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

Solid-State Lighting

R&D Plan

May 2015

Prepared for:

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

DOE/EE-1228

DOE SSL Program, "R&D Plan," prepared by Bardsley Consulting, SB Consulting, SSLS, Inc., LED Lighting Advisors, and Navigant Consulting, Inc., May 2015.

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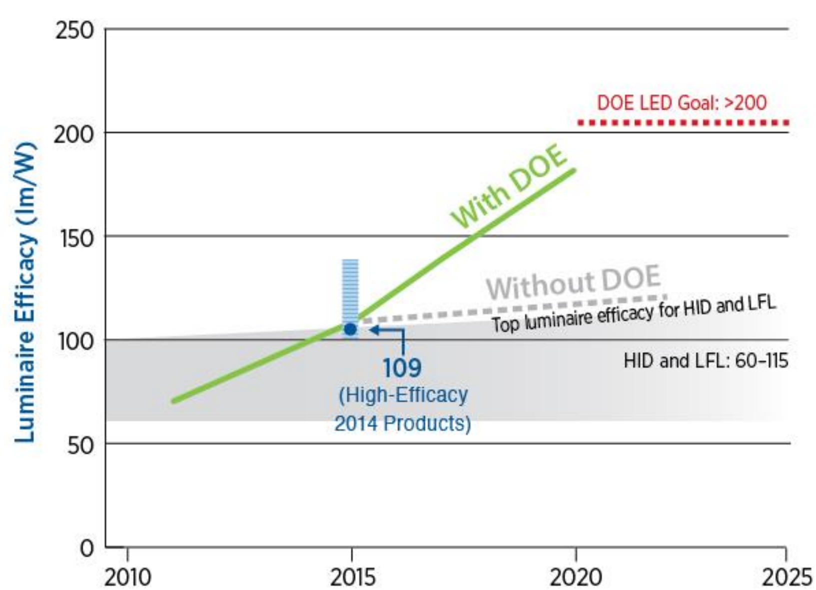
Executive Summary

The solid-state lighting (SSL) revolution signals a profound shift in how we will 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, a small fraction, less than 10%, of existing lighting installations use SSL products. For example, Strategies Unlimited estimates that in 2014, light-emitting diode (LED)-based lamps comprised just 5% of unit sales and achieved 3% penetration of the installed base [1]. Nevertheless, they forecast dramatic growth in this market such that by 2020 LED-based lamps would comprise 42% of unit sales and represent 33% of the installed base. Other forecasts also anticipate extraordinary growth over the next 5 to 10 years. By any measure these are dramatic growth projections and present significant challenges for the industry. These challenges include further efficiency improvement, continued price reduction, manufacturing scale-up, and the integration of new value and features that can accelerate adoption and provide further energy savings. Addressing these challenges also offers the U.S. the opportunity to secure a dominant role in the technology and manufacturing of these products.

In the U.S., LED lighting is forecasted to account for the majority of installations by 2030, representing 88% of the lumen-hours being generated by general illumination [2]. The high efficacy of SSL sources is a critical factor in the drive for higher adoption. LED lighting is already as efficient, or more efficient, than most incumbent technologies, but there is plenty more to come. Using fairly conservative projections for performance improvements, the Department of Energy (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 counter-factual "no-LED" scenario. Assuming the more aggressive projections, outlined in this report, can be realized through continuing investment in Research and Development (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 twenty times that of solar power in 2030. At an average

