorporation of wire grids reduces the conductivity requirements placed on the anode sheet, so the material can be chosen based on other properties, such as injection efficiency, and even polymer materials (e.g., PEDOT-PSS) can be used. However, the height of the grid lines is substantial, usually around 1 µm, and planarization layers may be required to avoid shorting across the organic stack.

Integrated Substrates

Because there is significant interplay among the layers discussed above, there is great interest in the development of integrated substrates that afford adequate protection for the delicate organic layers, facilitate distribution of the current across the panel, and allow most of the light to escape. For rigid displays, glass companies have led this effort. PPG has focused upon manufacturing techniques that can be applied at the time of formation of the glass, arguing that this will be the most economic approach in high volume. PPG's approach is illustrated in Figure 6.26.

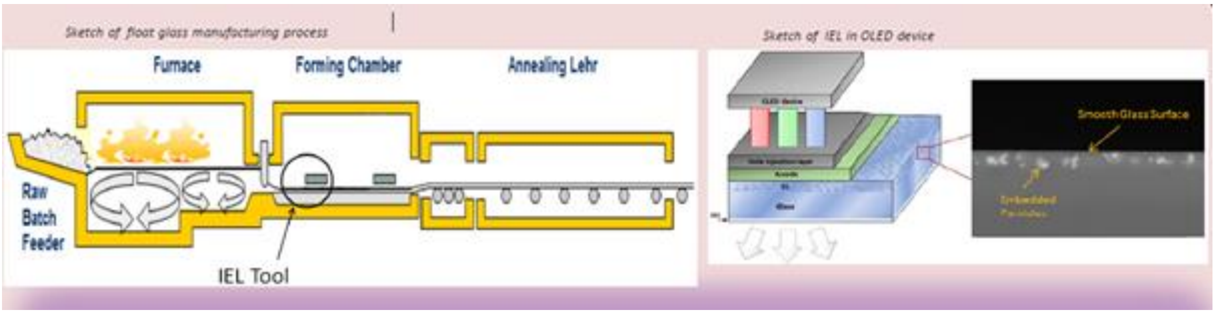


Figure 6.26 IEL Layer Applied in a Float Glass Manufacturing Process
Source C.H. Hung, "Manufacturing Process for OLED Integrated Substrate," DOE SSL R&D Workshop Poster Session, Raleigh, NC, February 2016 [182]

The anode structure can then be applied while the glass is relatively warm, giving higher conductivity and a smoother upper surface. Sheet resistance is less than 10Ω/□ and transparency is 85% with RMS surface roughness less than 2 nm. The anode work function is more than 5V, and PPG reports that a separate hole injection layer is not needed.

The Corning approach is to use their ultra-thin Willow glass that enables the fabrication of conformable panels and is compatible with R2R processing. Although Corning has not revealed the nature of their extraction enhancement layers, it has achieved enhancement factors of 2.1 with a low-cost solution [183].

Two other leading glass manufacturers, Nippon Electric Glass (NEG) and Saint-Gobain have formed a joint venture, OLED Materials Solutions, to develop an integrated substrate, but have not yet released details of their IES structure or any performance data [184]. This partnership can draw upon the experience of NEG with ultra-thin glass and Saint-Gobain's development of the Silverduct transparent anode [185].

Long-term research is focused on integrated structures based upon plastic substrates. In a DOE SSL project, Sinovia is depositing its transparent anode structures onto the Vitriflex barriers on inexpensive PET or PEN substrates, using R2R processing at Vitriflex and at Eastman Kodak [186]. Ag nanowire anodes are also being used in two university projects with similar goals. To enhance extraction, Princeton University is using scattering centers formed by air voids in a layer of colorless polyimide [187]. The University of California, Los Angeles, is testing similar structures, but with an extraction enhancement layer composed of high-index scattering particles in a polymer binder [188].

Short Reduction Layer

Many early failures of OLED panels are due to shorts caused by particulates trapped in the panels, rough anode surfaces, scratches, or other defects in the layers below the organics. The low temperature processing required on plastic substrates makes it more difficult to avoid rough surfaces; the use of nanowires, nanotubes, or wire grids in electrode structures can exacerbate the problem.

The growth of damaging shorts can be suppressed by the addition of a short reduction layer (SRL) that is thick enough to cover many particulates or other inhomogeneities. The resistance of the layer should be sufficiently high to constrain the growth of local currents, but should not add more than 0.1V to the voltage needed to achieve the desired current density across the panel. One implementation involves a 100 nm-film formed by co-sputtering ITO and ZSO (ZnS:SiO2). OLEDWorks is pursuing a DOE SSL project to identify optimal structures for the SRL [189].

Active Organic Layers

The standard approach to creating the organic stacks in efficient lighting panels involves passing the substrates through about 20 linear sources, currently with widths of around 500 mm. A study funded by the South Korean government showed that this technology can be scaled to widths of over 1 m and that material utilization can be increased to over 60%. However, analysis by OLEDWorks has shown that with a TAKT time of 2 minutes, the depreciation charge associated with such equipment, would be \$200/m^2, which is well above the target for the total expense of panel production [190].

With funding from DOE and New York State, OLEDWorks is constructing and testing a new linear source that should lead to substantial savings in material cost and depreciation charge. Closed-loop control of deposition rates reacts quickly and is especially helpful for temperature-sensitive materials. The goal is to reduce cycle time to 1 minute and deposit 60% of the organics onto the panel [190].

Aixtron has continued to invest heavily in organic vapor pressure deposition (OVPD) technology, in which the organic molecules are carried from the source to the substrate in an inert gas mixture and dispersed evenly over large areas through a close-coupled showerhead nozzle array, allowing excellent materials utilization efficiency and short cycle times. Aixtron has optimized its own source technology short thermal exposure source (STExS), which enables a precisely measured volume of material, dependent on relevant substrate size and requirements, to be transformed into the gas phase in a rapid, material-efficient process [191]. This source technology also enables vaporization to be initiated within just a few seconds and then stopped again once a substrate has been processed. Tests performed on 2,250 mm x 2,250 mm substrates have achieved material utilization rates of more than 70%. Deposition has been demonstrated at a rate of 5 nm/s. To promote its deposition technology and collaborative efforts, Aixtron has installed an OVPD system at Institut Lafayette (part of the Georgia Institute of Technology international campus in Metz). It also has its 8.5-Gen organic large area demonstrator system ready for customer tests [192].

Advocates of solution processing have been heartened by the success of Kateeva in demonstrating the ability to scale inkjet printing to substrates with dimensions over 2 m, as shown in Figure 6.27.

Figure 6.27 InkJet Printing Platform for Gen 8 Substrates
Source: Kateeva Finally Unveils its Yieldjet OLED TV Inkjet Printing System **[193]**

Great care is taken to prevent particulate contamination by minimizing contact with the substrate and processing in a nitrogen atmosphere. Deposition is controlled by a laser-based drop inspection instrument that is 50 times faster than previous technology for measuring drop volume and velocity.

Print software automatically recalibrates before every plate if any nozzles do not meet specifications, ensuring every print is good. First sales of this equipment have been for the deposition of the organic components in multi-layer barriers. Kateeva also has been working with DuPont and Sumitomo Chemical to print RGB emitters side by side in a single layer [194]. Although this will be first tested on OLED displays, the approach will greatly facilitate the fabrication of color-tunable lighting panels.

Sumitomo Chemical has announced that it will begin deliveries of its polymer OLED lighting panels in April 2016 and showed prototypes at Light & Build 2016 in Frankfurt [195]. The use of printing techniques leads to material utilization rates of more than 80%. Together with the simplicity of the structures, this could lead to a substantial cost advantage, but panel prices have not yet been released. Efficacies of 60 to 80 lm/W and operating lifetimes of 20,000 hours have been attained in laboratory panels, so details of the performance of the commercial panels are eagerly awaited [196].

Encapsulation

Several encapsulation methods are available that maintain the thin profile and low weight. As illustrated in Figure 6.28, a sheet of plastic with multi-layer barrier or ultra-thin glass can be laminated on top of the upper electrode. Care must be taken to prevent the ingress of oxygen and moisture through the edges. Adhesive materials with barrier or absorbing properties are available from several companies, such as Addison Clear Wave, DELO, Henkel, LG Chem, and SAES Getters. For downward-emitting structures, thin metal can be used as a cover, providing some mechanical stability as well as an effective surface barrier. This solution has already been implemented by LG Display.

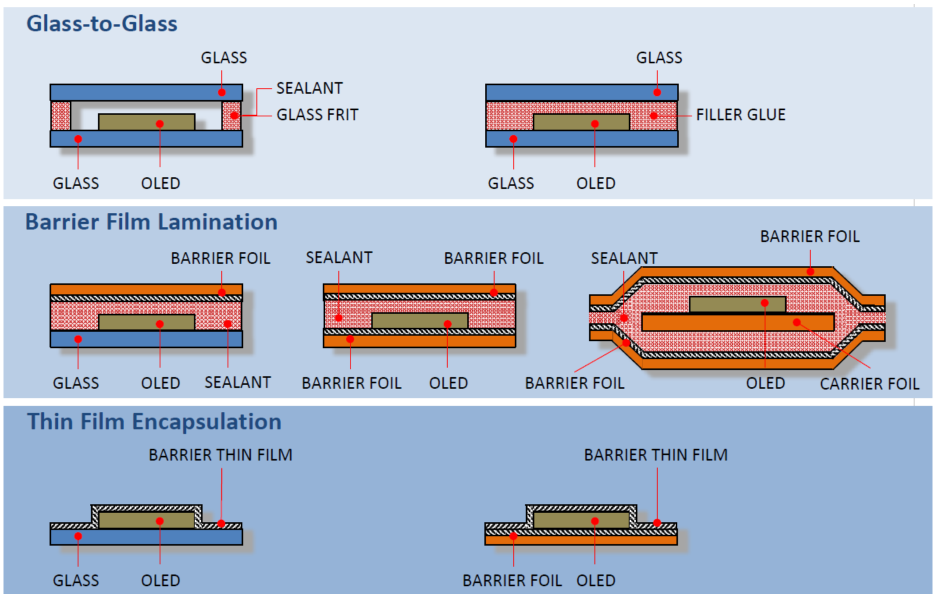


Figure 6.28 Alternative Approaches to OLED Encapsulation

Source: Dr. Mauro Riva, SAES Getters, OLED Summit, Berkeley, CA, October 2015 [197]

The edge effects can be minimized by in-situ deposition of a thin film barrier. High temperature processes must be avoided to prevent damage to the underlying layers. Patterning is needed to avoid coating the electrical contacts at the edge. This can be accomplished during deposition, for example by inkjet printing or slot-die coating.

6.2.3 Manufacturing Line Structures

OLED manufacture is often separated into four stages. The first involves the formation of the underlying layers onto which the organics are deposited. This usually involves the substrate, with barrier layers if necessary, extraction enhancement layers, and the anode structure. This can be performed by the panel manufacturer, as at LG, or may be subcontracted to another manufacturer. Careful inspection of the processed substrate is necessary, so that any defects or contaminants can be identified and repaired before the thin organic layers are added. The second stage is devoted to deposition of the organic layers. The third stage is metal deposition to create the second electrode (usually the cathode). Finally, the panel is encapsulated and tested.

Sheet to Sheet Processing

The standard approach to the fabrication of OLED lighting panels processes separate substrate sheets. Glass substrates of thickness 0.3 mm or more are self-supporting, whereas ultra-thin glass, thin metal foils, and plastic substrates may need to be attached temporarily to a rigid frame during manufacture to avoid distortion.

At LG and First O-Lite, around 20 deposition chambers are arranged in line, with the substrate passing at a uniform rate through the whole sequence. This requires coordination between the deposition rates for each layer, some of which are much thicker than others. This approach was adapted slightly in Aachen, in the factory designed by Philips and now operated by OLEDWorks, as shown in Figure 6.29.

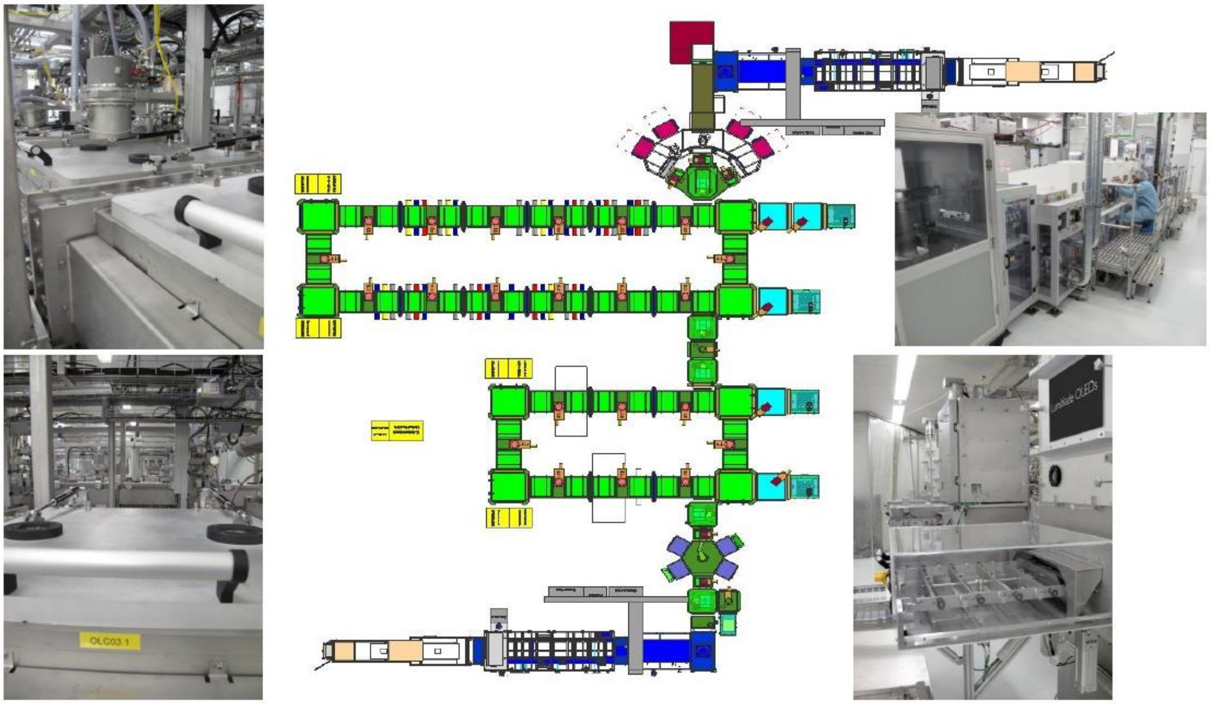


Figure 6.29 OLED Panel Production Line in Aachen, Germany
Source: U. Hoffman, China International OLED Summit, Beijing, 2015 [161]

One interesting feature of this arrangement is that the start and finish of deposition segments are close together. This is primarily so that the substrate carriers can be returned quickly, but it is possible that the partly processed substrates could be directed back through the cycle for the addition of further layers.

As shown in Figure 6.30, Aixtron has been exploring cluster configurations, which are more common in the integrated circuit industry. Aixtron claims that the flexibility offered by this approach will reduce both capital cost and floor space.

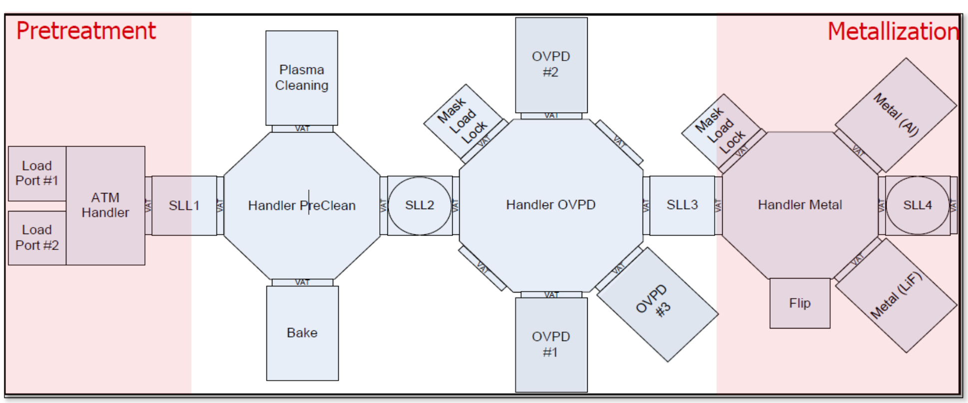


Figure 6.30 Cluster Configuration for OLED Panel Manufacturing
Source: Juergen Kreis, Aixtron, OLEDs World Summit, San Diego, CA, 2016 [198]

Roll-to-Roll Processing

R2R processing seems attractive for flexible substrates, because tension can be applied to keep the substrate flat and in the correct position. Simple operations can be carried out at high speed, and many have indicated that the approach will lead to significant savings. For example, at the DOE OLED community meeting in 2015, Corning estimated that R2R processing of ultra-thin glass could lead to cost reductions of 30%, by eliminating the need to laminate the fragile material to a rigid carrier and then release without damaging the OLED structure. However, all the processing steps must be synchronized to match the rate of web motion. Also the rolling and unrolling process introduces risk of contamination or other damage to the panel surfaces. Thus, difference in the yield of good products must be taken into account in comparing manufacturing costs for the two approaches.

Since the closure of the project at GE Research Center, the development of R2R methods for fabricating OLEDs has been led by Asian and European laboratories, with participation by U.S. suppliers of equipment and material. Konica Minolta has not released details about its high-volume production line. Because they have not produced any panels for commercial sale, even 18 months after the completion of the line, it is not possible to gauge the quality of the products or the manufacturing cost.

Figure 6.31 shows the prototype line used at the Fraunhofer Institute FEP in Dresden, which hosts many projects supported by the European Commission, the German Federal Government, and the State of Saxony. The approach is almost entirely based upon vacuum processing, and it has used both flexible glass and plastic substrates.

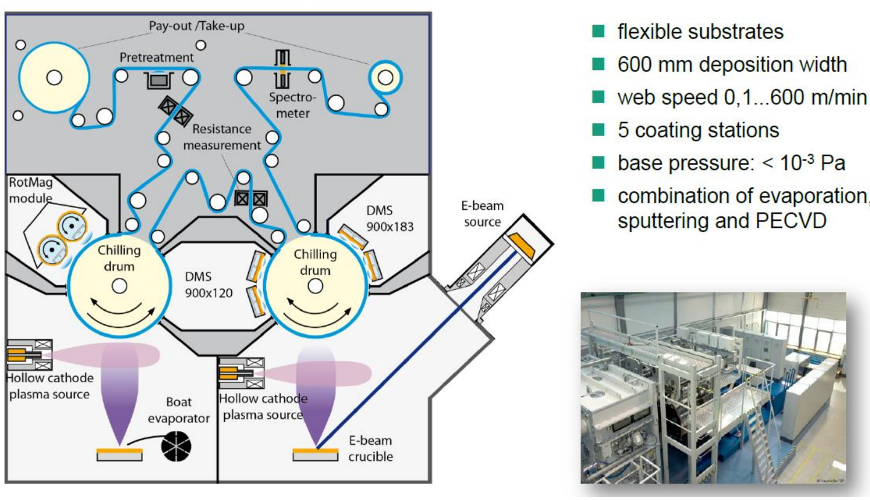


Figure 6.31 Prototype Line used at the Fraunhofer Institute FEP in Dresden

Source: Christian May, Fraunhofer FEP, Smithers Apex OLEDs World Summit, Berkeley, CA, October 2015 [199]

The Holst Centre in Eindhoven has focused upon coating techniques that can be applied at full atmospheric pressure and so may lead to less expensive equipment bills. To guard against contamination, Holst employs several clean room levels and has the capability to carry out some operations in a nitrogen atmosphere [166].