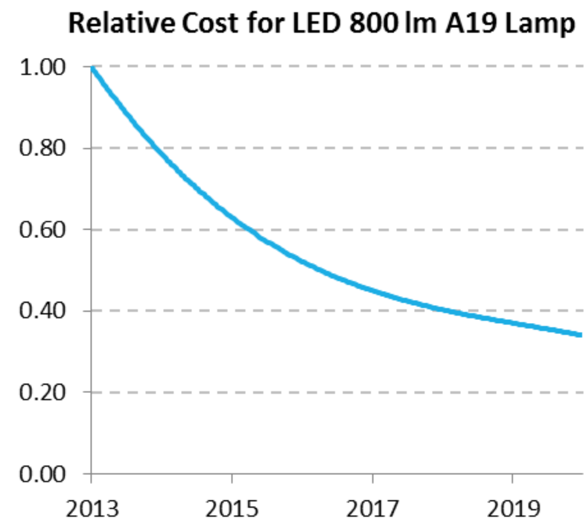


commercial price of $0.10/kilowatt-hour, this would correspond to an annual dollar savings of about $40 billion [2]. However, in order to reach the performance levels assumed in this analysis, substantial improvements to efficacy and pricing are necessary. This underscores the importance of SSL and SSL R&D in any discussion of energy policy, due to its unprecedented opportunity to reduce energy consumption, thereby improving domestic energy security, and reducing greenhouse gas emissions.

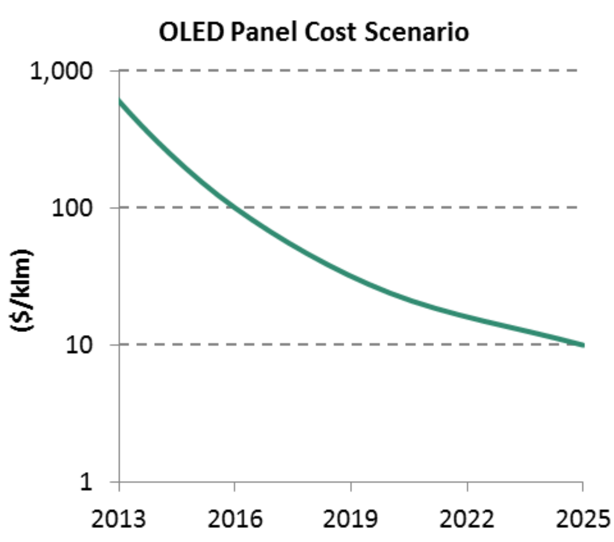
The DOE has set some tough targets and fashioned its program to remove technology barriers and accelerate adoption. DOE support is essential to achieving the 200 lumens per watt (lm/W) luminaire efficacy program goal by 2020, reducing SSL manufacturing costs, and realizing huge energy savings. To achieve these goals and maintain the pace of development of the underlying LED and organic light-emitting diode (OLED) device technologies, the DOE advocates continuous focus on R&D. It is already apparent that 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 and the need to develop new high efficiency, narrow line-width 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, and novel form factors. 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 create added 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 in the area of visible light communications, such as Li-Fi and 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. Control over the light spectrum is creating new opportunities in areas as diverse as horticulture and human health.

Understandably, 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 40 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 illuminance, 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 both LED and OLED technologies. LED package prices are down to $1/klm and OLED panels are down to $200/klm. The LED-based dimmable A19 60W-equivalent replacement lamp has dropped below $10 ($11/klm), still more expensive than conventional incandescent and compact fluorescent (CFL) lamps, but rebates and incentives can further reduce price to below $5. Market factors heavily influence prices, and the A19 replacement lamp remains the most competitive product sector while other products have shown less dramatic price reductions. 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, leading to payback periods of less than one year in certain high usage applications. Additionally, with the ability to provide new value added funcitonality, price parity is not a strict requirement.



The DOE SSL Program has developed a comprehensive R&D strategy to support advancements in SSL technology and maximize energy savings. This document, the DOE SSL 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 October 2014 and at the DOE SSL R&D Workshop, held in January 2015 in San Francisco, California. The plan reflects the consensus view of the community on key barriers, technology challenges to address and where R&D efforts are required 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.

As the technology matures and barriers are gradually addressed, the relative emphasis between core technology research, product development and manufacturing R&D changes, requiring the balance between these factors to be re-assessed on a regular basis. In the early stages of technology development, the focus is, generally, on core technology research which then shifts to product development as the technology matures and practical products become feasible. Next, a technology transfer phase occurs as the transition is made to full scale manufacturing, often through an initial pilot production phase. R&D continues to be required across all stages of the technology development from core to manufacturing, but the relative urgency will vary. In addition, ongoing research on the status of commercial products is necessary to identify and head off product disappointments.