The Industrial Technology Research Institute (ITRI) of Taiwan has been developing prototype OLED panels for several years and launched the OLED Lighting Commercialization Alliance in July 2014 [200]. The Alliance—which involves suppliers of materials, such as Corning and Merck, and potential manufacturers, such as WiseChip—intends to offer panels with CCT of 1900K to minimize the blue light impact in health facilities and bedrooms [201]. ITRI has announced the construction of a R2R production line with low-volume production of panels on flexible glass to begin in 2017 [202].

6.2.4 Impact of OLED Display Production

The OLED lighting industry hopes to leverage the advancements made in the display industry. The use of OLED displays in smartphones, TVs, and wearables has accelerated. Around 250 million OLED panels were produced in 2015, leading to revenues of near $12 billion. This total includes around 400 thousand TV panels with revenues of close to $1 billion [203].

Massive new investments in manufacturing capacity are being driven by the expectation that Apple will switch from LCD technology to OLED in its smartphones, and that OLEDs will capture a significant portion of the global TV market of 200 million sets per year [204, 205, 206, 207]. The market leader, Samsung Display, is investing some $4 billion between 2015 and 2017 to expand its production capacity for small displays [208]. The South Korean Display Industry Association also has reported that Samsung will invest $3 billion in a Gen-8 OLED TV fab, but the company has not yet announced its schedule for reentry into the OLED TV market [209]. Meanwhile, LG Display has dominated the manufacturing of OLED TV panels and plans to spend over $9 billion to expand production at two sites in South Korea and build a module assembly plant in Vietnam [210]. LG Display, having taken over LG Chem's OLED lighting efforts, has announced its investment in a Gen-5 OLED lighting line with an initial planned capacity of 15,000 substrates per month. Mass production is planned for the first half of 2017 [211]. Several Chinese companies have announced major construction plans for OLED displays.

Two aspects of OLED display manufacturing are of special interest for lighting applications. The first is the development of flexible and transparent panels. IDTechEx predicts that revenues for plastic or flexible OLEDs will grow to $16 billion by 2020, while UBI Research anticipates that the market for large area transparent OLEDs will reach $5.3 billion by the same year [212, 151]. Samsung Display produces roughly 9 million flexible OLED panels each month, and is increasing its capacity with a $325 million investment [213]. The dominant substrate is polyimide, which is deposited in-situ by slot-die coating onto a carrier glass and then removed by laser lift-off, as shown in Figure 6.32. The bending radius of the Samsung Edge displays is already less than 1 cm. The development of foldable OLED panels is well underway, with a target of surviving 200,000 folds with a bending radius of 1 mm [214].

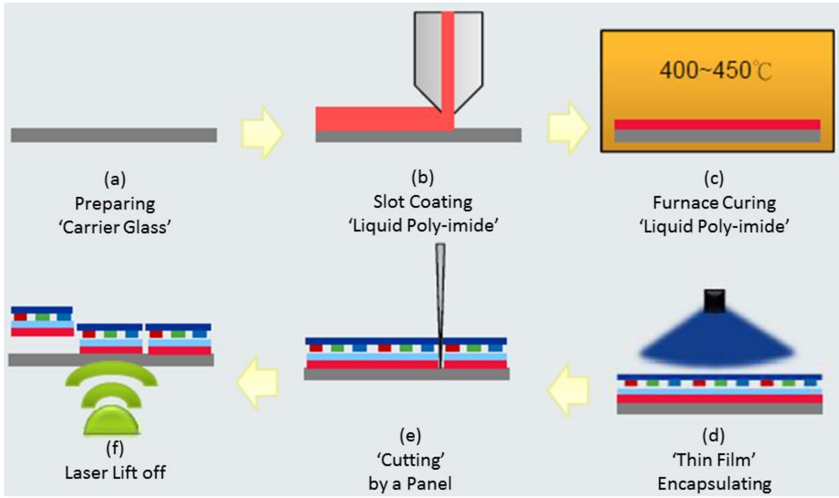


Figure 6.32 Use of Carrier Glass in Fabrication of OLED Panels on Plastic Substrates
Source: David Hsieh, CIOS 2016 [214]

The second aspect is the success of large OLED panels for TV and advertising applications. Substantial reduction in the cost per unit area of OLED displays will be needed if OLED TVs are to succeed in the high-volume market. To compete with LCD displays, the cost of a 55 inch panel needs to be around \$250 or \$300/m^2. If this can be achieved, much of the manufacturing experience will be transferable to lighting panels. LG Display's manufacturing approach is to build a white OLED and add a color filter to separate the colors in the sub-pixels. The methods used for deposition of the organic materials can also be used in manufacture of lighting panels. However, the choice of emitter materials may be different, as color gamut is more important in display applications and less priority is given to efficacy.

6.2.5 Cost Reduction

One important driver for cost reduction is production volume. Little progress has been made in lighting markets, but OLED display sales have been increasing rapidly. The manufacturing cost of OLED panels for cell phones is now very close to that of the traditional LCD panels, at about \$15 for a 5 inch diagonal display [214]. This corresponds to \$2,250/m^2, but includes the cost of forming the TFT backplane and RGB patterning of the OLED emitters, which may not be necessary for lighting applications. Estimates by UBI Research and IHS suggest that sales of organic materials rose to \$465 million, with about 40% attributed to emitter materials from Universal Display Corporation (UDC) and Idemitsu Kosan [215, 216, 217]. The total panel area of OLEDs produced in 2015 was about 1.8 million m^2, so that the cost of organic materials was about \$250/m^2, or 12% of total costs. Financial data from UDC suggests that the cost of phosphorescent materials fell by about 15% from 2014 to 2015.

The acquisition of the OLED business of Philips has given OLEDWorks a better appreciation of the manufacturing cost of lighting panels using current methods. Figure 6.33 shows their forecast of the evolution of the costs over the next 3 years, compared to DOE targets expressed in past R&D plans.

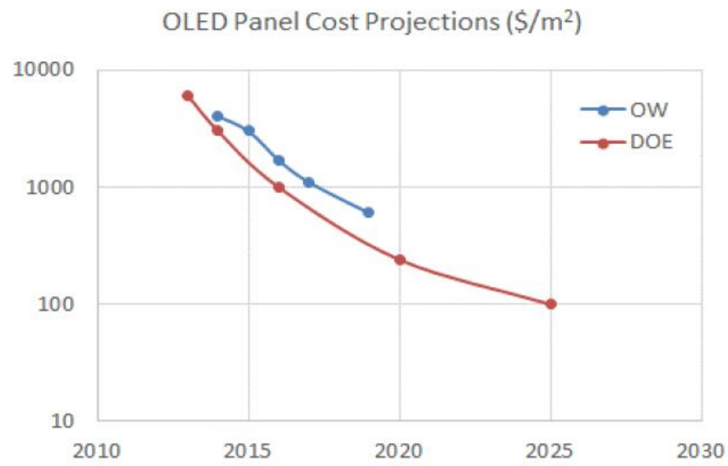


Figure 6.33 Anticipated Cost of OLED Panel Production
Source: OLEDWorks, DOE SSL R&D Workshop, Raleigh, NC, January 2016 **[218]**

Faster decreases in costs could be achieved by the construction of high-volume manufacturing lines, either using sheet-to-sheet or R2R techniques; however, this will require confidence that the market will support a rapid increase in production capacity. Alternatively, either simpler structures must be implemented or less expensive solutions found for each of the main components.

One possible scenario to reach the cost goal of $100/m^2 by 2025 is presented in Table 6.3. Depreciation is calculated on a 5-year straight-line basis. It is assumed that LG Display, or another company, proceeds with its plan to build a new factory in 2017 and makes significant progress with respect to cycle time and yield in the following year.

Table 6.3 Estimated Cost of Panels Produced by Traditional Methods

	2015	2016	2018	2020	2025
Substrate Area (m^2)	0.17	0.17	1.38	2.7	5.5
Capital Cost ($M)	75	75	200	300	400
Cycle Time (minutes)	3	2	1.5	1	1
Capacity (1000 m^2/year)	14	25	300	1,000	2,400
Depreciation ($/$m^2$)	1,050	600	125	60	35
Organic Materials ($/$m^2$)	200	150	100	35	15
Inorganic Materials ($/$m^2$)	200	200	120	50	30
Labor ($/$m^2$)	150	100	20	10	5
Other Fixed Costs ($/$m^2$)	75	50	15	10	5
Total (unyielded) ($/$m^2$)	1,675	1,100	355	160	90
Yield of Good Product (%)	50	60	70	80	90
Total Cost ($/$m^2$)	**3,350**	**1,850**	**550**	**200**	**100**

7.0 R&D Plan

To reach the full energy savings potential of SSL, continued R&D is required. Despite rapid advances, SSL technology is actually in its early years. When it comes to U.S. energy and carbon savings from SSL, 95% of the potential remains untapped [1]. Continued innovation and breakthroughs in materials, processes, product designs, control systems, manufacturing, and applications are still needed to realize the full potential of the technology.

7.1 Process and Discussion

The DOE SSL Program has responded to the SSL opportunity by providing direction and coordination of multiple R&D efforts intended to advance the technology and to promote energy savings.[u] The R&D elements within the DOE SSL Program are: Core Technology R&D, Product Development, Manufacturing R&D, and Technology Adoption R&D. Core Technology R&D focuses on applied research for SSL to improve efficiency, performance, and cost. Product Development projects work to improve commercially available materials, devices, or systems. Manufacturing R&D seeks to reduce cost and improve quality through advancements in manufacturing equipment, processes, and monitoring technology with the additional benefit of fostering U.S. leadership in SSL manufacturing. Finally, Technology Application R&D provides field and laboratory evaluations of emerging products to provide performance feedback and identify technical issues.

The DOE SSL Program uses a systematic process, shown in Figure 7.1, for collecting inputs from the varied stakeholder base to understand the critical technology and adoption issues. Each year, the DOE SSL Program hosts roundtable (LED) and stakeholder (OLED) meetings to identify critical technology challenges and suitable R&D actions. These inputs are then used to drive the planning for the annual DOE SSL R&D Workshop. At the DOE SSL R&D Workshop there is further discussion on the key issues and direct stakeholder input for identifying and prioritizing necessary R&D actions. The outcome of these discussions is used to update the R&D Plan and identify priority R&D task areas. These priority R&D tasks subsequently feed into the solicitation process and lead to the next round of R&D project awards. Feedback from the projects within the portfolio helps identify the next round of challenges to be addressed and the process is repeated.

[u] For more information on the DOE SSL Program please see: http://energy.gov/eere/ssl/about-solid-state-lighting-program

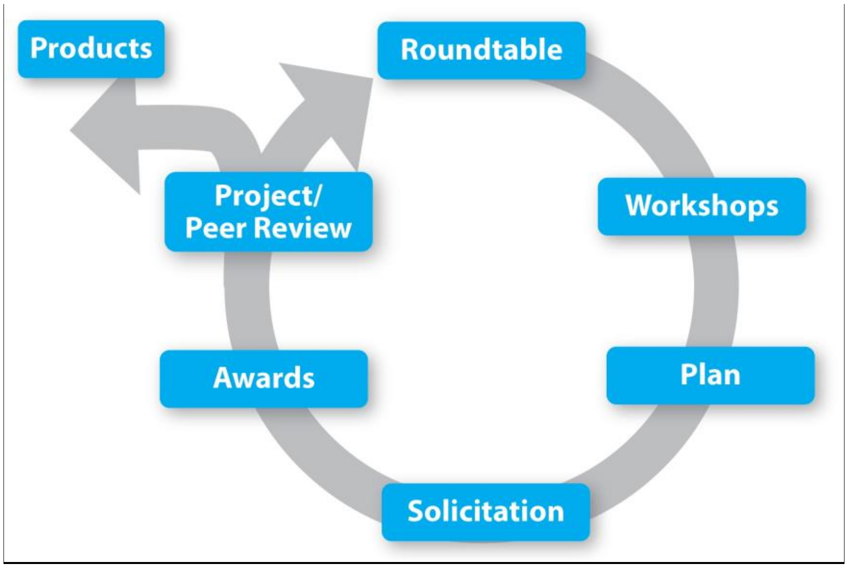


Figure 7.1 DOE SSL Program Input Strategy

The DOE SSL Program continues to use the FOA R&D support process as the primary mechanism for supporting critical SSL R&D and advancing the state of the art of SSL technology. Unfortunately, not all R&D topics are suitable for the typical DOE SSL FOA process. The FOA process supports competitively selected R&D projects of 1 to 3 years in duration and have the goal of advancing applied scientific understanding or the global state of the art of the technology. DOE has used different support mechanisms to fund R&D topics that are not suited for the FOA process to maximize DOE SSL Program influence toward the objective of maximizing lighting energy savings.

The DOE SSL Program has worked with DOE's Office of Basic Energy Science, NIST, PNNL, and the Next Generation Lighting Industry Alliance (NGLIA) to support R&D topics not suited for the FOA process. Most notably the DOE SSL Program has supported the following non-FOA research:

- Color accuracy and preference with NIST
- LED lighting reliability research through the LSRC facilitated through NGLIA
- A wide range of application R&D through PNNL
- OLED compatibility testing through competitively selected external laboratories

7.2 Measuring Progress

7.2.1 Goals and Projections

High-level goals for the DOE SSL Program were described in the Introduction (Section 1.0). This section describes expectations for progress toward DOE efficiency goals over time based on performance to date. These projections have not changed much over the last two years, as progress has been generally as expected. The projections are based on best-in-class performance, normalized to particular operating conditions in order to track progress; however, the program goal is for the industry to achieve these performance levels with commonly available products, which is necessary to achieve the energy savings promised by the technology.

Metrics specific to each individual task are described in this section, together with individual goals that will enable us to achieve the program goals.

Efficacy Projections for LEDs

Figure 7.2 and Table 7.1 project LED package efficacy over time for warm white and cool white pc-LEDs based on a logistic fit to experimental data, and assuming an upper asymptote of 255 lm/W, as explained in Section 5.1. The assumed operating conditions for qualified data points may not correspond to current practice, especially considering the use of hybrid solutions combining pc-LEDs with monochromatic LEDs, and the increasing use of lower drive currents to minimize current droop. These are important innovations along the pathway to high-efficiency products. Nevertheless, using a standard current (or power density) at a fixed operating temperature and selecting devices within limited ranges of CCT and CRI allow for evaluation of developments in emitter efficiency (including the reduction of current and thermal droop) and down-converter performance.

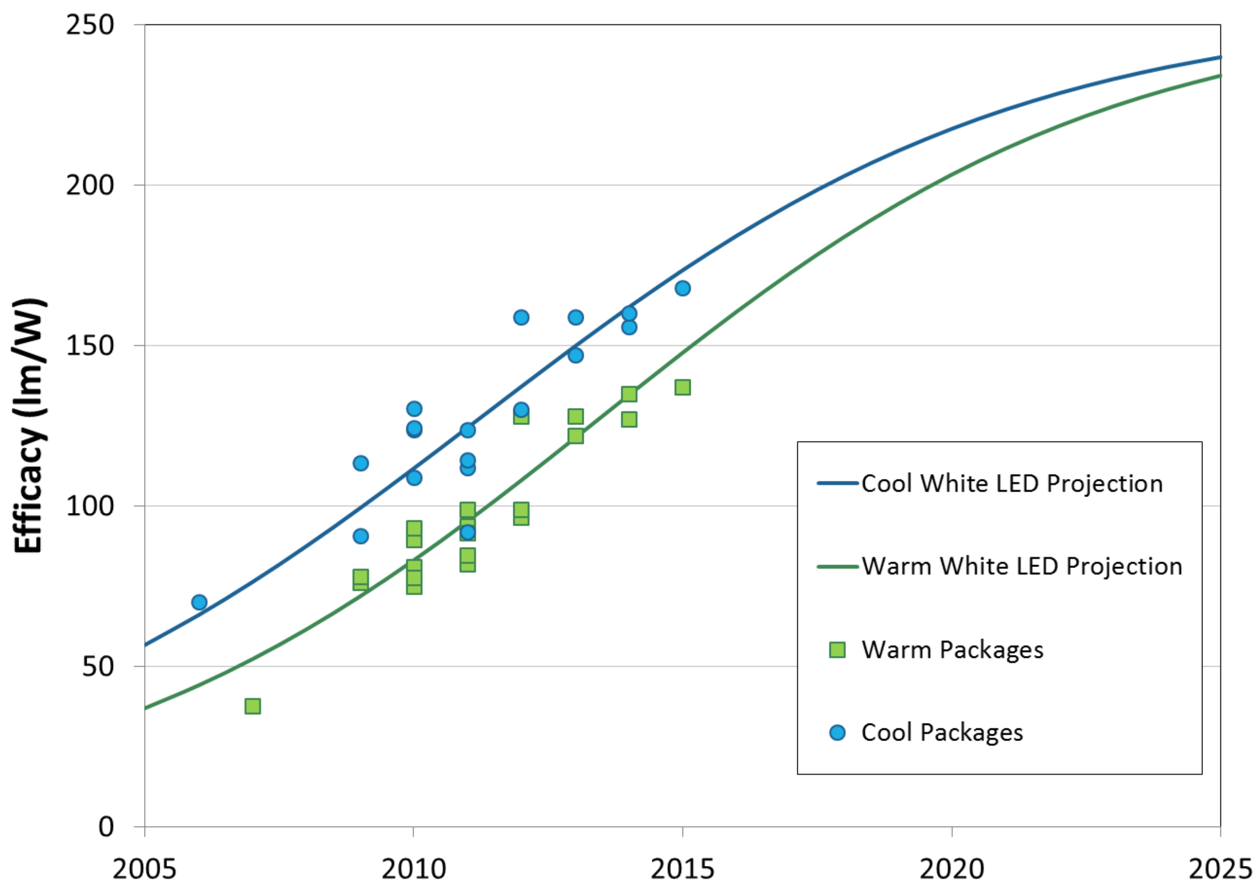


Figure 7.2 LED Package Efficacy Projections for Commercial Products

Table 7.1 LED Package Efficacy Projections

Metric	Type	2014	2015	2016	2017	2018	2019	2020	2025	Goal
LED Package Efficacy (lm/W)	Cool White	158	168	184	194	203	211	218	240	255
	Warm White	131	137	150	164	175	194	208	237	255

Almost all products produced to date use phosphor-converted or hybrid architectures. Hybrid LEDs will meet the asymptote more quickly than pc-LEDs due to the availability of narrow linewidth red LED sources. Pc-LEDs will approach the goal more gradually as the power conversion efficiency (PCE) of the blue LED pump increases and narrower linewidth down-converters are developed (especially for the red source). Cm-LEDs offer the prospect of even higher efficacies, provided green and amber LED sources can be developed with PCEs in excess of 60%.

Efficacy Projections for OLEDs

As described in Section 6.1, considerable progress has been made in improving each aspect of OLED performance. The major challenge is to bring all aspects together to achieve further enhancement of light extraction, while keeping manufacturing cost reasonable. Figure 7.3 and Table 7.2 project OLED panel efficacy based on past performance and anticipated progress. Data on panels remain rather sparse and show a lot of variation, so there is considerable uncertainty in the projected curve. The average of qualified data for each year was used to fit the data. Qualified points reflect efficacy reports for panels with a minimum area of 50 cm^2 and CRI greater than or equal to 80, with CCT between 2580K and 3710K. Where these parameters are known, the data point is considered qualified.

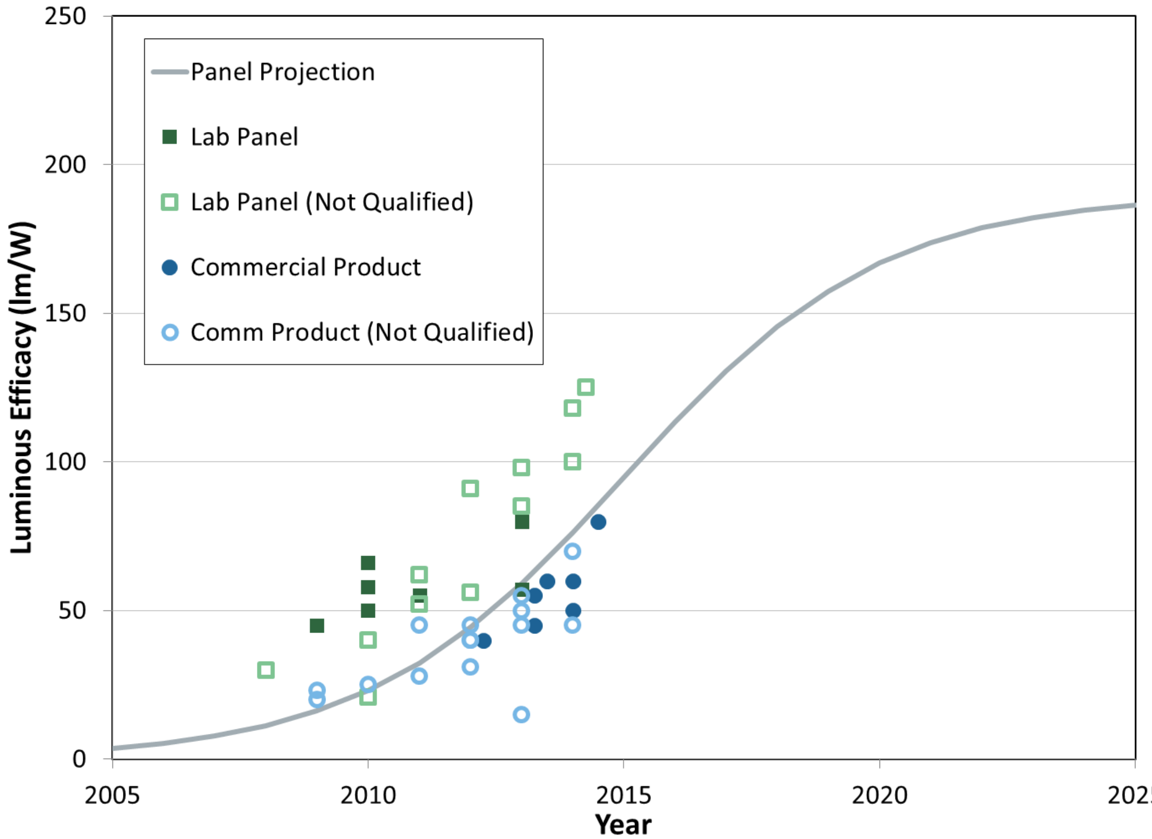


Figure 7.3 White-Light OLED Panel Efficacy Projections

Table 7.2 summarizes a path toward achievement of an efficacy of 190 lm/W with low rates of lumen depreciation. This table is constructed on the assumption that all-phosphorescent emitters will be used in conjunction with a two-stage tandem structure, but there may be other routes to achieve the same goals.

Table 7.2 OLED Panel Efficacy Projections

Metric	2015	2017	2020	2025	Goal
Panel Efficacy (lm/W)	60	100	125	160	190

Note: Projections assume CRI > 80, CCT = 2580-3710K.

Achieving efficiency gains and lumen depreciation goals will not be sufficient to make commercially viable lighting products. The films must also be producible in large areas at low cost, which may limit materials choices. Improvements to the shelf life of OLED luminaires must also be realized. OLEDs are sensitive to oxygen, moisture, and other pollutants in the operating environment, which requires extensive encapsulation of the OLED panel, particularly on flexible substrates. In addition, oxygen, moisture, and other contaminants can become embedded into the OLED in the fabrication process, reducing the panel lifetime.

7.2.2 Program Milestones and Interim Goals

LED Milestones

The LED package and luminaire program milestones, listed in Table 7.3, were revised in 2010 to reflect recent progress in the industry. Fiscal year (FY) 2010 and FY 2015 milestones reflect efficacy and/or price targets for LED packages with lumen maintenance values of 50,000 hours.

Table 7.3 LED Package and Luminaire Milestones

Year	Milestones
FY10	Package: >140 lm/W (cool white); >90 lm/W (warm white); <$13/klm (cool white)
FY12	Luminaire: 100 lm/W; ~1,000 lm; 3500K; 80 CRI; 50,000 hours
FY15	Package: ~$1/klm (cool white); ~$1.1/klm (warm white)
FY17	Luminaire: >3,500 lm (neutral white); <$100; >150 lm/W
FY20	Luminaire: 200 lm/W Connected troffer with integrated controls: <$85
FY25	Full-color tunable luminaire: 200 lm/W (@ 3000K, CRI = 90), >3,500 lm

Note: Packaged devices measured at 25°C and 1 W/mm^2. Prices are for 1000-off quantities

In FY 2015, prices for LED packages fell to $1/klm while retaining the high efficacy of over 100 lm/W and 50,000 hours lumen maintenance. By 2017 (3 years ahead of the original schedule), DOE expects to shift focus toward realization of a commodity-grade luminaire product with output exceeding 3,500 lumens and priced below $100, while maintaining reasonable efficacy. By 2020, DOE anticipates the introduction of cost-effective connected lighting in the form of troffers with integrated communication and controls and a price below $85. At this price point, LED sources will represent a significant improvement in price, performance, and total cost of light compared to conventional lamp and luminaire systems. Looking toward 2025, DOE anticipates the focus will shift towards full-color tunable products that reflect the value of expected advancements in green, amber, and red direct emitter LED efficiency in terms of luminaire performance (200 lm/W) and value.

The LED package and luminaire milestones have represented distinct steps in developing low-cost, high-performance SSL luminaires. The first step, completed about a decade ago, was to develop a reasonably efficient white LED package that is sufficient for the lighting market. LED packages continue to improve in efficiency while decreasing in price to realize the best possible energy savings. The availability of LED packages with efficacies at and above 150 lm/W has shifted the focus toward the development of efficient luminaires with performance and value appropriate for the intended application. High-efficiency LED packages not only enable high efficacy lighting products, they also offer the headroom to make design tradeoffs between efficacy, cost, beam distribution, lifetime, color quality, and form factor. Further technological progress is necessary to reduce these tradeoffs to the point where LED lighting products simultaneously offer significant value in terms of efficacy, aspects of lighting performance critical for the application, and cost. This progress continues to be supported through DOE SSL Program R&D initiatives.

OLED Milestones

The overarching DOE milestones for OLED-based SSL are shown in Table 7.4. The milestones for 2010 and 2012 referred to laboratory panels and were met. The focus in 2015 and beyond is on commercial panels and luminaires. Both LG Display and OLEDWorks indicated that they are able to meet the 2015 price target of $200/klm and the L_{70} lifetime of 40,000 hours from an initial luminance of 3,000 cd/m^2. All panels from LG now have CRI of 87 or higher, but most others are below this goal. The main challenge for manufacturers is to meet the efficacy milestones without compromising other parameters. However, while OLED technology is capable of meeting the 2015 milestone, commercial production of these products has been delayed. Manufacturing yield and market influences may be affecting the commercial promise of these products and forcing manufacturers to reconsider the business model.

Table 7.4 OLED Panel and Luminaire Milestones

Year	Milestones
FY10	Panel: >60 lm/W
FY12	Laboratory Panel: 200 lm/panel; >70 lm/W; >10,000 hours
FY15	Commercial Panel: <$200/klm (price); >80 lm/W; 40,000 hours; CRI>90
FY17	Commercial Panel: 100 lm/W; CRI >90; L_{70} 50,000 hours
FY20	Luminaire: 100 lm/W; $50/klm
FY25	Commercial Panel: 160 lm/W

The panel milestones for FY 2017 include efficacy of 100 lm/W at 10,000 lm/m^2, CRI greater than90 and lifetime (L_{70}) of 50,000 hours. As the industry best is currently only 60 to 65 lm/W, this is an important and aggressive milestone for the OLED community.

By 2020 it is anticipated that high-performance panels will be available allowing for the fabrication of 100 lm/W luminaires. The key milestone for 2020 is achieving a price of $50/klm for luminaires. This aggressive price target is necessary for OLEDs to move beyond niche applications and installations and hurdle the cost barrier to widespread adoption.

The 2025 milestone for OLED development is to achieve a drastic improvement in efficacy for commercial panels. To reach the targeted 160 lm/W, refined materials sets and light extraction designs will need to be implemented and designs improved.

7.3 Key Issues & Challenges

There has been significant progress over the years in LED and OLED lighting performance, as many LED products have made it to market and commercial OLED luminaires have been introduced. Yet many challenges remain to meet DOE's overarching goals and maximize SSL energy savings. A number of key R&D issues were identified at DOE stakeholder meetings held over the last year.

For LED lighting, while there are many technology challenges facing the LED industry, stakeholders selected the following topics as the most pressing R&D needs to address current performance shortcomings, barriers to adoption, and application benefits in LED lighting.

Core Technology R&D

- **LED efficiency**–Peak efficiency and at high light output levels (droop, thermal droop) across the visible spectrum including blue, green, amber, and red IQE improvements.
- **Down converters (on package**)–Efficiency, stability, spectral efficiency, spectral control, and long persistence phosphors to simplify driver design.
- **Physiological Responses to Light**–Blue light hazard, health, and productivity for humans; understanding and optimizing productivity and well-being of livestock through lighting impacts; understanding and optimizing productivity of horticulture through lighting impacts; and understanding and minimizing direct impacts of artificial lighting on the environment.

Product Development

- **Application of LED lighting technology**–Improve efficacy, building integration, design for manufacture, value (e.g., roadway safety, productivity, application specificity), and/or controls for specific lighting applications.
- **Power supply**–Increase use of solid state components; design for full efficiency-no flicker across all operating conditions; use of modular controls/sensors, and/or multi-channel individualized control approaches for advanced luminaires.
- **Package materials and processes** – Develop silicone/phosphor system for higher output operation, wafer scale phosphor/encapsulant deposition processes.

Manufacturing R&D

- **Flexible luminaire manufacturing** to support large scale manufacturing of multiple product families.

For OLEDs, steady progress continues to be made in terms of technical performance, and commercially viable lighting products continue to be introduced. Stakeholders identified these fundamental technical challenges that could be addressed through DOE-supported R&D:

- **Materials research**–Target emitter systems (emitters, hosts, transport materials) designed to simultaneously achieve long lifetimes and high efficacy, particularly for blue emitters where performance is lagging.
- **Light extraction**–Focus on cost-effective manufacturable solutions that will allow for substantial improvements in panel efficiency by extracting light trapped in organic/anode wave-guided

modes and/or reducing surface plasmonic losses. The ability to control the distribution of the emitted light would be an additional benefit.

- **Luminaire development**–Aim to accelerate the marketability of OLED lighting by product differentiation, integratability, ease of installation, or other attributes promoting the appeal and implementation of OLED lighting.
- **Manufacturing R&D**–Direct toward improving yield and reliability.
- **Manufacturing on flexible substrates**–Pursue the advancement of processes and materials required for the production of conformable/flexible OLED lighting, possibly through the use of R2R manufacturing.

These R&D issues center on three key goals:

1) Performance improvements, particularly in terms of efficacy enhancements.
2) Product differentiation through the development of conformable/flexible lighting or other means.
3) Cost reductions.

While this list does not include all of the important research that could be supported to advance OLED lighting technology, these topics were identified as priority research areas at DOE SSL R&D Workshops and the preceding OLED stakeholder meeting.

7.4 LED Priority Research Areas

Specific tasks were identified to address the most critical R&D priority tasks described above. DOE SSL program funding solicitations will be selected from these priority tasks, taking into consideration available resources and the current project portfolio. It may not be possible for DOE to fund all of the priority tasks in any particular year; however, that does not diminish each task's importance in overcoming key barriers to success. Industry researchers are encouraged to address as many of the priority tasks as possible. In fact, all of the R&D task areas deserve continued R&D attention. The limited number of priority R&D tasks reflects the practical reality that DOE must leverage limited R&D funding to achieve the most meaningful advancements possible.

The specific task tables that follow reference color or descriptive terms for color temperature. Ranges of the various color wavelengths and explanations of the meaning of the color temperature terms are shown in Table 7.5.

Table 7.5 Assumptions for Wavelength and Color as Used in the Task Descriptions

Color	Peak Wavelength or CCT	CRI
Blue	440-460 nm	N/A
Green	520-540 nm	N/A
Amber	580-595 nm	N/A
Red	610-620 nm	N/A
Warm White	3000K	≥80
Cool White	5700K	≥70

The milestones provided in the tasks described below represent the minimal descriptions for progress. All of these tasks will require some additional system-level performance description, though the specifics of the system vary widely. Researchers in these areas are expected to possess and communicate a system-level understanding of the role of the described research.

7.4.1 LED Core Technology Research Priority Tasks

Core technology research remains central to the DOE SSL Program. Most of the performance metrics and goals have not changed. Current density droop for the blue emitters remains a source to unlock a lower cost structure for LED lighting by accessing more light from less LED material. An efficient green emitter remains elusive. The drive for higher LER requires the development of efficient, narrow-band emitters/down-converters, particularly in the red/amber spectral region, where a sharper long wavelength cut-off is required for highly efficacious warm white sources. This can be met by improved red direct emission LEDs with high efficiency at high temperatures, or improved down converters such as phosphors or quantum dots. Thus, work on improvements in down-conversion materials remains a priority. In addition, the spectral, intensity, and distribution control offered by LED lighting has demonstrated the promise of having significant impacts on human health and productivity, livestock well-being and productivity, horticultural productivity, and the direct ecological impact of using artificial light, particularly at night. Such benefits could be achieved while simultaneously saving significant amounts of energy. However, it is necessary to improve understanding of the underlying physiological responses to light of the affected organisms to properly develop such systems.

A.1.2 Emitter Materials Research		
Description: Identify fundamental physical mechanisms of efficiency droop for blue LEDs through experimentation using state-of-the-art epitaxial material and device structures in combination with theoretical analysis and advanced characterization approaches. Identify and demonstrate means to reduce current droop and thermal sensitivity for all colors through both experimental and theoretical work. Develop efficient red, green, or amber LEDs, which allow for optimization of spectral efficiency with high color quality over a range of CCT, and which also exhibit color and efficiency stability with respect to operating temperature.		
Metrics	**2015 Status**	**2020 Targets**
IQE at 35 A/cm^2	79% (Blue)[1] 39% (Green) 75% (Red) 13% (Amber)	90% (Blue) 54% (Green) 87% (Red) 32% (Amber)
External Quantum Efficiency (EQE) at 35 A/cm^2, 25°C	69%(Blue) 32% (Green) 54% (Red) 10% (Amber)	81% (Blue) 46% (Green) 65% (Red) 24% (Amber)
Power conversion efficiency[2] at 35 A/cm^2	66% (Blue) 22% (Green) 44% (Red) 8% (Amber)	80% (Blue) 35% (Green) 55% (Red) 20% (Amber)
Current droop – Relative EQE at 100 A/cm^2 vs. 35 A/cm^2	85%	95%
Thermal stability – Relative optical flux at 100°C vs. 25°C	92% (Blue) 85% (Green) 50% (Red) 25% (Amber)[3]	98% (Blue, Green) 75% (Red, Amber)

1. The reduction in 2015 status of blue IQE is due to developments of LED structures with improved droop characteristics but with reduced peak IQE that result in improved IQE at typical operating conditions.
2. Optical power out divided by electrical power in for the LED package.
3. This status is representative of direct emitters. Amber pc-LEDs can achieve thermal stability of up to 83%.

A.1.3 Down-Converters

Description: Explore new, high-efficiency wavelength conversion materials for the purposes of creating warm white LEDs, with a particular emphasis on improving spectral efficiency with high color quality and improved thermal stability and longevity. Non-rare earth metal and nontoxic down-converters are encouraged.

Metrics	2015 Status	2020 Targets
Quantum yield (25°C) across the visible spectrum	98% (Green) 90% (Red)	99% (Green) 95% (Red)
Thermal stability – Relative quantum yield at 150°C vs. 25°C	90%	95%
Spectral FWHM	100 nm (Red/Green)	30 nm (Red) 70 nm (Green)
Color shift over time (when integrated into pc-LED)	Δu'v' < 0.007 at 6,000 hours	Δu'v' < 0.002 over life
Flux density saturation – Relative quantum yield (QY) at 1 W/mm^2 (optical flux) vs. peak QY	-	95%

A.8.2 Physiological Impacts of Light		
Description: Develop an improved understanding of the underlying physiological responses to light for humans, livestock, plants, or nocturnal animals. Such understanding should enable development of SSL products that improve well-being or productivity in humans, increase well-being and productivity in livestock production, increase productivity and reduce cost of indoor crop production, or minimize ecological impacts of lights at night. Researchers in this area should define the current status of the underlying physiological responses to light and describe research targets as well as the impact of the proposed research in terms of energy savings, productivity, well-being, and ecological impacts. Work to develop novel, specialized LED research tools that enable specific R&D in this topic may also be considered.		
Metrics	**2015 Status**	**2020 Targets**
Human Physiological Impacts	Applicant define and substantiate	Applicant define and substantiate
Livestock Production Impacts		
Horticultural Production Impacts		
Ecological Impact Minimization		

7.4.2 LED Product Development Priority Tasks

Product development tasks encompass a variety of aspects related to specific LED products but are not restricted to the development of LED packages, modules, or luminaires that may appear as lighting products in the marketplace. The prioritized list includes work on components and subsystems, and also addresses novel luminaire designs and smart controls and connected systems.

B.3.2 Encapsulation		
Description: Improve the LED package light extraction/light mixing/optical scattering/absorption system through development of new encapsulant-phosphor-LED chip materials and configurations. Develop new encapsulant formulations that provide a tuned refractive index to improve light extraction from the LED package. Explore new materials such as improved silicone composites or glass for higher temperature, more thermally stable encapsulants to improve light output, improve long-term lumen maintenance, and reduce color shift. Develop matrix materials for phosphor or quantum dot down-converters with improved understanding of how the chemical interactions affected performance and reliability. Develop materials and approaches that enable low-cost wafer scale deposition of phosphor and encapsulant materials.		
Metrics	**2015 Status**	**2020 Targets**
Refractive index across the visible spectrum	1.54	1.8
Thermal conductivity	0.2 W/mK	1 W/mK
Thermal stability (at given temperature and optical flux density) – user defined for specific use case	User defined # hours at given operating condition	Proposed improvement in # of hours or increase temperature and/or flux density

B.6.4 Advanced Luminaire Systems		
Description: Develop novel luminaire system architectures and form factors that take advantage of the unique properties of LEDs to improve efficacy, save energy, and define a pathway toward greater market adoption. Novel form factors, advanced luminaire system integration, optimized performance for specific lighting applications, and improved utilization of light are topics that will be considered. Another important element of this task could be the integration of energy-saving controls and sensors to add value to the lighting application and save additional energy.		
Metrics	**2015 Status**	**2020 Targets**
Luminaire efficacy (depends on application – user may define metrics for other use cases)	~120 lm/W Depends on CCT, CRI, beam angle, luminance distribution, etc.	200 lm/W
Light utilization (depends on application – user may define metrics for other use cases)	General: 85% Task: 65%	General 90% Task 85%
First Cost (depends on application – user may define metrics for other use cases)	Cobra head: 4,000 lm, $200 Downlight: 650 lm, $20	Cobra head: 4,000 lm, $40 Downlight: 650 lm, $5

B.7.0 LED Power Supply		
Description: Develop power supplies for luminaires with improved efficiency, reliability, and functionality. Explore new materials, circuit, and system designs for improved power supply system reliability. Develop power supply systems with full dimmability, minimal flicker, and maximum efficiency across the LED lamp or luminaire operating range. Enhance luminaire functionality through low-cost modular control and communication systems integrated with the power supply, including multi-channel control for multiple strings of LEDs.		
Metrics	**2015 Status**	**2020 Targets**
Power supply efficiency	88%	93% at full power 90% in dimmed state
Flicker	Application dependent/Applicant define and substantiate	No perceptible flicker across luminaire operating range
Power supply reliability	Applicant estimated lamp/luminaire survival factor	95% survival factor at claimed L_{70} life
Power supply functionality	User defined functionality	Proposed impact on performance and/or adoption case

7.4.3 LED Manufacturing R&D Priority Tasks

Advancements in LED lighting product manufacturing across the value chain have enabled significant cost reductions and performance improvements. However, the vast range of lighting product types and form factors coupled with ongoing advancements in technology and new features such as product connectivity create the need for ongoing manufacturing advancements. The prioritized manufacturing R&D task is Flexible Luminaire Manufacturing.