Over the past five years, the manufacturing activity for LEDs has matured, and the R&D emphasis has started to shift back toward breaking down technology barriers than can provide step function improvements in cost and performance. These types of barriers require more fundamental technological development, requiring a shift back toward core and product development activities.

For OLEDs, the balance between these phases is more evenly distributed. One of the most critical issues relates to optimizing technology transfer into full scale manufacturing and therefore part of the focus remains on manufacturing R&D. Another part of the focus remains on certain technologies which are not yet completely developed but will be critical to achieving ultimate performance and cost goals. Therefore, the development and optimization of these critical technologies is handled in parallel with the establishment of an effective and efficient manufacturing capability.

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, stabile, and narrow linewidth materials.
- **Encapsulation materials:** targeting high refractive index and improved thermal stability.
- **Novel Emitter Architectures:** developing advanced device architectures for enhanced performance.
- **Higher Integration Levels:** investigating flexible integration of package, driver and optics elements.
- **Novel Luminaires:** developing luminaire concepts to achieve enhanced light distribution control, improved building integration, intuitive control, and enhanced lighting performance.

OLED-based Lighting R&D Priorities

- **Materials research:** developing high efficiency and long lifetime emitter systems, particularly for blue.
- **Light extraction:** developing cost effective and manufacturable light extraction solutions.
- **Luminaire development:** advancing key attributes of OLED technology to realize product differentiation and accelerate time to market.
- **Improved manufacturing technologies:** focusing on yield and reliability
- **Manufacturing on flexible substrates:** developing materials and processes for manufacturing on flexible substrates.

During the Roundtable and Workshop, there were other R&D initiatives highlighted as priorities that do not fit within the typical R&D funding opportunity announcement (FOA) framework. These may require longer term R&D, government led industry group cooperation, or may be outside of the FOA defined funding levels.

Additional R&D Priorities

- **Smart Controls and Sensors**
    - Investigate interoperability of lighting control, communication, and sensor platforms.
    - Develop systems for real-time energy monitoring and feedback
- **Power supply reliability and performance metrics**
- **LED and OLED system reliability**
- **Human physiological response to lighting including productivity benefits**
- **Light quality research and characterization**

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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 directed 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, is a consolidation of the DOE SSL Multi-Year Program Plan (MYPP) and the DOE SSL Manufacturing R&D Roadmap that DOE has published and updated in previous years.[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 will be updated annually to reflect ongoing progress towards the DOE SSL goals and the shifting R&D priorities that will have the biggest impact on achieving the program goals. The Appendices contain basic background 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 program. Details on the legislation and policies defining the program are not included in this document, but may be found elsewhere on the SSL website at www.ssl.energy.gov/about.html and www.ssl.energy.gov/partnerships.html.

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

2.0 Benefits of Solid-State Lighting

The initial drivers for the pursuit of LED and OLED SSL were the promise of high efficacy and the prospects of low cost (through the adoption of high volume processing technologies from the semiconductor industry for LEDs and the adoption of roll-to-roll processing technologies for OLEDs). While there is still considerable room for improvement, SSL is already fulfilling that promise as it continues to demonstrate ever-improved efficacy over conventional lighting sources and prices that enable a payback within reasonable time periods. These attributes have contributed to increasing adoption of SSL sources, already resulting in significant energy savings. In addition to improved efficacy, SSL sources 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 offers a huge opportunity to improve the performance and value of lighting and to create new paradigms. The ability to engineer the spectral output of an SSL source, both statically and dynamically, enables new lighting features, functions, and benefits that were not feasible with previous lighting technologies. LED and OLED lighting can be engineered to have specific spectral power distributions to match specific applications, including actively controllable spectral power distributions such that the spectrum of the emitted light can be dynamically controlled. For example, recent research has shown that humans have a physiological response to changes in the spectrum of daylight through the course of a day, and this changing spectrum can now be replicated with LED-based interior lighting [3]. LEDs can also be rapidly modulated (beyond human perception) which could enable the use of lighting as a communications medium. Visible light communication (VLC) incorporates a modulated light channel within the generated light for illumination to communicate between the lighting system and other electronic devices such as smart phones. All of this new lighting functionality, coupled with new wireless communications protocols, the ubiquity of smart phones, the emergence of home automation, the Internet of things, and large scale data collection and analytics will enable a vast new range of features that can be embedded into SSL products and expand the range of lighting applications.