M.L.1 Flexible Luminaire Manufacturing		
Description: Develop flexible manufacturing technologies and approaches for state-of-the-art LED luminaires. Suitable development activities would likely include on or more of the following areas: • Advanced LED package and die integration enabling an array of lumen packages for a variety of lighting applications • Optimized designs for efficient and low-cost manufacturing • More efficient use of components and raw materials • Use of novel, low environmental impact materials • Reduction in part count through the use of multi-functional components • Product designs using common components to reduce inventory and part count across a range of products or applications • Reduced manufacturing cost through the development of advanced automated assembly approaches and/or improvements to manufacturing tools		
Metrics	**2015 Status**	**2020 Targets**
Lamp bill of materials (BOM) cost		Reductions beyond luminaire cost reduction projection in figure
Assembly cost ($)		Reductions beyond luminaire cost reduction projection in figure
Product environmental impact reduction beyond energy savings		Description of reduced environmental impact of lighting products

7.5 OLED Priority Research Areas

The OLED priority tasks identified based on discussions at the R&D Workshop are outlined below.

7.5.1 OLED Core Technology Research Tasks

Cost and performance improvements are necessary for OLED lighting to reach its full potential and gain widespread adoption. Improving the efficacy of white OLED devices remains a high priority. This must be accomplished without compromises in lifetime or color quality. Because much of the progress has been accomplished by using more complex structures with greater manufacturing costs, there is growing interest in the development of simpler stack structures that can be manufactured with higher yields and lower material costs. In addition, improvements in light extraction techniques to bolster efficacy are required. While external and internal extraction layers have been developed and demonstrate reasonable success, much light is still lost to the excitation of SPPs. Novel methods to achieve the next level of light extraction enhancement are key to achieving performance beyond 100 lm/W. Likewise, new manufacturing techniques are needed to enhance performance and reduce costs. Improvements in layer uniformity, deposition quality, throughput, and the availability of low cost equipment and processes are desired to meet program goals. In particular, the development of methods and equipment to enable the R2R manufacture of OLED lighting devices is needed. The development of novel materials and manufacturing methods to reduce the cost of high performance OLEDs are goals represented in Tasks C.1.2 and C.3.1. Task C.6.3 seeks efficacy improvements through novel light-extraction techniques that go beyond internal and external scattering layers.

C.1.2 Stable White Devices		
Description: Develop novel materials and structures that can help create a highly efficient, stable white device. The device should have good color, long lifetime, and high efficiency, even at high brightness. The approach may include development of highly efficient blue emitter materials and hosts, or may comprise a device architecture leading to longer lifetime. Any proposed solutions should keep cost, complexity, and feasibility of scale-up in mind. Materials/structures should be demonstrated in OLED devices that are characterized to ascertain the performance as compared to the metrics below. Novel materials/structures should demonstrate high stability, while maintaining or improving other metrics.		
Metrics	**2015 Status**	**2020 Target**
Lumen maintenance (L_{70}) from 10,000 lm/m^2	40,000	> 50,000 hrs
Efficacy without extraction enhancement (lm/W)	35 lm/W	50 lm/W
CRI	87	> 90

C.3.1 Fabrication Technology Research		
Description: Develop new practical techniques to support the advancement of OLED lighting manufacture. Improvements in materials deposition, device fabrication, or encapsulation of high-performance OLED panels are desired. Approaches should use technologies showing the potential for scalability and reduced cost (e.g., by enabling significant advances in yield, quality control, substrate size, process time, or materials usage). In addition to refinements on traditional manufacturing approaches, solution-based deposition (of organic materials or electrodes), manufacture on flexible substrates, flexible encapsulation, and novel patterning schemes are also considered under this task. For instance, projects related to the development of R2R manufacture, which may enable low-cost manufacture of large area devices on flexible substrates, are supported under this topic area. Contemplated approaches should demonstrate the viability of the processing technique via its use in fabricating a state-of-the-art OLED lighting device, and proposed approaches should be justified with a cost-benefit analysis.		
Metrics	**2015 Status**	**2020 Targets**
Cost Reduction	1 cost (relative)	1/10 cost
Performance Improvements		User Defined
Yield	90%	95%

C.6.3 Novel Light Extraction and Utilization		
Description: Devise new optical and device designs for improving OLED light extraction while retaining the thin profile and state-of-the-art performance of OLED panels. The proposed solution could involve modifications within the OLED stack, within or adjacent to the electrodes, or external to the device. Applicants should consider how their approach affects the energy loss due to wave-guided and plasmon modes and should include modeling or quantitative analysis that supports the proposed method. Solutions can also explore light-shaping techniques that can be integrated with the proposed light extraction technology to attain increased utilization efficiency of the generated light. Such methods should allow some control of the angular distribution of intensity, but minimize the variation of color with angle. The approach should provide potential for low cost and should be demonstrated in an OLED device of at least 1 cm^2 in size to demonstrate applicability and potential scalability to large-area (panel-size) devices.		
Metrics	**2015 Status**	**2020 Target**
Extraction efficiency (EQE/IQE)	40%	70%

7.5.2 OLED Product Development Tasks

Product development tasks have been defined to address some of the challenges that are faced by luminaire manufacturers. OLEDs have distinguishing features (flexibility, thinness, transparency, color-tunability, excellent color quality, and uniform diffuse-area light) that can provide luminaire manufacturers the ability to create unique product offerings. However, there have been delays and hesitation in the introduction of OLED lighting products to the market. A key issue for luminaire manufacturers is the difficulty in implementation of OLED modules, due largely to the absence of OLED-specific drivers and connectors. Tasks D.4.2 and D.5.3 call for innovative luminaires and the development of efficient, long-life OLED light engines to enable such designs.

Developments in the OLED panel are still necessary, especially in regard to light-extraction technologies. While many approaches have been proposed, most have not proven suitable for large-area, low cost manufacture. Products to date only incorporate external extraction mechanisms that can provide around 1.6 times the extraction enhancement. Cost-effective, scalable internal extraction techniques that allow for greater than two times extraction enhancement have been demonstrated, but these techniques need to be developed and implemented into panel products to reach efficacy goals.

D.4.2 OLED Luminaire		
Description: Develop general illumination OLED luminaires that provide a path toward greater market adoption. Proposed luminaires should primarily be based on OLED light sources and should have a unique set of features that justifies marketability and product demand. Example characteristics include, but are not limited to: high performance (efficacy, long lifetime, color quality); low cost; color tunability; modularity; unique form factor (thin, flexible); efficient power supplies; and improved electrical connections. Proposals should provide quantitative targets for distinctive performance. Potential customer appeal as well as market size and penetration should be supported with a cost-benefit comparison and a competitive analysis that considers competitive products based on other lighting technologies.		
Metrics	**2015 Status**	**2020 Target**
Efficacy	51 lm/W	106 lm/W
Lumen Maintenance (L_{70})		50,000 hours

D.5.3 OLED Light Engine		
Description: Develop efficient, long-life OLED light engines combining one or more hig- performance OLED panels with driver electronics. Drivers should efficiently convert line power to acceptable input power for the OLED source(s) and maintain their performance over the life of the device. Full dimmability with constant flux and color, as well as high efficiency across the operating range, are desired. The light engine should be designed with user-friendly configurability and a reasonable total light output such that luminaire manufacturers can use the light engine to more rapidly turn out OLED lighting products.		
Metrics	**2015 Status**	**2020 Targets**
Driver efficiency		90%
Lifetime		50,000 hours
Dimmability		Continuous down to 1%

D.6.3 Panel Light Extraction and Utilization		
Description: Demonstrate manufacturable approaches to improve light extraction efficiency for OLED panels. The approach should retain the thin profile and state-of-the-art performance of OLED panels (for example, extraction layers should not lead to voltage increases, reduction in device efficacy, and angular dependence of color). Further, panel yield, lifetime, performance and cost should not be compromised by the proposed technology. Solutions could involve modifications within the OLED stack, within or adjacent to the electrodes, and/or external to the device. The approach should be demonstrated with high-performance, large-area OLED devices (>25 cm^2), and must be amenable to low-cost manufacture.		
Metrics	**2015 Status**	**2020 Target**
Extraction efficiency (EQE/IQE)	40%	70%
Incremental cost		< $\$10/m^2$
Angular variation in color (0-75°)	Δu'v' ≤ 0.004	Δu'v' ≤ 0.002

7.5.3 OLED Manufacturing R&D Tasks

Many different processes are being used for the production of OLED lighting panels, but none shows a clear path to rapid cost reduction. Manufacturing processes and equipment are needed to improve quality and yield while reducing panel costs. Task M.O.5 provides opportunity to focus efforts on the aspects that form the major obstacles to reaching goals of producing high-quality panels at low costs, notably panel yield, consistency and reliability.

Task M.O.3 focuses on the development of processes that facilitate manufacturing of high-quality materials for OLED panels. Because cost reduction is critical, establishing the optimal balance between material quality and cost is of utmost importance. The availability of integrated substrates would be advantageous to panel manufacturers, who would then not be required to invest in the equipment and technology required to produce effective light extraction films and appropriate transparent conductors. However, given that extraction schemes and stack structure are so closely coupled, a fully integrated substrate solution may not always present the best approach. Thus, this task supports work for the manufacturing of integrated substrates, as well as components thereof. Encapsulation also remains a weak link for the industry. Better and cheaper technologies for thin-film encapsulation are needed, especially as the industry transitions to such encapsulation methods for flexible panels.

M.O.3 OLED Substrate and Encapsulation Manufacturing

Description: Support for the development of advanced manufacturing of low-cost, integrated substrates (substrate, light extraction layer(s), anode, current spreading layers, or combination thereof) and/or encapsulation materials. Contemplated approaches should demonstrate the performance of the manufactured materials in a state-of-the-art OLED lighting device and should be justified with a cost-benefit analysis.

Metrics		2020 Targets
Substrate	Total cost – dressed substrate	\$60/m^2
	Extraction efficiency	50%
	Luminance uniformity	
Encapsulation	Permeability of H_2O	10^{-6} g/m^2/day
	Permeability of O_2	10^{-4} cc/m^2/day/atm
	Cost	\$35/m^2

M.O.5 OLED Panel Manufacturing

Description: Support for development of manufacturing processes for practical OLED panels. Suitable development activities would likely focus on one or more of the following areas:

- Integration of processing steps
- Reliability
- Reproducibility and yield
- Changes in design or process flow to reduce manufacturing costs
- Optimized designs or processes for efficient and low-cost manufacturing

The work should enable higher quality panels, improved color consistency, lower manufacturing costs, and/or higher yields. Developed strategies should be demonstrated in panels having market relevant performance levels. Project approach should be justified by comparing the approach to state of the art manufacturing methods. Detailed analysis of actual yield, including catastrophic early failures; main defects; TAKT time; material utilization; equipment uptime; and process flow may be helpful to identify opportunities for improvements in terms of cost and performance.

Metrics	2015 Status	2020 Target
Panel Yield		≥ 80%
Reliability (catastrophic failure)	< 1/1000	< 1/10000
Panel to panel color control – Δu’v’	±0.004	±0.002
Panel price	< $200/klm	< $100/klm

8.0 Appendices

8.1 Definitions and Background

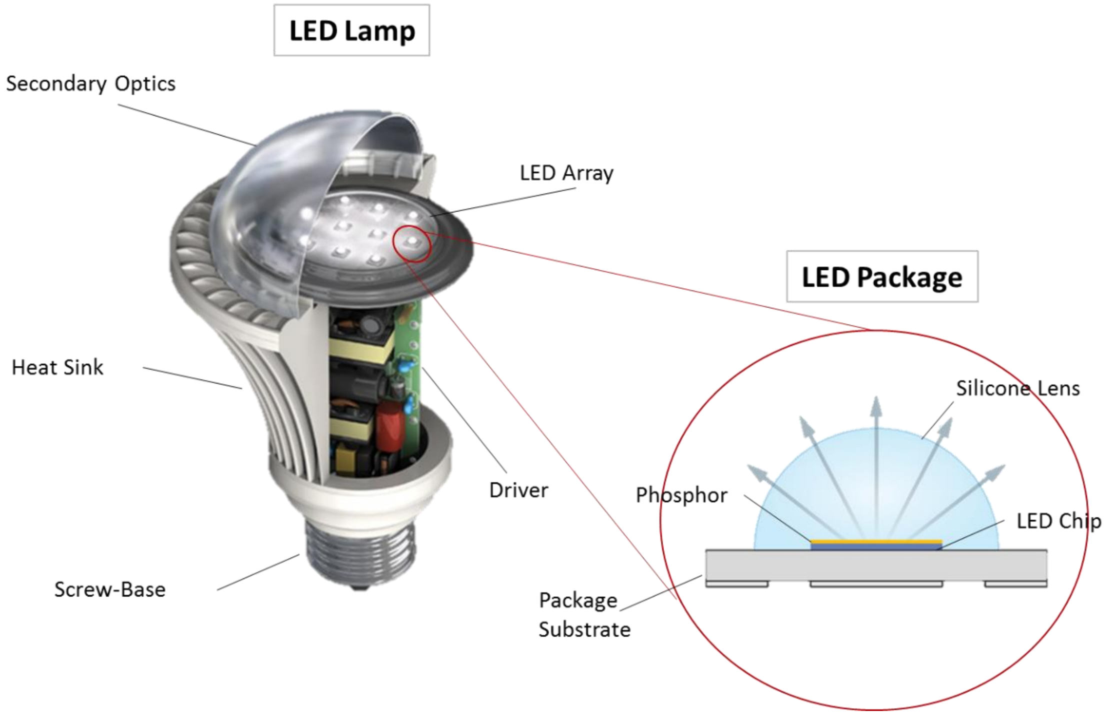


Figure 8.1 Components of an LED Lamp

Image Sources: a) Lamp: http://electronics.stackexchange.com/questions/76883/how-do-led-light-bulbs-work, b) Package: Tuttle & McClear, LED Magazine Feb. 2014.

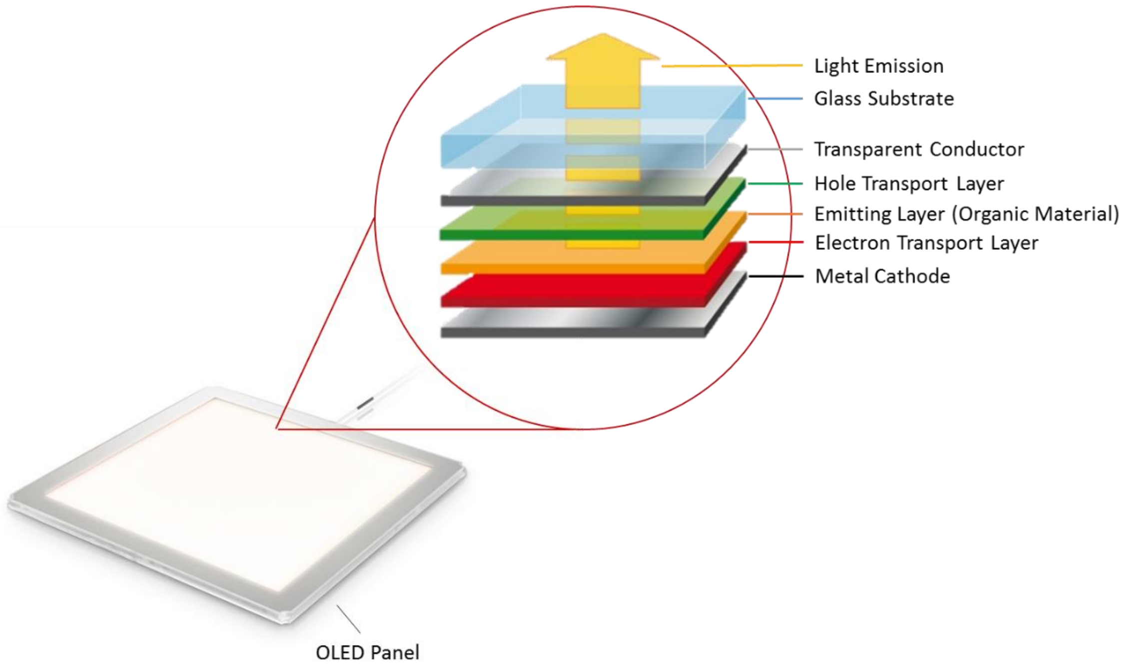


Figure 8.2 Components of an OLED Panel

Image Sources: a) Panel: http://www.printedelectronicsworld.com/articles/7799/oledworks-buy-philips-oled-lighting *b) Stack: http://www.androidauthority.com/amoled-vs-lcd-differences-572859/*

Table 8.1 Summary of LED Application-Based Submarkets with Examples of Products in Each

SUBMARKET	LIGHTING PRODUCT	DESCRIPTION	Examples[1]:
A-type	Lamps	All A-type lamp shapes with a medium-screw base.	
Decorative	Lamps	All bullet, candle, flare, globe, and any other decorative lamp shapes.	
Directional	Lamps and Luminaires	Includes reflector, BR, MR, and PAR lamps as well as recessed and surfaced mounted downlights and indoor accent, track, and spot light luminaires.	
Linear Fixtures	Lamps and Luminaires	All troffer, panel, suspended, and pendant luminaires, as well as, LED linear replacement lamps.	
Low/High Bay	Luminaires	Includes LED low- and high-bay luminaires.	
Parking (Garage)	Lamps and Luminaires	Includes LED lamps and luminaires for attached and stand-alone parking garages	
Parking (Lot)	Luminaires	Includes LED luminaires used in parking lot illumination.	See Street light/Roadway Examples
Street lights/ Roadway	Luminaires	Includes LED luminaires installed in street and roadway applications.	
Building Exterior	Lamps and Luminaires	Includes all lamps fixtures installed in façade, spot, architectural, flood, wallpack, step/path applications.	
Other	Lamps and Luminaires	Includes all other special use lighting applications such as tunnel, signage, wall-wash, and cove.	

[1]*Image Sources: Grainger and Home Depot Websites.*

8.2 List of Acronyms

Abbreviation	Definition
$/klm	U.S. dollars per kilolumen
2-D	2-dimensional
3-D	3-dimensional
A/cm^2	amperes per square centimeter
AC	alternating current
Ag	Silver
ALD	atomic layer deposition
AlInGaP	aluminum indium gallium phosphide
ALT	accelerated life tests
ANSI	American National Standards Institute
app	Application, i.e. for smartphones, computers etc.
ASU	Arizona State University
BLE	Bluetooth Low Energy
°C	degrees Celsius
CCT	correlated color temperature
cd/m^2	candelas per square meter
CFL	Compact Fluorescent Lamp
cm-LED	color mixed LED
COB	chip-on-board
CRI	Color Rendering Index
CSP	chip scale package
DALI	digitally addressable lighting interface
DC	direct current
DOE	Department of Energy
D_{uv}	distance from the blackbody locus in u-v colorspace
EEL	external extraction layer
EMC	epoxy molding compound
EQE	external quantum efficiency
ESD	electrostatic discharge
eV	electron volt
FOA	funding opportunity announcement
FWHM	full width half maximum
FY	fiscal year
HID	high intensity discharge
HMDSO	hexamethyldisiloxane
IEL	internal extraction layer
IES	Illuminating engineering society
InGaN	Indium Gallium Nitride
IQE	internal quantum efficiency

ITO	indium tin oxide
K	Kelvin
klm/m^2	kilolumen per square meter
L_{50}	duration of lumen maintenance to 50% initial brightness
L_{70}	duration of lumen maintenance to 70% initial brightness
LCA	Life-cycle assessment
LED	Light-Emitting Diode
LER	luminous efficacy of radiation
lm/W	lumens per watt
LSRC	LED Systems Reliability Consortium
MC-PCB	metal-core printed circuit board
MOCVD	metal organic chemical vapor deposition
MYPP	Multi-Year Program Plan
NGLIA	Next Generation Lighting Industry Alliance
NIST	National Institute of Standards and Technology
nm	nanometer
OLED	Organic Light Emitting Diode
PCE	power conversion efficiency
pc-LED	phosphor-converted LED
PECVD	plasma enhanced chemical vapor deposition
PEN	polyethylene naphthalate
PET	polyethylene terephthalate
PNNL	Pacific Northwest National Laboratory
PPA	polyphtalamide
Q3	quarter 3
R&D	Research and Development
R2R	roll-to-roll
RGBA	red, green, blue and amber
SBIR	Small Business Innovation Research
SiNx	silicon nitride
SPP	surface plasmon polaritons
SSL	Solid-State Lighting
STExS	short thermal exposure source
TADF	thermally activated delayed fluorescence
TAKT	process cycle time
TCO	total cost of ownership
TWh	terawatt-hours
UNEP	United Nations Energy Programme
V	volts
VLC	visible light communication
W	Watt

W/mm^2	watts per square millimeter
WHTOL	wet high temperature operating life
ZSO	zinc sulfide silicone dioxide ($ZnS:SiO_2$)
Δu'v'	Magnitude of color shift in the CIE 1976 chromaticity diagram (u', v')
µm	micrometer
Ω/□	resistivity per unit area
Ωm	Resistance of a given material

8.3 SSL Supply Chain – Additional Information

8.3.1 LED

LED, lamp, and luminaire manufacturing are global enterprises with a global supply chain. Some geographical production trends can be identified; however, many of the input materials and semiconductor processing tools are produced worldwide. Table 8.2 and Table 8.3 highlight the global nature of SSL manufacturing by listing some of the key companies in each major geographical region involved in the manufacturing of LED-based SSL products and in the supply of equipment and materials to that market. These tables categorize geographical location based on company headquarter location and may not accurately reflect the balance of manufacturing activity.

Table 8.2 The LED Supply Chain: LED Die, LED Package, and Luminaire Manufacturers

Supply Chain	North America	Europe	Asia
Die Manufacturing	• Cree • Lumileds • Bridgelux • Soraa • SemiLEDs • Luminus Devices	• OSRAM Opto Semiconductors • Optogan • Plessey Semiconductors	• Nichia • Toyoda Gosei • Toshiba • Sharp • Epistar • SemiLEDs Optoelectronics • MLS Lighting • OptoTech • FOREPI • Everlight • Lumens • Kingbright • Samsung • LG Innotek • Seoul Semiconductor • Elec-Tech Opto • Epilight • HC SemiTek • Sanan Optoelectronics
LED Package Manufacturing	As above	As above	As above and: • Lite-On • Unity Opto • Lextar • Nationstar • Shenzhen Jufei • Honlitronic • Refond
Luminaire Manufacturing	• GE Lighting • Eaton/Cooper Lighting • Hubbell Lighting •Soraa •MSi •Kim Lighting • Acuity Brands • Cree • Lighting Science Group •Feit	• Philips • Osram Sylvania • Zumtobel	• Panasonic • Toshiba • Sharp • LG • Samsung • Forest Lighting • Kingsun • Zhejiang Yankon • Shenzhen Changfang • Opple Lighting • PAK Corp • Nationstar • NVC Lighting Tech Corp • FSL

Table 8.3 The LED Supply Chain: Equipment and Materials Suppliers

	Supply Chain	North America	Europe	Asia
Equipment Suppliers	**Epitaxial growth**	• Veeco Instruments	• Aixtron	• Taiyo Nippon Sanso
	Wafer processing	• Plasma-Therm • Lam Research • Ultratech • JPSA • Temescal	• Oxford Inst. Plasma Tech • EV Group • SUSS MicroTec • Logitech	• Nikon Corp • Canon Inc. • Ushio Inc.
	LED packaging	• Palomar Tech • Heller • Nordson ASYMTEK	• Besi	• ASM Pacific Tech • TOWA • Disco • Kulicke & Soffa (K&S)
	Luminaire assembly	• Speedline Tech • Conveyor Tech	• ASM Siplace • Assembleon	• Panasonic • Fuji Machines • Nutek
	Test and inspection	• KLA-Tencor • Cascade Microtech • Wentworth Labs • Orb Optronix • Lighting Sciences Inc. • Gamma Scientific • Radiant Zemax • SphereOptics • Daitron • Optest • Nanometrics • Chroma • Rudolph Tech • Labsphere	• Laytec • Bede • Bruker • Instrument Systems • Cameca • SUSS MicroTec • Ismeca	• Quatek • Fittech Co • QMC • Shibuya • Panasonic • Fujikom

Table 8.3 (continued)

	Supply Chain	North America	Europe	Asia
Materials Suppliers	**Substrates**	• Rubicon • Silian • Cree • Kyma	• Monocrystal • Ammono • St. Gobain • Soitec	• Astek • STC • LG Siltron • Crystalwise Tech • Air Water Inc. • TeraXtal • ProCrystal • Crystaland • Samsung • Kyocera • Namiki • Mitsubishi Chem Corp • Hitachi Cable
	Chemical reagents	• SAFC Hitech • Dow Electronic Materials • Air Products • SAES Pure Gas • Pall Corporation	• AkzoNobel • Linde Industrial Gases • Air Liquide	• Showa Denko KK • Matheson Tri Gas
	Packaging	• Bergquist Company • Cambridge America • CofanUSA • Indium Corp. • DuPont • Laird Tech / • Cookson Electronics	• Heraeus	• Chin-Poon • Gia Tzoong • HolyStone • Iteq • Leatec • Polytronics Tech • TA-I Tech • Tong Hsing • Univacco Tech • Taiflex • Viking Tech • Zhuhai Totking • Denka • Kyocera • NRK
	Phosphors/ Down-converters	• Intematix • Dow Electronic Materials • Philips Lumileds (internal) • GE (internal) • Phosphortech • QD Vision • Nanosys • Pacific Light Tech	• Merck • Osram Opto Semiconductors (internal)	• Nichia (internal) • Mitsubishi Chemical Corp • Shin-Etsu • Denka
	Encapsulation	• Momentive Performance Materials (InvisiSil) • NuSil • Dow Corning	• Wacker Chemie (LUMISIL)	• Shin-Etsu

8.3.2 OLED

The global extent of the OLED supply chain can be assessed from Table 8.4 and Table 8.5. However, these lists are incomplete, and some of these companies are still at the development stage and may not yet have commercial offerings.

Table 8.4 The OLED Supply Chain: Global Equipment and Materials Suppliers

	Supply Chain	North America	Europe	Asia
Equipment Suppliers	**Vapor deposition**	• Kurt Lesker • Trovato Mfg	• Aixtron • VG Scienta • Von Ardenne	• AMS • Canon Tokki • Choshu • GJM • Hitachi Zosen • Jusung • SFA • SNU Precision • Sunic Systems • ULVAC • YAS
	Coaters, printers, and patterners	• Dimatix • NovaCentrix • nTact • Sono-Tek • Xenon Corp	• 4Jet Technologies • Ceradrop • Coatema • Manz • Mbraun • Meyer Burger	• Dai Nippon Screen • Screen Holdings • Seiko Electron • Sung Am Machinery • Tazmo • Tokyo Electron • ULVAC
	Encapsulation	• Applied Materials • Coherent • Kateeva • Lotus • Veeco	• Aixtron • Beneq • Encapsulix • Kurdex	• AsiaTree • Avaco • Canon Tokki • FujiFilm • HB Industries • Jusung • Shimadzu • ULVAC • Wonic IPD • YAS
	Test and inspection	• Colnatec • Radiant Zemax	• Laytec • Instrument Systems • SEMPA • Schenk Vision • VG Scienta • Vinci Tech	• Chroma ATE • Hitachi High-Tech • Kisco Uniglaobe • KMAC • Konica Monolta • Micro Inspection • Micronics
Materials	**Substrates**	• Alcoa • DuPont-Teijin • Pilkington • Corning • PPG	• ArcelorMittal • St. Gobain • Schott Glass	• Asahi Glass • LG Chem • Nippon Electric Glass • SKC Kolon • Ube
	Extraction materials	• 3M • Pixelligent • Luminit	• Covestro	• Kimoto Tech • Toppan Printing

Active organic materials	• DuPont • PPG • R-Display • UDC	• BASF • Cynora • Merck • Novaled • Ossila • Sensient	• Aglaia • Doosan • Dow Electro-Materials • Duksan Hi-Metal • eRay Opto • Hodogaya • Idemitsu Kosan • Jilin Optical • Kyulux • LG Chem • Lumtech • Mitsubishi Chem • Mitsui Chemical • Nippon Steel Sumikin • Nissan Chemical • RuiYuan • Samsung SDI • Sumitomo Chemical • Sun Fine Chemical • Wan Hsiang OLED
Conductors	• Cambrios • Chasm • DuPont • ElectronInks • Intrinsiq Materials • Micro-continuum • Sinovia	• Agfa • Genes'Ink • Heraeus • Inkron • SEFAR AG	• DNP • Nagase • OLED Materials Solutions
Encapsulation	• DuPont • 3M • Vitriflex	• Delo • Henkel • SAES Getters • Sud-Chemie • Tesa	• Dynic • Fujifilm • Futaba • Jindal • LG Chem • Konica Minolta • Samsung SDI • Tera Barrier

Table 8.5 The OLED Supply Chain: Global Panel and Luminaire Producers

Supply Chain	North America	Europe	Asia
Panels	• OLEDWorks •	• Astron-Fiamm • Osram Opto	• Ason • First O-Lite • Kaneka • Konica Minolta • LG Display • Lumiotec • MC Pioneer • NeoView Kolon • Showa Denko • Sumitomo Chemical • Visionox • WiseChip • Yeolight
Luminaires	• Acuity • Alkilu • Visa • Workrite • OTI Lumionics	• Blackbody	• Feelux • First O-Lite • Fursis Ilroom • Morikawa • Synqroa • Verbatim • Wooree

The key cost drivers for each major element of the OLED supply chain are summarized in Table 8.6.

Table 8.6 The OLED Supply Chain: Key Cost Drivers

Supply Chain		Cost Drivers			
Equipment Suppliers	Sealing	• Seal integrity	• Process time		
	Evaporators	• Deposition rate	• Materials utilization	• Capital cost	
	Wet Coaters	• Drying time	• Patterning		
	Luminaire Assembly	• Modularization	• Automation		
	Test & Inspection	• Throughput	• Accuracy		
Materials Suppliers	Substrates	• Material selection	• Surface condition		
	Organic Stack	• Sales volume	• Efficacy	• Lifetime	
	Encapsulation	• Increased sales volume	• Elimination of desiccants		
	Electrodes	• Material selection	• Patterning		
	Extraction Structures	• Processing yield	• Performance		
Panel Manufacturing		• Yield	• Throughput	• Capital	• Testing
Luminaire Manufacturing		• Panel price	• Labor	• Modularization	• Testing

8.4 DOE Program Status

8.4.1 Funding Levels

DOE received $24.0 million from Congress for SSL R&D in FY 2016, which began in October 2015. These levels are consistent with congressional appropriations from previous years, which have hovered around $25 million each year as seen in Figure 8.3. In FY 2009, an additional, one-time funding of $50 million was provided through the American Recovery and Reinvestment Act of 2009, to be used to accelerate the SSL R&D Program and jump-start the manufacturing R&D initiative.

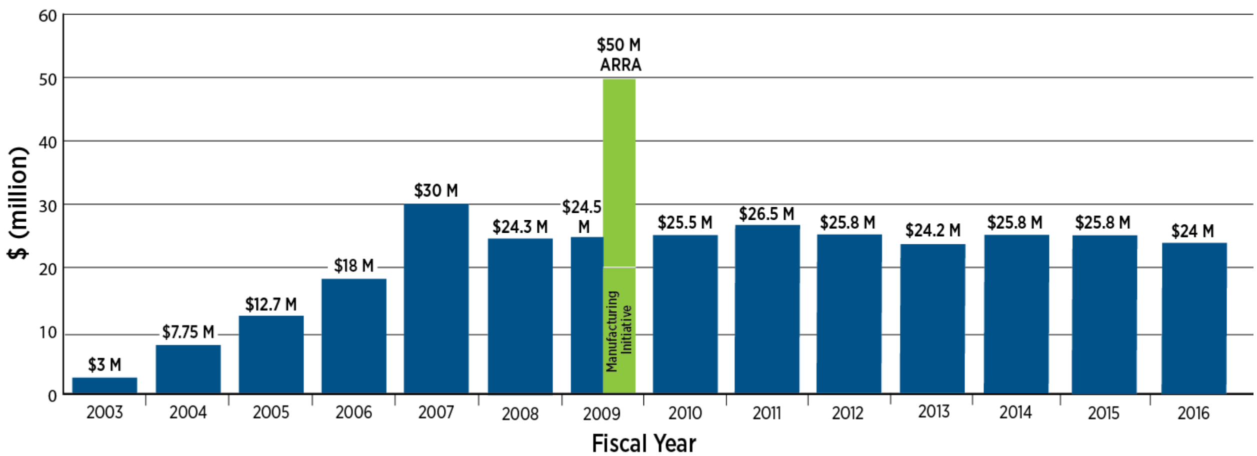


Figure 8.3 Funding Allocations for SSL, FY 2003 to 2016
Source: James Brodrick, DOE SSL R&D Workshop, Raleigh, NC, January 2016 [219]

8.4.2 Current SSL Portfolio

The active DOE SSL R&D Portfolio,[v] as of March 2016, shown in Figure 8.4, includes 33 projects that address LED and OLED technologies across core technology research, product development, and manufacturing. Projects balance long-term and short-term activities, as well as large and small business, national laboratory, and university participation. The portfolio totals some $45.0 million in government and industry investment.

[v] For the full list of all current and previous DOE SSL funded projects see: http://energy.gov/sites/prod/files/2016/01/f28/2016_ssl-project-portfolio.pdf

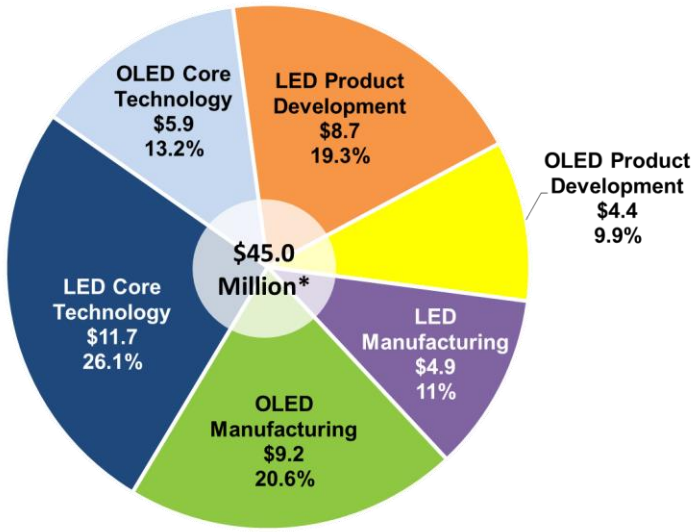


Figure 8.4 DOE SSL Total Portfolio Summary, March 2016

Figure 8.5 provides a graphical breakdown of the funding for the current SSL project portfolio as of March 2016. DOE is providing $32.6 million for the projects, and the remaining $12.3 million is cost-shared by project awardees. Of the 33 active projects in the SSL R&D portfolio, 20 focus on LED and 13 focus on OLED technology.

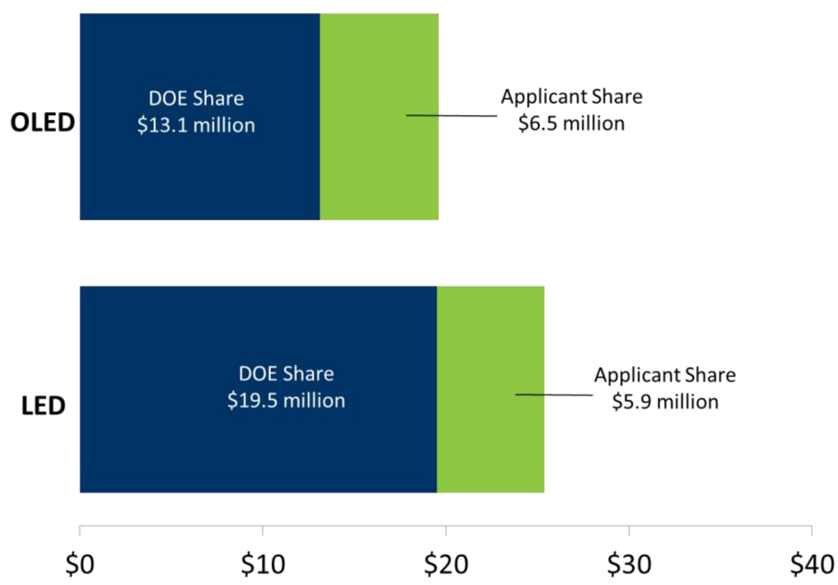


Figure 8.5 Funding of SSL R&D Project Portfolio by Funder, March 2016

DOE supports SSL R&D in partnership with industry, small business, national laboratories, and academia. Figure 8.6 provides the approximate level of R&D funding contained in the current SSL portfolio among the four general groups of SSL R&D partners.

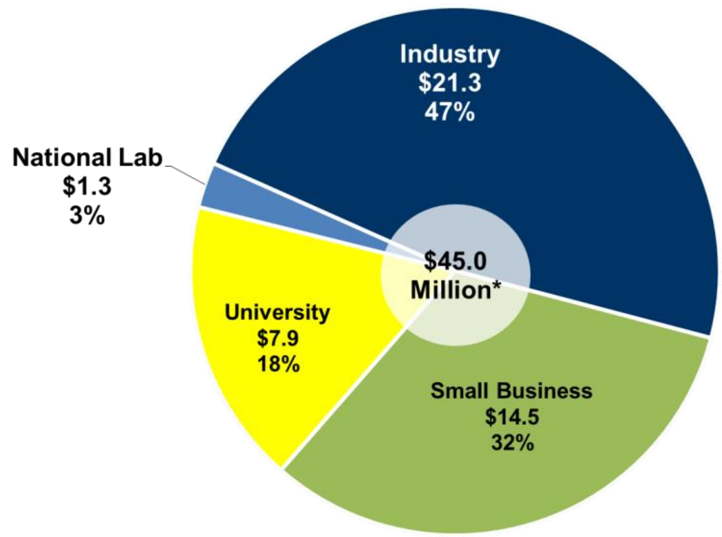


Figure 8.6 DOE SSL Total Portfolio Summary by Recipient Group, March 2016

Table 8.7, Table 8.8, and Table 8.9 show the total number of SSL R&D core technology research, product development, and manufacturing projects, respectively, and total project funding for each. Tables show the categories in which there are active projects that DOE funded or has selected to fund, maintaining alignment with the evolving priorities.

Table 8.10 lists all active research projects, including core technology research, product development, and manufacturing projects.