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

2.1 Source Efficacy

LED luminaires are already more efficient than incandescent lamps, halogen lamps, compact fluorescent lamps (CFL), and most linear fluorescent luminaires, while initial OLED luminaire products have efficacy nearing that of CFLs. Table 2.1 shows a comparison between the price and performance of typical SSL products and conventional lighting technologies available at the end of 2014. The table shows that LED products are already as efficient, or more efficient, than most incumbent technologies, but also have higher purchase prices.

Table 2.1 Typical 2014 Price and Performance of SSL Compared to Other Lighting Technologies

Product Type	Luminous Efficacy (lm/W)	CCT (K)	L_{70} (hours)	Price ($/klm)
LED A19 Lamp (Dimmable, Warm-White)[1]	78	2700	25,000	$11
LED PAR38 Lamp (Warm-White) [1]	67	3000	28,000	$23
LED T8 Tube (Neutral-White) [1]	108	4100	45,000	$16
LED 6" Downlight (Warm-White) [1]	60	3500	36,000	$30
LED Troffer 2' x 4' (Warm-White) [1]	93	3500	56,000	$31
LED High/Low-Bay Fixture (Warm-White) [1]	90	4000	75,000	$38
LED Street Light[1]	93	5000	55,000	$50
OLED Luminaire[2]	46	3000	40,000	$870
HID (High Watt) System[3]	115	3100	15,000	
Linear Fluorescent System[3]	108	4100	25,000	$4
HID (Low Watt) System[3]	104	3000	15,000	
CFL A19 Replacement	70	2700	12,000	$2
CFL (Dimmable) A19 Replacement	70	2700	12,000	$10
Halogen A19	20	2750	8,400	$2.5
Incandescent A19	15	2760	1,000	$0.6

Notes:

1. 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 **[4]**. 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.
2. Based on Acuity Brands Luminaires' *Chalina 5-Panel Brushed Nickel OLED Pendant* available from Home Depot April 2015 **[5]**.
3. 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 250 lumens per watt (lm/W) is an achievable performance target for LED packages and excellent progress toward this target has been demonstrated in the laboratory. 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 best current LED products have good efficacy, but many products from the LED Lighting Facts database offer lower efficacy with minimal benefit over incumbent technologies. OLED technology is still in its infancy but offers a similar promise for high efficacy and low cost. Section 6.1 analyzes how OLED technology could reach 190 lm/W while offering a low-brightness and low-glare light source.