Table 8.7 SSL R&D Portfolio: Core Technology Research Projects, March 2016

Task	Number of Projects	Funding ($ million)
Light-Emitting Diodes	**6**	**$11.7**
Emitter Materials	2	$3.1
Optimizing System Reliability	3	$5.1
Down Converters	1	$3.6
Organic Light-Emitting Diodes	**5**	**$5.9**
Novel Light Extraction Approaches	3	$3.3
Novel Materials	2	$2.6
Total	**11**	**$17.7**

Table 8.8 SSL R&D Portfolio: Product Development Projects, March 2016

Task	Number of Projects	Funding ($ million)
Light-Emitting Diodes	**13**	**$8.7**
Phosphor	5	$2.5
Package Optics	1	$0.2
Encapsulation	1	$2.0
LED Yield and Manufacturing	1	$0.2
Novel Luminaire System	3	$1.9
Lighting System and Controls	2	$2.0
Organic Light-Emitting Diodes	**5**	**$4.4**
OLED Materials	1	$0.2
Substrate	1	$1.0
Low Cost Electrode Structure	1	$1.8
OLED Luminaire	1	$0.5
Light Extraction	1	$1.0
Total	**18**	**$13.1**

Table 8.9 SSL R&D Portfolio: Manufacturing Projects, March 2016

Task	Number of Projects	Funding ($ million)
Light-Emitting Diodes	**1**	**$4.9**
Luminaire Manufacturing	1	$4.9
Organic Light-Emitting Diodes	**3**	**$9.2**
OLED Deposition	1	$2.1
Integrated Substrate Manufacturing	1	$4.7
Panel Manufacturing	1	$2.5
Total	**4**	**$14.2**

Table 8.10 SSL R&D Portfolio: Current Research Projects, June 2016

	Research Organization	Project Title
LED	Carnegie Mellon University	Novel Transparent Phosphor Conversion Matrix with High Thermal Conductivity for Next Generation Phosphor-Converted LED-based Solid State Lighting
	Cree	Materials and Designs for High-Efficacy LED Light Engines
	University of California, Santa Barbara	Identification and Mitigation of Droop Mechanism in GaN-Based LEDs
	Eaton Corporation	Print-Based Manufacturing of Integrated, Low-Cost, High- Performance SSL Luminaires
	Los Alamos National Laboratory	Next Generation 'Giant' Quantum Dots: Performance Engineered for Lighting
	Philips Research North America	Innovative Office Lighting System with Integrated Spectrally Adaptive Control
	Research Triangle Institute	Luminaires for Advanced Lighting in Education
	Research Triangle Institute	System Reliability Model for SSL Luminaires
	Momentive Performance Materials Quartz, Inc.	Next-Generation LED Package Architectures Enabled by Thermally Conductive Transparent Encapsulants
	Philips Research North America	Innovative Patient Room Lighting System with Integrated Spectrally Adaptive Control
	Lumileds	Improved InGaN LED System Efficacy and Cost via Droop Reduction
	Vadient Optics*	Alternative Interconnect Manufacturing—Printed SSL Optics
	SC Solutions*	Real-Time Learning Temperature Control for Increased Throughput in LED Manufacturing
	UbiQD*	Non-radiative Recombination Pathways in Non-carcinogenic Quantum Dot Composites
	Lumisyn*	High Performance Colloidal Nanocrystals
	PhosphorTech*	Hybrid Down-Converting Structures for Solid State Lighting
	Innosys*	Lowering Barriers to Intelligent SSL Adoption through a Combination of a Next Generation Installation/configuration Software Platform and a Novel Luminaire
	Lucent Optics*	Ultra-Thin Flexible LED Lighting Panel
	Lumisyn*	LED Down-converter Phosphor Chips Containing Nanocrystals
	PhosphorTech*	Plasmonic-enhanced High Light Extraction Phosphor Sheets for Solid State Lighting
OLED	Arizona State University	High-Efficiency and Stable White OLED Using a Single Emitter
	University of California, Los Angeles	The Approach to Low-Cost High-Efficiency OLED Lighting
	University of Michigan	Stable, High Efficiency White Electrophosphorescent Organic Light Emitting Didoes by Reduced Molecular Dissociation
	OLEDWorks, LLC	High-Performance OLED Panel and Luminaire
	OLEDWorks, LLC	Innovative, High-Performance Deposition Technology for Low-Cost Manufacturing of OLED Lighting
	Sinovia Technologies	Integrated Plastic Substrates for OLED Lighting

	Pixelligent Technologies, LLC	Advanced Light Extraction Structure for OLED Lighting
	PPG Industries	Manufacturing Process for OLED Integrated Substrate
	Princeton University	ITO-free White OLEDs on Flexible Substrates with Enhanced Light Outcoupling
	Acuity Brands Lighting	OLED Luminaire with Panel Integrated Drivers and Advanced Controls
	OLEDWorks*	Development of high-efficiency white OLEDs using TADF emitters

*SBIR projects.

8.4.3 Patents

As of January 2016, 109 SSL patents have been awarded to research projects funded by DOE. Since December 2000, when DOE began funding SSL research projects, 261 patent applications have been submitted, including those from large businesses (83), small businesses (97), universities (69), and national laboratories (12). These patents are listed on the DOE website at: http://energy.gov/sites/prod/files/2016/01/f28/patents_factsheet_jan2016.pdf.

8.4.4 Products

DOE began funding SSL R&D in 2000, and to date has supported 230 cost-shared SSL projects in the areas of applied research, product development, and manufacturing R&D. This support has directly advanced the understanding and performance of SSL through the publication of articles in technical journals, the creation of intellectual property, and the direct development of nearly 200 state-of-the-art products. More information on these products—which include lamps, luminaires, LED components, power supplies, materials, and manufacturing tools— can be found at: http://energy.gov/sites/prod/files/2015/07/f24/comm-product-factsheet_jun2015.pdf.

[This page has intentionally been left blank.]

9.0 Bibliography

[1] DOE SSL Program, "Adoption Analysis," March 2016. [Online].

[2] DOE SSL Program, "Energy Savings Forecast of Solid-State Lighting in General Illumination Applications," August 2014. [Online]. Available: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/energysavingsforecast14.pdf. [Accessed May 2016].

[3] G. C. Brainard, J. P. Hanifin, J. M. Greeson, B. Byrne, G. Glickman, E. Gerner and M. D. Rollag, "Action Spectrum for Melatonin Regulation in Humans: Evidence for a Novel Circadian Photoreceptor," *The Journal of Neuroscience,* vol. 21, no. 16, pp. 6405-6412, 2001.

[4] Lumileds, "LUXEON CoB With CrispWhite Technology," 2016. [Online]. Available: http://www.lumileds.com/products/cob-leds/luxeon-cob-with-crispwhite. [Accessed April 2016].

[5] T. Pocok, "Tuning the Spectrum for Plant Growth," DOE SSL Technology Development Workshop, Portland, OR, November 2015. [Online]. Available: http://energy.gov/sites/prod/files/2015/11/f27/pocock_keynote_portland2015.pdf. [Accessed April 2016].

[6] DOE SSL Program, "Lifetime of White LEDs," September 2009. [Online]. Available: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/lifetime_white_leds.pdf. [Accessed May 2016].

[7] Lawrence Berkeley National Laboratory, "The Evolving Price of Household LED Lamps: Recent Trends and Historical Comparisons for the US Market," November 2014. [Online]. Available: http://eetd.lbl.gov/sites/all/files/lbnl-6854e.pdf. [Accessed May 2016].

[8] Acuity Brands, "Chalina OLED Pendant Product Specifications," 15 December 2014. [Online]. Available: http://www.acuitybrands.com/products/detail/316294/acuity-brands/chalina-pendant/oled-decorative-pendant-for-consumers/-/media/products/acuity_brands/316294/document/chalina_pm_pdf.pdf. [Accessed May 2016].

[9] DOE SSL Program, "Energy Efficiency of LEDs Technology Factsheet," March 2013. [Online]. Available: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/led_energy_efficiency.pdf. [Accessed May 2016].

[10] E. L. Elliot, Ed., Good Lighting and the Illuminating Engineer, Volume 7, Illuminating Engineering Publishing Co., 1912, p. 190.

[11] J. Edmond, "Reinventing Lighting," DOE SSL R&D Workshop, San Francisco, CA, 27 January 2015. [Online]. Available: http://www.energy.gov/sites/prod/files/2015/02/f19/edmond_reinventing_sanfrancisco2015.pdf. [Accessed May 2016].

[12] Workrite Ergonomics, "Astra 2 Single Arm," 2016. [Online]. Available: http://workriteergo.com/astra-2-single-arm/. [Accessed May 2016].

[13] Workrite Ergonomics, "Natural OLED Desk Lamp," 2016. [Online]. Available: http://workriteergo.com/natural-oled/. [Accessed May 2016].

[14] J. Ryu, "Ultimate Lighting Design Freedom &," DOE SSL R&D Workshop, Raleigh, NC, February 2016. [Online]. Available: http://energy.gov/sites/prod/files/2016/02/f29/ryu_application_raleigh2016.pdf. [Accessed May 2016].

[15] Acuity Brands, "Acuity Brands Unveils Luminaires Using New Duet SSL Technology at Lightfair International," 5 May 2015. [Online]. Available: http://news.acuitybrands.com/US/ALL-Brands/acuity-brands-unveils-luminaires-using-new-duet-ssl-technology-at-lightfair-international/s/8d94f8e6-a974-4f18-bec0-f0892303e3e4. [Accessed May 2016].

[16] McKinsey and Company, "Reducing U.S. Greenhouse Gas Emissions: How Much at What Cost?," December

2007. [Online]. Available: http://www.mckinsey.com/business-functions/sustainability-and-resource-productivity/our-insights/reducing-us-greenhouse-gas-emissions. [Accessed May 2016].

[17] DOE SSL Program, "Life-Cycle Assessment of Energy and Environmental Impacts of LED Lighting Products," April 2013. [Online]. Available: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/lca_factsheet_apr2013.pdf. [Accessed May 2016].

[18] C. Chipalkatti, "SSL Systems: Opportunity for Sustainability Beyond Energy Savings," DOE SSL Technology Development Workshop, Portland, OR, November 2015. [Online]. Available: http://energy.gov/sites/prod/files/2015/11/f27/chipalkatti_lifecycle_portland2015.pdf. [Accessed May 2016].

[19] Philips, "SlimStyle LED Dimmable A-Shape," 2016. [Online]. Available: http://www.usa.lighting.philips.com/prof/lamps/led-lamps-and-systems/led-lamps/slimstyle-a-shape-dimmable-led. [Accessed May 2016].

[20] Cree, "A Better LED Bulb," 2015. [Online]. Available: http://creebulb.com/media/document/file/p/r/product-document-gen3-point-5.pdf. [Accessed May 2016].

[21] OSRAM, "LED Retrofit Classic A," [Online]. Available: http://www.osram.com/osram_com/products/lamps/led-lamps/consumer-led-lamps-with-filament-style-led-technology/led-retrofit-classic-a/index.jsp. [Accessed May 2016].

[22] A. Wojtysiak, "The Physiological Impact of Lighting," DOE SSL R&D Workshop, San Francisco, CA, 29 January 2015. [Online]. Available: http://www.energy.gov/sites/prod/files/2015/02/f19/wojtysiak_physiological_sanfrancisco2015.pdf. [Accessed May 2016].

[23] International Solid-State Lighting Alliance, "Global Solid State Lighting Industry Status Report and Market Trends 2014," 2014.

[24] R. Spivock, "Horticultural Lighting: DOE Emerging Trends," DOE SSL R&D Workshop, San Francisco, CA, 27 January 2015. [Online]. Available: http://www.energy.gov/sites/prod/files/2015/02/f19/spivock_horticultural-lighting_sanfrancisco2015.pdf. [Accessed May 2016].

[25] DOE SSL Program, "2016 Animal Responses to Light Meeting Report," Expected June 2016. [Online].

[26] COP21, "United Nations Conference on Climate Change," December 2015. [Online]. Available: http://www.cop21.gouv.fr/en/195-countries-adopt-the-first-universal-climate-agreement/. [Accessed May 2016].

[27] United Nations Enviornment Programme, "Green Paper: Policy Options to Accelerate the Global Transition to Advanced Lighting," November 2014. [Online]. Available: http://www.enlighten-initiative.org/Portals/0/documents/global-forum/Green_Paper_FINAL%20reduced.pdf. [Accessed May 2016].

[28] International Energy Agency, "Tracking Clean Energy Progress 2015," May 2015. [Online]. Available: http://www.iea.org/publications/freepublications/publication/Tracking_Clean_Energy_Progress_2015.pdf. [Accessed May 2016].

[29] Acuity Brands, "Acuity Brands Reports Record Second Quarter Results," 6 April 2016. [Online]. Available: http://www.acuitybrands.com/investors/news-releases. [Accessed May 2016].

[30] OSRAM, "Strong Second Quarter Results: Q2 FY16 Earnings Release," 27 April 2016. [Online]. Available: http://www.osram-group.com/~/media/Files/O/Osram/documents/en/publications/quarterly-reports/2016/2016-q2-osram-earnings-release.pdf. [Accessed May 2016].

[31] Philips, "Philips Reports Q1 Comparable Sales Growth of 3% to EUR 5.5 Billion and a 14% Improvement in Adjusted EBITA to EUR 374 Million," 25 April 2016. [Online]. Available: http://www.philips.com/corporate/resources/quarterlyresults/2016/Q1_2016/philips-first-quarter-results-2016-report.pdf. [Accessed May 2016].

[32] Zumtobel Group AG, "Q1-Q3 2015/16 Results," 2 March 2016. [Online]. Available: http://www.zumtobelgroup.com/download/Analyst_Presentation_Zumtobel_Group_Q3_2015-16.pdf. [Accessed May 2016].

[33] W. Rhodes, "Illuminating Your IQ, Smart Lighting Market Market Today and Future," in *Smart Lighting*, Berlin, Germany, May 2015.

[34] S. Pruitt, "Testimony to National Academy of Science Committee on Solid State Lighting," Washington, DC, November 2015.

[35] National Electrical Manufacturers Association, "LED A-Line Lamp Shipments Posted Another Strong Quarter to Close 2015," 29 February 2016. [Online]. Available: https://www.nema.org/news/Pages/LED-A-Line-Lamp-Shipments-Posted-Another-Strong-Quarter-to-Close-2015.aspx. [Accessed May 2016].

[36] Japanese Lighting Manufacturers Association, "Ministry of Economy, Trade and Industry production dynamics statistics," 2016. [Online]. Available: http://www.jlma.or.jp/tokei/pdf/kigu_tokei_nen.pdf.

[37] Japanese Lighting Manufacturers Association, "2016 production and sales statistics graphs: Lamps," 2016. [Online]. Available: http://www.jlma.or.jp/tokei/pdf/lamp_graph01.pdf.

[38] LEDinside, "Japan to Phase-out Incandescent and Fluorescent Lights by 2020," 27 November 2015. [Online]. Available: http://www.ledinside.com/news/2015/11/japan_to_phase_out_incandescent_and_fluorescent_lights_by_2020. [Accessed May 2016].

[39] China-LED, "2014 China LED general lighting industry market research report released," 12 February 2015. [Online]. Available: http://www.china-led.net/news/201502/12/18491.html. [Accessed May 2015].

[40] China-LED, "2015, China's semiconductor lighting industry and development survey data," 31 December 2015. [Online]. Available: http://www.china-led.net/news/201512/31/31868.html. [Accessed May 2016].

[41] China-LED, "LED industry overcapacity, 4000 LED Companies exit from the market," 14 December 2015. [Online]. Available: http://www.china-led.net/news/201512/14/31661.html. [Accessed May 2016].

[42] China-LED, "LED Price War, There are No Winners," 15 February 2016. [Online]. Available: http://www.china-led.net/news/201602/15/32343.html. [Accessed May 2016].

[43] China-LED, "Silicon substrate LED industry will become a new growth pole of Jiangxi Province Industrial," 15 February 2016. [Online]. Available: http://www.china-led.net/news/201602/15/32338.html. [Accessed May 2016].

[44] China Association of Lighting Industry, "2015 LED Products Exported to Ten," 11 March 2016. [Online]. Available: http://www.cali-light.com/cali/news/0311_18446.html. [Accessed May 2016].

[45] China-LED, "State Data to See Opportunities: Which Countries Receive LED Lighting Industry Exports?," 16 May 2015. [Online]. Available: http://www.china-led.net/news/201605/16/33539.html. [Accessed May 2016].

[46] ELCOMA, "PM Launches National Programme For LED-Based Home And Street Lighting," 7 January 2015. [Online]. Available: http://www.elcomaindia.com/pm-launches-national-programme-for-led-based-home-and-street-lighting. [Accessed May 2016].

[47] S. Sujan, "LED, the Future of Lighting in India," in *ISA International SSL Forum*, Guangzhou, China, June 2015.

[48] India Times, "LED Bulb Prices in Range of Rs 75-95: EESL," 5 April 2016. [Online]. Available: http://articles.economictimes.indiatimes.com/2016-04-05/news/72070430_1_eesl-rs-204-rs-104. [Accessed May 2016].

[49] LEDinside, "Jharkhand State in India Gives out More than 30,000 LED Bulbs Daily," 14 March 2016. [Online]. Available: http://www.ledinside.com/news/2016/3/jharkhand_state_in_india_gives_out_more_than_30000_led_bulbs_daily. [Accessed May 2016].

[50] Snapdeal, "Snapdeal Partners with EESL for the Domestic Efficient Lighting Program (DELP), a Government of India Initiative," 2016. [Online]. Available: http://www.snapdeal.com/offers/delp-led. [Accessed May 2016].

[51] EESL, "National Ujala Dashboard: Total LEDs distributed as on May 19, 2016," Government of India Ministry of Power, [Online]. Available: http://www.ujala.gov.in/. [Accessed 19 May 2016].

[52] EESL, "SLNP Dashboard: Total Streetlight Completed as on May 19, 2016," Government of India Ministry of Power, 19 May 2016. [Online]. Available: http://www.eeslindia.org/slnp/. [Accessed May 2016].

[53] ELCOMA, "ELCOMA Vision 2020," 2014. [Online]. Available: http://www.elcomaindia.com/wp-content/uploads/ELCOMA-Vision-2020.pdf. [Accessed May 2016].

[54] OSRAM, "Osram Announces Name of Lamps Business: LEDVANCE," 15 January 2016. [Online]. Available: http://www.osram.com/osram_com/press/press-releases/_business_financial_press/2016/osram-announces-name-of-lamps-business-ledvance/index.jsp. [Accessed May 2016].

[55] New York Times, "Philips to Pursue I.P.O. of Lighting Business in Amsterdam," 3 May 2016. [Online]. Available: http://www.nytimes.com/2016/05/04/business/dealbook/philips-to-pursue-ipo-of-lighting-business-in-amsterdam.html?_r=0. [Accessed May 2016].

[56] OSRAM, "Investments of About €3 Billion Create New Growth Prospects for Osram," 10 November 2015. [Online]. Available: http://www.osram.com/osram_com/press/press-releases/_business_financial_press/2015/investments-of-about-3-billion-create-new-growth-prospects-for-osram/index.jsp?mkturl=q42015_1. [Accessed May 2016].

[57] Netherlands Times, "Philips Lighting IPO on May 27 Valued at up to €3.4 Billion," 16 May 2016. [Online]. Available: http://www.nltimes.nl/2016/05/16/philips-lighting-ipo-may-27-valued-e3-4-billion/. [Accessed May 2016].

[58] Bloomberg, "Philips Said to Face Headwinds on Sale of Lighting Business," 2 February 2016. [Online]. Available: http://www.bloomberg.com/news/articles/2016-02-02/philips-said-to-face-headwinds-on-sale-of-lighting-business. [Accessed May 2016].

[59] European Council for an Energy Efficient Economy, "EC Confirms: Mains-Voltage Directional Halogen Lamps to be Phased out September 2016," 15 September 2015. [Online]. Available: http://www.eceee.org/all-news/news/news-2015/2015-09-15a. [Accessed May 2016].

[60] European Commision, "Phase-Out of Inefficient Lamps Postponed to 1 September 2018," 17 April 2015. [Online]. Available: https://ec.europa.eu/energy/en/news/phase-out-inefficient-lamps-postponed-1-september-2018. [Accessed May 2016].

[61] Lighting Europe, "Lighting Europe Guidance Document on Commision Regulation (EU) 2015/1428 of 25 August 2015," 10 December 2015. [Online]. Available: http://www.lightingeurope.org/uploads/files/LE_Special_Purpose_Lamps_Position.pdf. [Accessed May 2016].

[62] VITO, "Preparatory Study on Light Sources for Ecodesign and/or Energy Labelling Requirements: Final Report, Task 7," 31 October 2015. [Online]. Available: http://ecodesign-lightsources.eu/sites/ecodesign-lightsources.eu/files/attachments/LightSources%20Task7%20Final%2020151031.pdf. [Accessed May 2016].

[63] ATKearney, "Investment and Finance Study for Off-Grid Lighting," June 2014. [Online]. Available: http://docplayer.net/423352-Investment-and-finance-study-for-off-grid-lighting.html. [Accessed May 2016].

[64] E. Mills, "Health and Safety Benefits of Modern Off-grid Lighting," Lawrence Berkeley National Laboratory, 2015. [Online]. Available: https://www.lightingglobal.org/wp-content/uploads/bsk-pdf-manager/104_mills-health-lighting.pdf. [Accessed May 2016].

[65] Bloomberg New Energy Finance and Lighting Global, "Off-Grid Solar Market Trends Report 2016," February 2016. [Online]. Available: http://www.gogla.org/sites/www.gogla.org/files/archive/2016/03/Off-Grid-Solar-Market-Trends-Report-2016.pdf. [Accessed May 2016].

[66] E. Biery, "Creating Value Through Controls," DOE SSL R&D Workshop, San Francisco, CA, 27 January 2015. [Online]. Available: http://www.energy.gov/sites/prod/files/2015/02/f19/biery_controls_sanfrancisco2015.pdf. [Accessed May 2016].

[67] G. Arnold, "Why Lighting Systems Need to Evolve," DOE Connected Lighting Systems Meeting, Portland,OR,

November 2015. [Online]. Available: http://energy.gov/sites/prod/files/2015/11/f27/arnold_whyevolve_portland2015.pdf. [Accessed May 2016].

[68] T. Griffiths, "Integrating the Internet of Awareness into our smart SSL systems (MAGAZINE)," LEDs Magazine, 23 February 2015. [Online]. Available: http://www.ledsmagazine.com/articles/print/volume-12/issue-2/features/connectivity/integrating-the-internet-of-awareness-into-our-smart-ssl-systems.html. [Accessed May 2016].

[69] M. Poplawski, "Control System Interoperability: Can We Talk?," DOE SSL Market Introduction Workshop, Detroit, MI, 13 November 2014. [Online]. Available: http://energy.gov/sites/prod/files/2014/11/f19/poplawski_interoperability_detroit2014.pdf. [Accessed May 2016].

[70] Wink, "Wink: A Simpler Way to a Smarter Home," [Online]. Available: http://www.wink.com/. [Accessed May 2016].

[71] H. Prasad, "Intelligent Cities," DOE SSL R&D Workshop, Raleigh, NC, February 2016. [Online]. Available: http://energy.gov/sites/prod/files/2016/02/f29/prasad_connected_raleigh2016.pdf. [Accessed May 2016].

[72] GE Lighting, "LightGrid™ Outdoor Wireless Control System," 2016. [Online]. Available: http://www.gelighting.com/LightingWeb/na/solutions/control-systems/lightgrid-outdoor-wireless-control-system.jsp. [Accessed May 2016].

[73] M. Hansen, Interviewee, *Personal Corrspondance with Philips Lighting.* [Interview]. May 2016.

[74] Cisco, "Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2015–2020," 1 February 2016. [Online]. Available: http://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/mobile-white-paper-c11-520862.html. [Accessed May 2016].

[75] P. Jauregui, "Exploring and Addressing Security Risk in Smart Lighting Systems," in *Strategies in Light*, Las Vegas, NV, 2015.

[76] Cree, "Cree® XLamp® XT-E LEDs Datasheet," [Online]. Available: http://www.cree.com/~/media/Files/Cree/LED%20Components%20and%20Modules/XLamp/Data%20and%20Binning/XLampXTE.pdf. [Accessed May 2016].

[77] P. C. Hung and J. Y. Tsao, "Maximum white luminous efficacy of radiation versus color rendering index and color temperature: exact results and a useful analytic expression," *Journal of Display Technology,* vol. 9, no. 6, pp. 405-412, 2013.

[78] J. Y. Tsao, M. E. Coltrin, M. H. Crawford and J. A. Simmons, "Solid-State Lighting: An Integrated Human Factors, Technology, and Economic Perspective," *Proceedings of the IEEE,* vol. 98, no. 7, July 2010.

[79] E. Nelson, I. Wildeson and P. Deb, "Efficacy Droop in c-plane AlInGaN LEDs," DOE SSL R&D Workshop, Raleigh, NC, February 2016. [Online]. Available: http://energy.gov/sites/prod/files/2016/02/f29/nelson_leddroop_raleigh2016_0.pdf. [Accessed May 2016].

[80] P. Pattison, J. Tsao and M. Krames, "Lighting-Emitting-Diode Technology Status and Directions: Opportunities for Horticultural Lighting," *Acta Horticulturae,* vol. VIII International Symposium on Light in Horticulture, May 2016.

[81] B. Hahn, "Closing the Green Efficiency Gap... Status and Recent Approaches," DOE SSL R&D Workshop, Raleigh, NC, February 2016. [Online]. Available: http://energy.gov/sites/prod/files/2016/02/f29/hahn_leddroop_raleigh2016.pdf. [Accessed May 2016].

[82] Philips, "Details of the 200lm/W TLED Lighting Technology Breakthrough Unraveled," 11 April 2013. [Online]. Available: http://www.newscenter.philips.com/main/standard/news/articles/20130411-details-of-the-200lm-w-tled-lighting-technology-breakthrough-unraveled.wpd#.VWiVYM9Viko. [Accessed May 2016].

[83] Cree, "Cree Shatters Efficiency Benchmark with First 200-Lumen-Per-Watt LED Luminaire," 23 January 2014. [Online]. Available: http://www.cree.com/News-and-Events/Cree-News/Press-Releases/2014/January/200-LPW-fixture. [Accessed May 2016].

[84] OSRAM, "Osram constructs the world's most efficient LED lamp," 28 March 2014. [Online]. Available:

http://www.osram.com/osram_com/press/press-releases/_trade_press/2014/osram-constructs-the-worlds-most-efficient-led-lamp/index.jsp. [Accessed May 2016].

[85] Lumileds, "Luxeon T Datasheet," 2015. [Online]. Available: http://www.lumileds.com/uploads/383/PB106-pdf. [Accessed May 2016].

[86] Lumileds, "Luxeon XR-TX Datasheet," 2016. [Online]. Available: http://www.lumileds.com/uploads/598/PB160-pdf. [Accessed May 2016].

[87] Seoul Semiconductors, "Acrich2.5 - 30W Datasheet," 2 October 2015. [Online]. Available: http://www.seoulsemicon.com/_upload/Goods_Spec/SMJQ13XXFNSX_Rev1.5.pdf. [Accessed May 2016].

[88] Seoul Semiconductor, "Acrich3 - Indoor Monules," 1 April 2016. [Online]. Available: http://www.seoulsemicon.com/_upload/Goods_Spec/Specification_SMJE-XD12W4PD_Rev1.2.pdf. [Accessed May 2016].

[89] Frost and Sullivan, "Frost and Sullivan Honours Cambridge Nanotherm for its Chip on Heat Sink Technology for Thermal Management," 19 December 2013. [Online]. Available: http://www.best-practices.frost-multimedia-wire.com/cam-2013. [Accessed May 2016].

[90] S. Haque, "Wafer Scale Packagin Manufacturing Challenges," DOE SSL R&D Workshop, Raleigh, NC, February 2016. [Online]. Available: http://energy.gov/sites/prod/files/2016/02/f29/haque_led-mfg_raleigh2016.pdf. [Accessed May 2016].

[91] Samsung, "Samsung Introduces Full Line-up of LED Components Based on Chip-Scale Packaging Technology," 14 March 2016. [Online]. Available: http://www.samsung.com/us/samsungsemiconductor/media-center/index.html. [Accessed May 2016].

[92] Illuminating Engineering Society, "LM-80-08: Measuring Lumen Maintenance of LED Light Sources," 2008.

[93] Illuminating Engineering Society, "TM-21-11: Projecting Long Term Maintenance of LED Light Sources," 2011.

[94] M. Hansen, "The True Value of LED Packages," in *Strategies in Light*, Las Vegas, NV, February 2015.

[95] M. Hansen, "Package Impact on Color Shift in LEDs," in *Strategies in Light*, Santa Carla, CA, March 2016.

[96] LED Systems Reliability Consortium, "LED Luminaire Lifetime: Recommendations for Testing and Reporting, Third Edition," September 2014. [Online]. Available: http://www1.eere.energy.gov/buildings/ssl/pdfs/led_luminaire_lifetime_guide_sept2014.pdf. [Accessed May 2016].

[97] L. Davis, "Accelerated Life Testing Results for SSL Luminaire Electronics," DOE SSL R&D Workshop, San Francisco, CA, January 2015. [Online]. Available: http://www.energy.gov/sites/prod/files/2015/02/f19/davis-l_reliability_sanfrancisco2015.pdf. [Accessed May 2016].

[98] LEDs Magazine, "Philips Delivers Brighter OLED panels, Drives Cost Down (UPDATED)," 14 October 2014. [Online]. Available: http://www.ledsmagazine.com/articles/2014/10/philips-delivers-brighter-oled-panels-drives-cost-down.html. [Accessed May 2016].

[99] LG Chem, "LG Chem Exhibits the World's Top Performing OLED Light Panels at Light and Building 2014," 1 April 2014. [Online]. Available: http://www.lgchem.com/global/lg-chem-company/information-center/press-release/news-detail-623. [Accessed May 2016].

[100] LEDinside, "Panasonic to Shutdown OLED Business," 1 April 2014. [Online]. Available: http://www.ledinside.com/news/2014/4/panasonic_to_shutdown_oled_business. [Accessed May 2016].

[101] OLED-info, "LG Display Acquires LG Chem's OLED Lighting Business," 19 October 2015. [Online]. Available: http://www.oled-info.com/lg-display-acquires-lg-chems-oled-lighting-business. [Accessed May 2016].

[102] OLEDWorks, "OLEDWorks Finalizes Acquisition of Key Parts of Philips' OLED Light Source Components Business," 2 November 2015. [Online]. Available: https://www.oledworks.com/news/oledworks-finalizes-acquisition-of-key-parts-of-philips-oled-light-source-components-business/. [Accessed May 2016].

[103] T. Reusch, "OLED for Automobile Applications," DOE SSL R&D Workshop, Raleigh, NC, February 2016.

[Online]. Available: http://energy.gov/sites/prod/files/2016/02/f29/reusch_application_raleigh2016.pdf. [Accessed May 2016].

[104] OSRAM, "ORBEOS SDW-058+: The Next Step to General Lighting," 2014. [Online]. Available: http://www.osram-oled.com/oled/en/products/orbeos-sdw-058-plus/index.jsp. [Accessed May 2016].

[105] DOE SSL Program, "GATEWAY Demonstrations: OLED Lighting in the Offices of Aurora Lighting Design, Inc.," March 2016. [Online]. Available: http://energy.gov/sites/prod/files/2016/04/f30/2016_gateway_aurora-oled.pdf. [Accessed May 2016].

[106] OLED-info, "Konica Minolta break their own record with world's most efficient OLED panel (139 lm/W)," 7 June 2014. [Online]. Available: http://www.oled-info.com/konica-minolta-break-their-own-record-worlds-most-efficient-oled-panel-139-lmw. [Accessed May 2015].

[107] T. Komoda, "Key Technologies for Realization of High Efficient White OLED for Lighting Application," in *China International OLEDs Summit*, Shanghai, China, January 2015.

[108] LG Display, "LG Display OLED Light Catalog," 2016. [Online]. Available: http://www.lgoledlight.com/resources/LG_Display_OLED_light_Catalogue.pdf. [Accessed May 2016].

[109] OLEDWorks, "Brite 2 Shines," March 2016. [Online]. Available: https://www.oledworks.com/products/brite-2/. [Accessed May 2016].

[110] T. Komoda, "Overview of White OLED Technologies for Lighting Application," in *Printed Electronics USA*, Santa Clara, CA, November 2014.

[111] OLEDWorks, "Lumiblade OLED Panel Brite FL300 ww Datasheet," April 2016. [Online]. Available: https://www.oledworks.com/wp-content/uploads/2016/04/Data-sheet-Lumiblade-OLED-Panel-Brite-FL300-ww-1.pdf. [Accessed May 2016].

[112] LG Chem, "OLED Light Panel: User Guide v1.0," [Online]. Available: http://www.plusopto.co.uk/cms/uploads/LG_Chem_OLED_Light_User_Guide.pdf. [Accessed May 2016].

[113] Y. Kondakov, T. D. Pawlik, T. K. Hatwar and J. P. Spindler, "Triplet annihilation exceeding spin statistical limit in highly efficiency fluorescent organic light emitting diodes," *Journal of Applied Physics,* vol. 106, no. 124510, 2009.

[114] M. Thompson, "OLED Materials," DOE SSL R&D Workshop, San Francisco, CA, February 2016. [Online]. Available: http://energy.gov/sites/prod/files/2016/02/f29/thompson_oledmtrls_raleigh2016.pdf. [Accessed May 2016].

[115] T. Furukawa, H. Nakanotani, M. Inoue and C. Adachi, "Dual Enhancement of Electroluminescence Efficiency and Operational Stability by Rapid Upconversion of Triplet Excitons in OLEDs," *Scientific Reports,* vol. 5, no. 8429, 2015.

[116] H. Nakanotani, K. Masui, J. Nishide, T. Shibata and C. Adachi, "Promising Operational Stability of High-Efficiency Organic Light-Emitting Diodes Based on Thermally Activated Delayed Fluorescence," *Scientific Reports,* vol. 3, no. 2127, 2013.

[117] M. Kim, S. Jeon, S. Hwang and Y. Lee, "Stable Blue Thermally Activated Delayed Fluorescent Organic Light-Emitting Diodes with Three Times Longer Lifetime than Phosphorescent Organic Light-Emitting Diodes," *Advanced Materials,* vol. 27, no. 15, pp. 2515-2520, 2015.

[118] T. Baumann, "Blue TADF emitters for efficient display and lighting," DOE SSL R&D Workshop, Raleigh, NC, February 2016. [Online]. Available: http://energy.gov/sites/prod/files/2016/02/f29/baumann_oledmtrls_raleigh2016.pdf. [Accessed May 2016].

[119] OLED-info, "The EU launches a new project to commercialize TADF OLED emitters," 19 March 2015. [Online]. Available: http://www.oled-info.com/eu-launches-new-project-commercialize-tadf-oled-emitters. [Accessed May 2016].

[120] J. Li, "Efficient and Stable OLEDs Employing Square Planar Metal Complexes and Inorganic Nanoparticles," DOE SSL R&D Plan, Raleigh, NC, February 2016. [Online]. Available: http://energy.gov/sites/prod/files/2016/02/f29/li_oledmtrls_raleigh2016.pdf. [Accessed May 2016].

[121] T. Komoda, K. Yamae, V. Kittichungchit, H. Tsuji and N. Ide, "Extremely High Performance White OLEDs for Lighting," *SID Symposium Digest of Technical Papers,* vol. 43, no. 1, pp. 610-613, June 2012.

[122] K. Yamae, H. Tsuji, V. Kittichungchit, Y. Matsuhisa, S. Hayashi, N. Ide and T. Komoda, "High-Efficiency White OLEDs with Built-up Outcoupling Substrate," *SID Symposium Digest of Technical Papers,* vol. 43, no. 1, pp. 694-697, June 2012.

[123] M. Furno, R. Meerheim, S. Hofmann, B. Lüssem and K. Leo, "Efficiency and Rate of Spontaneous Emission in Organic Electroluminescent Devices," *Physical Review B,* vol. 85, no. 11, p. 115205, March 2012.

[124] W. Brütting, J. Frischeisen, T. Schnidt, B. Scholz and C. Mayr, "Device Efficiency of Organic Light-Emitting Diodes: Progress by Improved Light Outcoupling," *Physica Status Solidi A,* vol. 210, no. 1, pp. 44-65, 2013.

[125] OLED-info, "New microfabrication technology can enhance OLED light extraction efficiency," 2012. [Online]. Available: http://www.oled-info.com/new-microfabrication-technology-can-enhance-oled-light-extraction-efficiency. [Accessed April 2016].

[126] S. Murano, D. Pavicic, M. Furno, C. Rothe, T. W. Canzler, A. Haldi, F. Löser, O. Fadhel, F. Cardinali and O. Langguth, "Outcoupling Enhancement Mechanism Investigation on Highly Efficient PIN OLEDs using Crystallizing Evaporation Processed Organic Outcoupling Layers," *SID Symposium Digest of Technical Papers,* vol. 43, no. 1, pp. 687-690, June 2012.

[127] W. H. Koo, S. M. Jeong, F. Araoka, K. Ishikawa, S. Nishimura, T. Toyooka and H. Takezoe, "Light Extraction from Organic Light-Emitting Diodes Enhanced by Spontaneously Formed Buckles," *Nature Photonics,* vol. 4, pp. 222-226, February 2010.

[128] W. H. Koo, S. M. Jeong, F. Araoka, K. Ishikawa, S. Nishimura, T. Toyooka and H. Takezoe, "Polarization Conversion in Surface-Plasmon-Coupled Emission from Organic Light-Emitting Diodes Using Spontaneously Formed Buckles," *Advanced Materials,* vol. 23, no. 8, pp. 1003-1007, 2011.

[129] W. H. Koo, W. Youn, P. Zhu, X. H. Li, N. Tansu and F. So, "Light Extraction of Organic Light Emitting Diodes by Defective Hexagonal-Close-Packed Array," *Advanced Functional Materials,* vol. 22, no. 16, pp. 3454-3459, 2012.

[130] L. H. Smith and W. L. Barnes, "Using a low-index host layer to increase emission from organic light-emitting diode structures," *Organic Electronics,* vol. 7, no. 6, pp. 490-494, 2006.

[131] G. Cooper and G. Chen, "Light Extraction for OLEDs," DOE SSL R&D Workshop, San Francisco, CA, 28 January 2015. [Online]. Available: http://www.energy.gov/sites/prod/files/2015/02/f19/cooper_oled-integration_sanfrancisco2015.pdf. [Accessed April 2016].

[132] DOE SSL Program, "Advanced Light Extraction Structure for OLED Lighting," *2016 DOE SSL Project Portfolio,* p. 39, January January 2016.

[133] B. Scholz, "OLED Materials," *Optics Express,* vol. 20, no. A205, 2012.

[134] LG Chem, "LG Chem OLED Light Brochure: You Create. We Light.," 2015. [Online]. Available: http://www.dnaoled.cz/download/panels/2015-lg-oled-brochure.pdf. [Accessed May 2016].

[135] M. Lu, "OLED Lighting - Poised to Take Off," DOE SSL R&D Workshop, San Francisco, CA, January 2015. [Online]. Available: http://www.energy.gov/sites/prod/files/2015/02/f19/lu_oled_sanfrancisco2015.pdf. [Accessed May 2016].