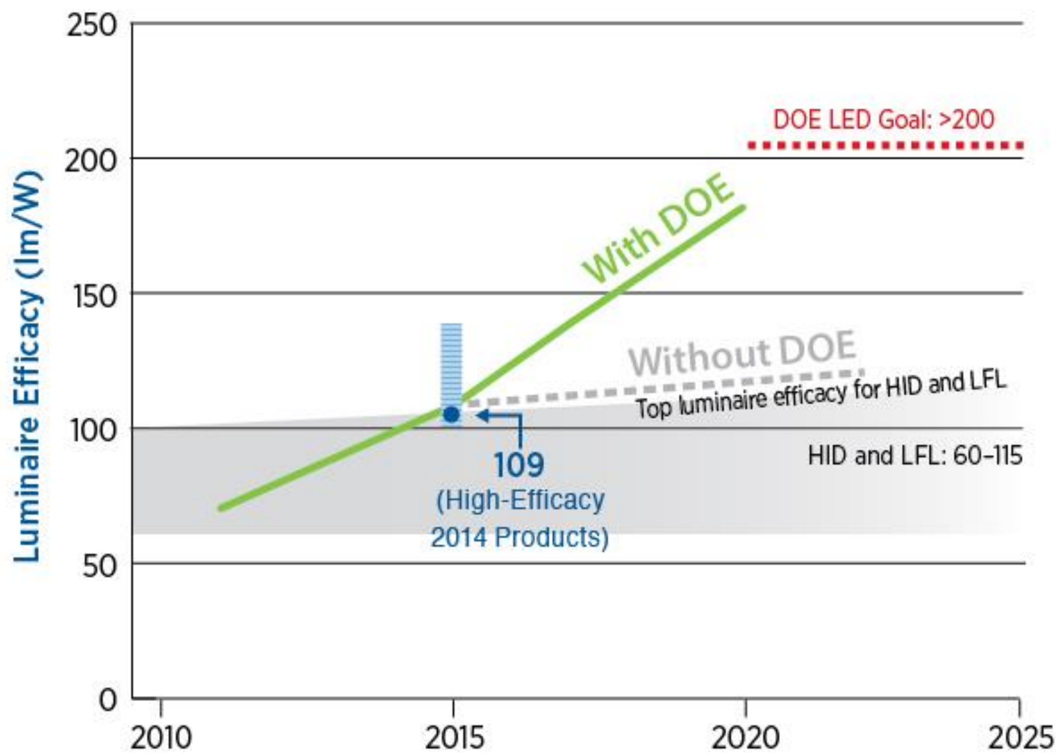

Figure 2.1 Comparison of LED and Incumbent Light Source Efficacies
Source: LED Lighting Facts Product Database

2.2 Light Utilization

Lamp and luminaire efficacy are important indicators of energy efficiency, but they do not tell the whole story. The true efficiency of a luminaire is also influenced by light utilization, which represents how well the generated light from the luminaire reaches the target application and provides suitable illumination. Two metrics are helpful in comparing light utilization between 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 [6]. 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 [7]. 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 which may lead to better light utilization, and therefore even more energy savings. 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 likely 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 an improved light distribution that reduces over-lighting of the target area, improves illuminance uniformity, and produces less wasted light falling outside the target area. Figure 2.2 and Figure 2.3 show examples of outdoor area LED retrofit projects with improved light utilization. Figure 2.2 shows an aerial view of Los Angeles, California in 2008, and the same view in 2012 after a four-year, citywide LED streetlight replacement program. Over 150 thousand LED streetlights have been installed, reducing energy usage by 63%, and saving $8 million in annual energy costs [8, 9]. The images shows that the LED streetlights significantly decreased the amount of light pollution compared to the incumbent high intensity discharge (HID) fixtures.

Figure 2.2 Los Angeles, CA Citywide Streetlight Retrofit (2008-2012)
Source: John Edmond, Cree Inc., SSL R&D Workshop, San Francisco, CA, January 2015 [9]

Figure 2.3 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. Additionally, significantly more of the parking lot area is illuminated, which is particularly advantageous for both driver and pedestrian safety.

Figure 2.3 Cree Edge Area Square, Edgewater Marketplace, Edgewater, CO.
Source: John Edmond, Cree Inc., SSL R&D Workshop, San Francisco, CA, January 2015 [9]

Effective light utilization is especially important to the value proposition for OLEDs; the low brightness and diffuse nature of OLED sources enables them to be used very close to the task area without generating excessive glare, enabling adequate illumination using less light. Acuity Brands has demonstrated, with the luminaire shown in Figure 2.4, how a combination of ambient, surround and task lighting can provide illumination of 400 lux at the work surface in conjunction with attractive lighting for room occupants, furniture, and walls.

Figure 2.4 Combination of Ambient, Surround and Task Lighting for Efficient Office Lighting
Source: Acuity Brands

New form factors, building integration approaches, and lighting layout concepts will enable further improvements to 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 impacting 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 2.5.

2.3 Cost of Ownership

The higher first cost of LED lighting products has been the primary deterrent for many individuals considering purchasing LED replacement products. Prices of LED products vary due to the range of reliability, color quality, efficacy, consistency, materials, aesthetics, and light output in LED lamps and luminaires. Higher operating efficiency and longer operating lifetimes (reduced maintenance and replacement costs) already ensure that LED lighting is highly competitive on a total cost of ownership (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. As shown in Figure 2.5, the payback from using an LED can be as quick as one year, depending on the specific conditions of operation.