[136] OLED-info, "Lumiotec's new P09 OLED lighting panels feature 45 lm/W, 40,000 hours lifetime," 2 February 2014. [Online]. Available: http://www.oled-info.com/lumiotecs-new-p09-oled-lighting-panels-feature-45-lmw-40000-hours-lifetime. [Accessed May 2016].

[137] LG Display, "LG Display OLED Light with High CRI," 2016. [Online]. Available: http://www.lgoledlight.com/video/lg-chem-oled-light-with-high-cri.do. [Accessed May 2016].

[138] OLEDWorks, "Brite 2 FL300 Family," March 2016. [Online]. Available: https://www.oledworks.com/wp-content/uploads/2016/03/Product-sheet-Lumiblade-OLED-Panel-Brite-2-FL300-family-preliminary-March-2016.pdf. [Accessed May 2016].

[139] M. Lu, "Hybrid OLED/LED Luminaires," in *OLED Stakeholder Meeting*, Pittsburgh, PA, September, 2015.

[140] Corning, "Corning Announces Collaboration with OLEDWorks," 13 April 2015. [Online]. Available: https://www.corning.com/asean/en/about-us/news-events/news-releases/2015/04/news_center_news_releases_2015_2015041301.html. [Accessed May 2016].

[141] K. Minolta, "OLED Installation," 2016. [Online]. Available: http://www.konicaminolta.com/oled/products/illumination.html. [Accessed May 2016].

[142] OLEDWorks, "Lumiblade Compatible Drivers," 2016. [Online]. Available: https://www.oledworks.com/products/lumiblade-compatible-drivers/. [Accessed May 2016].

[143] LG Display, "You Create We Light," 2015. [Online]. Available: http://www.lgoledlight.com/index.do. [Accessed May 2016].

[144] Astel Lighting, "Interior OLED Lights: Versa," 2016. [Online]. Available: http://www.astel-lighting.com/interior-oled-lights/105-versa.html. [Accessed May 2016].

[145] Fraunhofer FEP, "Transparent Color Tunable OLED," 5 February 2015. [Online]. Available: http://www.fep.fraunhofer.de/content/dam/fep/de/documents/Presse_Medien_JB/2015/Pressemitteilung_01_2015_EN.pdf. [Accessed May 2016].

[146] Konica Minolta, "Konica Minolta to Showcase OLED Lighting Panels, World's Thinnest and with World's First Color Tunable Function for Flexible Type," 12 February 2014. [Online]. Available: http://www.konicaminolta.com/about/releases/2014/0212_01_01.html. [Accessed May 2016].

[147] Universal Display Corporation, "Universal Display Corporation Presents OLED Display and Lighting Technology Advances," 5 June 2014. [Online]. Available: http://s2.q4cdn.com/831534118/files/doc_news/2014/OLED_News_2014_6_5_General_Releases.pdf. [Accessed May 2016].

[148] MC Pioneer, "Specifications of OLED Lighting Modules with Adjustable Color and Brightness," 2016. [Online]. Available: http://mcpioneer-oled.co.jp/en/product/color_feature/color_specification/. [Accessed May 2016].

[149] Universal Display Corporation, "Transparent OLEDs," [Online]. Available: http://www.udcoled.com/default.asp?contentID=608. [Accessed May 2016].

[150] Samsung, "Samsung Drives Connected, Dynamic Viewing Experiences with New Lineup of SMART Signage Solutions at DSE 2016," 17 March 2016. [Online]. Available: https://news.samsung.com/us/2016/03/17/samsung-drives-connected-dynamic-viewing-experiences-new-lineup-smart-signage-solutions-dse-2016/. [Accessed May 2016].

[151] UBI Research, "Transparent OLED Display Report 2016," 31 December 2015. [Online]. Available: http://www.ubiresearch.com/transparent_oled_display/. [Accessed May 2016].

[152] Fraunhofer FEP, "Full-Plastic OLED Lighting," OLED-Info, 6 April 2016. [Online]. Available: https://www.youtube.com/watch?v=CVtqpoGVWvM. [Accessed May 2016].

[153] Corning, "Corning and OLEDWorks Announce OLED Lighting Design Open Innovation Contest," 8 April 2016. [Online]. Available: https://www.corning.com/worldwide/en/about-us/news-events/news-releases/2016/04/corning-announces-oled-lighting-design-open-innovation-contest.html. [Accessed May 2016].

[154] D. Hulsey, "Developing OLED Lighting Products," DOE SSL R&D Workshop, Raleigh, NC, February 2016. [Online]. Available: http://energy.gov/sites/prod/files/2016/02/f29/hulsey_oledproducts_raleigh2016.pdf. [Accessed May 2016].

[155] J. Qiu, "OLED Luminaire Design Challenges," DOE SSL R&D Workshop, Raleigh, NC, February 2016. [Online]. Available: http://energy.gov/sites/prod/files/2016/02/f29/qiu_oledproducts_raleigh2016.pdf. [Accessed May 2016].

[156] N. DeMattia, "WORLD PREMIERE: BMW M4 GTS with 493 Horsepower," BMWBlog, 6 October 2015. [Online]. Available: http://www.bmwblog.com/2015/10/06/world-premiere-bmw-m4-gts-with-493-horsepower/. [Accessed May 2016].

[157] OSRAM, "R2D2 – Research Consortium for flexible OLEDs in Germany," 2015. [Online]. Available:

http://www.osram-oled.com/oled/en/news-and-knowledge/funded-projects/r2d2/index.jsp. [Accessed May 2016].

[158] GE Lighting, "Lumination LED Luminaires," 2012. [Online]. Available: http://www.gelighting.com/LightingWeb/aus/products/luminaires/lumination-led/overview/. [Accessed May 2016].

[159] Maxlite, "Direct Lit LED 2x2 Flat Panel Data Sheet," March 2015. [Online]. Available: http://site.takethreelighting.com/downloads/DataSheet_MLFP22DS4035.PDF. [Accessed May 2016].

[160] Lighting Inspiration, "Cooledge Flexible Light Sheet," 2016. [Online]. Available: http://www.lighting-inspiration.com/project/office/#prettyPhoto. [Accessed May 2016].

[161] U. Hoffman, "Manufacturing of High Quality OLED," in *China International OLED Summit*, Beijing, 2015.

[162] Konica Minolta, "Konica Minolta Constructs Plant for World's First Mass Production of Plastic Substrate Flexible OLED Lighting Panels," 18 March 2014. [Online]. Available: http://www.konicaminolta.com/about/releases/2014/0318_01_01.html. [Accessed May 2016].

[163] OLED-info, "Konica Minolta to build a flexible OLED lighting R2R fab with a monthly capacity of 1 million panels," 18 March 2014. [Online]. Available: http://www.oled-info.com/konica-minolta-build-flexible-oled-lighting-r2r-fab-monthly-capacity-1-million-panels. [Accessed May 2016].

[164] Konica Minolta, "OLED Lighting Examples: Tulips," January 2015. [Online]. Available: http://www.konicaminolta.com/oled/user_case/. [Accessed May 2016].

[165] Corning, "Our Products," 2015. [Online]. Available: http://www.corning.com/worldwide/en/products/display-glass.html. [Accessed April 2016].

[166] P. Groen, "Roll-to-Roll Processing for Solution Processed OLED Devices," DOE SSL Workshop, San Francisco, CA, 28 January 2015. [Online]. Available: http://www.energy.gov/sites/prod/files/2015/02/f19/groen_r2r-oled_sanfrancisco2015.pdf. [Accessed May 2016].

[167] C. Brown, "Inkjet Technology for OLED SSL Mass Production," DOE SSL R&D Workshop, San Francisco, CA, 28 January 2015. [Online]. Available: http://www.energy.gov/sites/prod/files/2015/02/f19/brown-madigan_inkjet_sanfrancisco2015.pdf. [Accessed May 2016].

[168] Veeco, "Fast-ALD for Flexible OLED Displays," [Online]. Available: http://www.veeco.com/products/ald-systems.aspx. [Accessed May 2016].

[169] N. Morrison, "Packaging of Moisture Sensitive Materials Used in New Form Factor Display Products," in *Flextech Alliance Flexible and Printed Electronics Conference 2016*, Monterey, CA, March 2016.

[170] D. Veri and M. Burger, "Breakthroughs in the Production of Flexible and Hybrid Electronics," in *Building the Innovation Ecosystem for Flexible Electronics*, Monterey, California, 2016.

[171] P. Mandlik, J. Gartside, L. Han, I.-C. Cheng, S. Wagner, J. A. Silvernail, R.-Q. Ma, M. Hack and J. J. Brown, "A single-layer permeation barrier for organic light-emitting displays," *Applied Physics Letters,* vol. 92, no. 103309, 2008.

[172] J. Kreis, "Cost Efficient OLED Manufacturing," in *Smithers Apex OLED World Summit*, Berkeley, CA, October 2015.

[173] LEDinside, "AIXTRON Sells Encapsulation Machine to Major Asian Display Manufacturer for OLED Barrier Film Deposition," 10 September 2015. [Online]. Available: http://www.ledinside.com/news/2015/9/aixtron_sells_encapsulation_machine_to_major_asian_display_manufacturer_for_oled_barrier_film_deposition. [Accessed May 2016].

[174] R. Prasad, "Transparent Barrier Films," in *DOE SSL Program OLED Stakeholder Meeting*, Pittsburgh, PA, September 2015.

[175] F. McCormick, "Light Extraction Films for OLED Solid State Lighting," DOE SSL R&D Workshop, Tampa, FL, January 2014. [Online]. Available: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/mccormick_extraction_tampa2014.pdf. [Accessed May 2016].

[176] T. Komoda, "Recent Progress and Future Trends of OLED Technologies for Lighting Applications," in *Smithers-Apex OLED World Summit*, Berkeley, CA, September 2014.

[177] D. Russel and A. Stabell, "White Paper: Scaling-up Pixelligent Nanocrystal Dispersions," Pixelligent Technologies, Baltimore, Maryland, 2016.

[178] G. Cooper, "Overview of Pixelligent's OLED Lighting Program," in *OLED World Summit*, Berkeley, CA, October 2015.

[179] W. Gaynor, "Poster Presentation," in *DOE SSL R&D Workshop*, Raleigh, NC, February 2016.

[180] E. Ruebingh, "Stepwise Process Optimization for Printing Electronics Manufacturing," in *IDTechEx Printed Electronics Europe*, Berlin, Germany, April 2014.

[181] M. Mastropietro, "Overview of Transparent Metal Mesh Electrode Technologies," DOE SSL R&D Workshop, San Francisco, CA, 29 January 2015. [Online]. Available: http://www.energy.gov/sites/prod/files/2015/02/f19/mastropietro_oled-mfg_sanfrancisco2015.pdf. [Accessed May 2016].

[182] C. Hung, "Manufacturing Process for OLED Integrated Substrate," in *DOE SSL R&D Workshop Poster Session*, Raleigh, NC, February 2016.

[183] Corning, "Thinness, Strength, and "Bend-ability" Render Visions of Wrap-around Displays," Corning, 2016. [Online]. Available: https://www.corning.com/worldwide/en/products/display-glass/products/corning-willow-glass.html. [Accessed 9 May 2016].

[184] OLED-info, "Nippon Electric Glass and Saint-Gobain Establish a New Japanese company to Develop and Make OLED Lighting Glass Substrate," 12 June 2014. [Online]. Available: http://www.oled-info.com/nippon-electric-glass-and-saint-gobain-establish-new-japanese-company-develop-and-make-oled-lighting. [Accessed May 2016].

[185] M. Dirjish, "OLEDs Get Ready to Break Size Barriers," Electronic Design, 28 February 2008. [Online]. Available: http://electronicdesign.com/displays/oleds-get-ready-break-size-barriers. [Accessed May 2016].

[186] DOE SSL Program, "Integrated Plastic Substrates for Organic Light Emitting Devices (OLED) Lighting," *2016 DOE SSL Project Portfolio,* p. 42, January 2016.

[187] B. Rand, "External vs. Internal OLED Outcoupling Strategies," DOE SSL R&D Workshop, Raleigh, NC, February 2016. [Online]. Available: http://energy.gov/sites/prod/files/2016/02/f29/rand_oled-substrates_raleigh2016.pdf. [Accessed May 2016].

[188] Q. Pei, "An Integrated OLED Substrate for Low-Cost and Enhanced Light Extraction," DOE SSL R&D Workshop, Raleigh, NC, February 2016. [Online]. Available: http://energy.gov/sites/prod/files/2016/02/f29/pei_oledsubstrates_raleigh2016.pdf. [Accessed March 2016].

[189] DOE SSL Program, "Shorting Reduction Layer Process Development for OLED Lighting Panels (Phase I)," *2016 DOE SSL Project Portfolio,* p. 37, January 2016.

[190] J. Hamer, "Poster Presentation," in *DOE SSL R&D Workshop*, Raleigh, NC, February 2016.

[191] Aixtron, "OVPD-200 Organic Vapor Phase Deposition," 15 December 2015. [Online]. Available: http://www.aixtron.com/fileadmin/documents/Technologien/AIX_Broschu___ere_OVPD_LOW_ES.pdf. [Accessed May 2016].

[192] Aixtron, "AIXTRON partners with Institut Lafayette on further advancement of organic deposition technology OVPD," April 2016. [Online]. Available: http://www.aixtron.com/en/press/press-releases/detail/detail/News/aixtron-und-institut-lafayette-entwickeln-gemeinsam-organische-depositionstechnologie-ovpd-weiter/. [Accessed May 2016].

[193] R. Mertens, "Kateeva finally unveil their YIELDjet OLED TV inkjet printing system," OLED-info, 2013. [Online]. Available: http://www.oled-info.com/kateeva-finally-unveil-their-yieldjet-oled-tv-inkjet-printing-system. [Accessed April 2016].

[194] C. Madigan, "Inkjet Technology for OLED Mass Production. From TFE to RGB: The Benefits of Scale," in *IDTech Printed Electronics*, Santa Clara, CA, November 2015.

[195] Sumitomo Chemical, "Sumitomo Chemical to Exibit Polymer OLED Lighting at Light and Building 2016," 15 February 2016. [Online]. Available: http://www.sumitomo-chem.co.jp/english/newsreleases/docs/20160215e.pdf. [Accessed May 2016].

[196] OLEDNet, "Sumitomo Chem. Aims for General Lighting Market with P-LED," 15 January 2016. [Online]. Available: http://www.olednet.com/en/sumitomo-chem-aims-for-general-lighting-market-with-p-led/?ckattempt=2. [Accessed May 2016].

[197] M. Riva, "The Encapsulation Question," in *OLED World Summit*, Berkeley, CA, October 2015.

[198] J. Kreis, "Scalable Deposition Technology for Barrier Films Yeilding Unique Material Property Set," in *OLEDs World Summit 2016*, San Diego, California, 2016.

[199] C. May, "Encapsulation and Integration of OLED on Flexible Substrates," in *Smithers Apex World Summit*, Berkeley, CA, October 2015.

[200] Industrial Technology Research Institute, "OLCA Aims to Lead the Next-Generation Solid-State Lighting Industrialization," 2014. [Online]. Available: https://www.itri.org.tw/eng/DM/PublicationsPeriods/620414544734011541/content/activity3.html. [Accessed May 2016].

[201] OLED-info, "Wisechip Blue-Light Free OLED Program Update," 15 December 2015. [Online]. Available: http://www.oled-info.com/wisechip-blue-light-free-oled-program-update. [Accessed May 2016].

[202] Electronics Weekly, "Taiwan's ITRI Building OLED Lighting Line," 16 April 2016. [Online]. Available: http://www.electronicsweekly.com/news/products/led/taiwans-itri-building-oled-lighting-line-2016-04/. [Accessed May 2016].

[203] B. Young, "Will OLEDs Achieve Their Potential," in *China International OLEDs Summit 2016*, Shanghai, China, January 2016.

[204] OLED Association, "DisplayMate Technologies Believes Apple Should Use OLEDs in iPhone 7," 3 May 2016. [Online]. Available: http://www.oled-a.org/news_details.cfm?ID=1360. [Accessed May 2016].

[205] OLED Association, "Truly Moves to Deploy OLED Production Resources," 17 May 2016. [Online]. Available: http://www.oled-a.org/news_details.cfm?ID=1395. [Accessed May 2016].

[206] OLED Association, "CSOT to invest US$7.74b in a Gen 11 LCD Fab," 19 April 2016. [Online]. Available: http://www.oled-a.org/news_details.cfm?ID=1335. [Accessed May 2016].

[207] OLED Association, "TV market Down 21% Y/Y in Q116," 3 May 2016. [Online]. Available: http://www.oled-a.org/news_details.cfm?ID=1361. [Accessed May 2016].

[208] LEDinside, "Samsung Display to Invest in OLED Production Line," 11 February 2015. [Online]. Available: http://www.ledinside.com/news/2015/2/samsung_display_to_invest_in_oled_production_line. [Accessed May 2016].

[209] OLED-info, "Reports suggest SDC aims to invest $3 billion in a new Gen-8 OLED TV fab," 18 February 2016. [Online]. Available: http://www.oled-info.com/reports-suggest-sdc-aims-invest-3-billion-new-gen-8-oled-tv-fab?utm_source=feedburner&utm_medium=feed&utm_campaign=Feed%3A+oled-info+%28OLED-Info%3A+OLED+tech+news+and+resources%29. [Accessed May 2016].

[210] Bloomberg Technology, "LG Display to Spend About $9 Billion on Factory for OLEDs," 26 November 2015. [Online]. Available: http://www.bloomberg.com/news/articles/2015-11-26/lg-display-to-spend-more-than-10-trillion-won-on-new-panel-plant. [Accessed May 2016].

[211] LG Display, "LG Display to Build World's First 5th Generation OLED Light Panel Plant," 17 March 2016. [Online]. Available: http://www.lgdisplay.com/eng/prcenter/newsView. [Accessed May 2016].

[212] G. Chansin, K. Ghaffarzadeh and H. Zervos, "OLED Display Forecasts 2016-2026: The Rise of Plastic and Flexible Displays," May 2016. [Online]. Available: http://www.idtechex.com/research/reports/oled-display-forecasts-2016-2026-the-rise-of-plastic-and-flexible-displays-000477.asp. [Accessed 2016 May].

[213] OLED-info, "Samsung Display to invest $325 million to double the capacity of its A3 flexible OLED line," 4 March 2016. [Online]. Available: http://www.oled-info.com/samsung-display-invest-325-million-double-capacity-its-a3-flexible-oled-line. [Accessed May 2016].

[214] D. Hsieh, "OLEDs from Emerging to Mainstream," in *China International OLEDs Summit 2016*, Shanghai, China, January 2016.

[215] UBI Research, "2016 OLED Emitting Material Annual Report," 20 April 2016. [Online]. Available: http://www.ubiresearch.com/2016-oled-emitting/. [Accessed May 2016].

[216] IHS, "Driven by TV Displays, Organic Light-Emitting Materials Used to Produce OLED Panels Grew 12 Percent in 2015, IHS Says," 18 February 2016. [Online]. Available: http://press.ihs.com/press-release/driven-tv-displays-organic-light-emitting-materials-used-produce-oled-panels-grew-12-p. [Accessed May 2016].

[217] OLEDNet, "UDC's 2015 OLED Emitting Materials Revenue $113 million, a 11% Decrease…Still Leading Market," 20 April 2016. [Online]. Available: http://www.olednet.com/en/udc-2015-materials/. [Accessed May 2016].

[218] M. Boroson, "High Performance OLED Panel and Luminaire Poster," in *DOE SSL R&D Workshop*, Raleigh, NC, January 2016.

[219] J. Brodrick, "R&D Program Direction," DOE SSL R&D Workshop, San Francisco, CA, 28 January 2015. [Online]. Available: http://www.energy.gov/sites/prod/files/2015/02/f19/brodrick_rd-update_sanfrancisco2015.pdf. [Accessed April 2016].