The prices of lighting sources are typically compared on a price per kilolumen ($/klm) basis. The prices for LED-based replacement lamps have dropped considerably over the past few years but remain higher than conventional lighting sources. Using the values shown in Table 2.1, Figure 2.5 shows the incremental cost of dimmable incandescent, halogen, and CFL A19 lamps compared to a typical dimmable LED A19 replacement over its lifetime of 25 years, assuming the lamp is operated 1,000 hours per year (approximately 3 hours per day) [10]. At the time of purchase, LEDs trail other technologies because of their higher purchase price, or first cost. However, the LED lamp pays for itself when the incremental cost reaches $0, and from that point forward the consumer will save money by using the LED lamp. Additionally, because incandescent, halogen and CFL lamps have shorter lifetimes than LED lamps, they would need to be replaced multiple times over the 25 year lifespan of an LED lamp. The cost of these replacements is factored into the incremental cost, and is represented in Figure 2.5 as the steps in the graph (i.e. an instantaneous expense at a given time due to purchase of a new lamp).

For both halogen and incandescent lamps, which are both cheap and inefficient, paying to replace the lamp has minimal significance compared to the cost of energy used despite needing to be replaced more often. Due to high power consumption with these lamps, payback occurs in just over 1 year. On the other hand, CFLs are fairly efficient so the cost and frequency of replacing the lamps is far more influential. Because dimmable CFLs have nearly the same first cost as dimmable LED lamps and are also less efficient, payback occurs in just over 2 years. Furthermore, LEDs offer additional benefits over CFLs when considering color quality, dimming compatibility, environmental impact, light distribution, and added functionality which will be discussed in the following Sections 2.5 and 2.6. Overall, an LED A19 lamp can offer up to $156 in savings over its 25 year life, and offers savings over all traditional competitors, as shown in Figure 2.5.

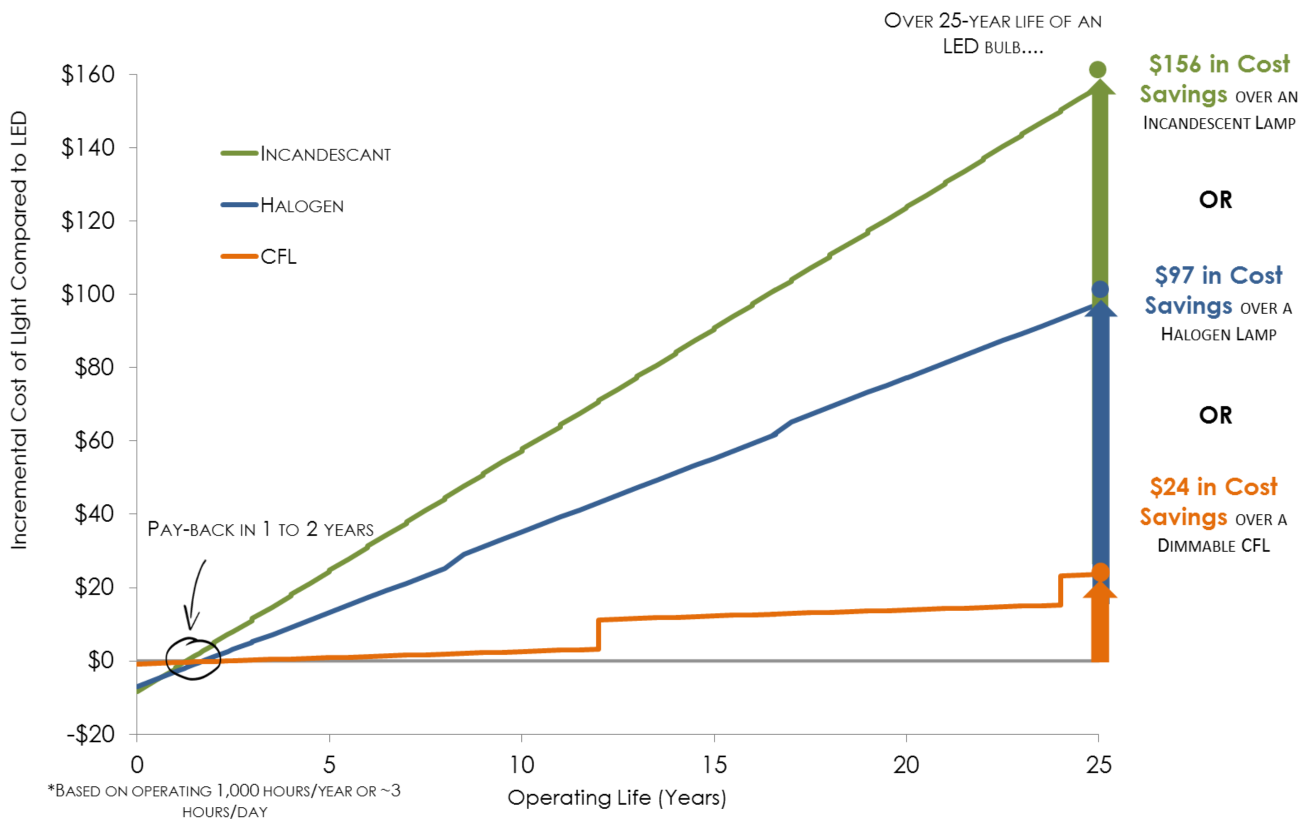

Figure 2.5 Dimmable LED Cost Savings Compared with Competing Dimmable A19 Technologies

2.4 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 40 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 through 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 not a natural thermal path to conduct heat away from the LED packages. Many lamps require light distribution beyond the hemi-spherical 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 integration flexibility since 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 is 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 the retrofit luminaire fits and connects into the building is defined by legacy lighting technologies. For integrated, recessed lighting, LED products will require less depth and volume and may help enable more compact building architectures. 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.

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.

An example of the design flexibility of LED lighting technology and the effective utilization of light is the LED lighting installation on the Bay Bridge connecting San Francisco to Oakland, shown in Figure 2.6 [11]. LED lamps were installed on one side of the roadway with their light distribution carefully designed to minimize glare, avoid stray light impacting oncoming traffic, and minimize light pollution into the bay and the sky. With their long lifetime, LED sources are a good fit for bridges or other situations where maintenance is difficult.

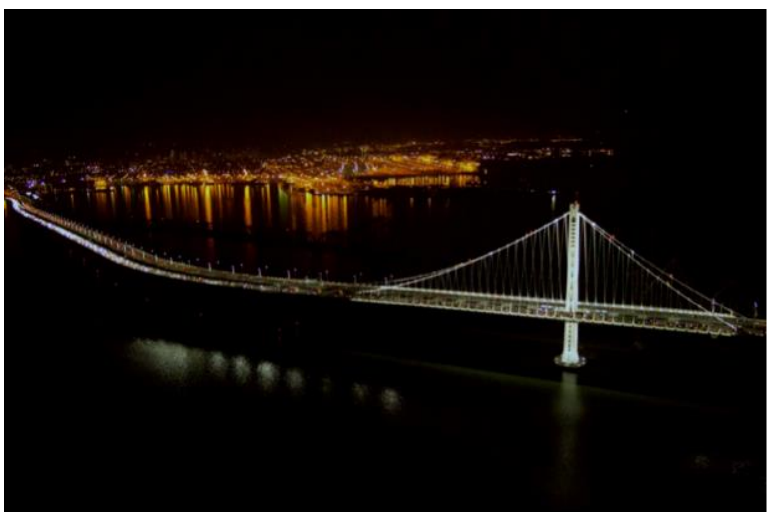

Figure 2.6 Image of Bay Bridge with Custom Luminaires Showing Minimal Light Pollution on Bay.
Source: Saeed Shahmirzai, Zoon Engineering Presentation, 2015 DOE SSL Workshop Presentation [11]

2.5 New Functionality in Lighting

Smart lighting, connected lighting, intelligent 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 dimmable, instant on/off, and can be engineered to be spectrally tunable, providing for new levels of control. The convergence of many technologies with SSL is providing new opportunities for connectivity with lighting. We are rapidly moving towards a future where all building systems, including lighting, HVAC, and security, will be networked through internet-enabled components. This will change the way lighting is valued. The integration of inexpensive and compact sensors, wireless network technology, smart phones, and sophisticated analytics is leading to new possibilities in the area of building energy management systems and could possibly lead to completely new business models such as offering lighting as a service. Figure 2.7 shows how these systems could work together.

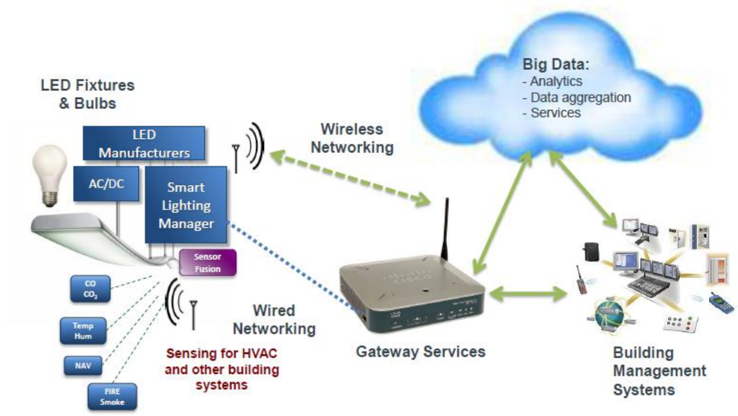

Figure 2.7 Lighting as Part of an Integrated Control System

Source: Tom Griffiths, Integrating the Internet of Awareness into our smart SSL systems, LEDs Magazine, February 2015 [12]

A networked building energy management system can provide simplified access to all pertinent energy systems' information and produce real-time reporting of energy consumption. This information would allow building managers to monitor energy consumption across all devices comprising the system, providing the ability to respond to specific energy consumption patterns (e.g. unplugging devices that consume energy but are not being used, or turning off lights in unoccupied spaces).

However, the implementation of a fully networked system can bring challenges of its own, such as integrating and managing disparate systems with varying communications protocols (both open source and proprietary) without compromising reliability and security.

2.5.1 Lighting Controls

Lighting controls save energy by automatically reducing or turning off light when it is not needed. Control systems might be based on occupancy sensing, daylight harvesting, or may be designed to respond to personal controls. Such systems are particularly well suited to SSL lighting and have been shown to provide additional energy savings of as much as 20 to 60% depending on the application and use-case [13].

Due to the large energy savings potential of lighting controls, California has expanded its requirements for the use of advanced dimming controls, and occupancy and daylight sensors, in nearly every application covered in their most recent Title 24 building code.[b] In particular the code has expanded the

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

requirements for demand-response, daylight harvesting, and aisle and open area occupancy sensing. To meet these requirements, controls will have to 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.

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, dimmer switches, and are interconnected with a wireless mesh. The scheme enables plug-and-play-like 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.

2.5.2 Communications and Interoperability

Communications

Most of the major lighting companies have implemented a preferred control system architecture using either wired or wireless interconnects to link lighting to sensors, switches and dimmers, and light fixtures to a centralized controller. 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, and building automation control protocols such as BACnet, LonWorks, and Konnex.

Over the past decade, the use of wireless communications networks 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 is not only a prime example of this trend, but has also initiated a change in the way people control devices. Lighting products can also benefit from this shift toward wireless connected systems. Lighting controls can become easier to use and create opportunities to offer new value added functionalities in addition to reducing energy use. For example, a user can define new functionality with an existing control system through a software application ("app") that can be downloaded on a smart phone. This ease of integration has led to organizations such as The Connected Lighting Alliance[c] to promote open wireless protocols including ZigBee (IEEE 802.15.4), Z-Wave, Bluetooth, and Wi-Fi. There are also efforts in support of Power over Ethernet control schemes and power-line control of lighting.

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[c] For more information on The Connected Lighting Alliance, please see: http://www.theconnectedlightingalliance.org/home/

Interoperability

Integrating disparate systems and getting them to communicate has long been a concern for lighting controls, and is the biggest roadblock preventing building energy management approaches from realizing their true potential. A networked control system comprises many layers; there are the physical and data link layers (where data is created), followed by the transport and network layers (where data is routed), and finally the applications layers (where data is handled and understood) [14]. 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 2.8.

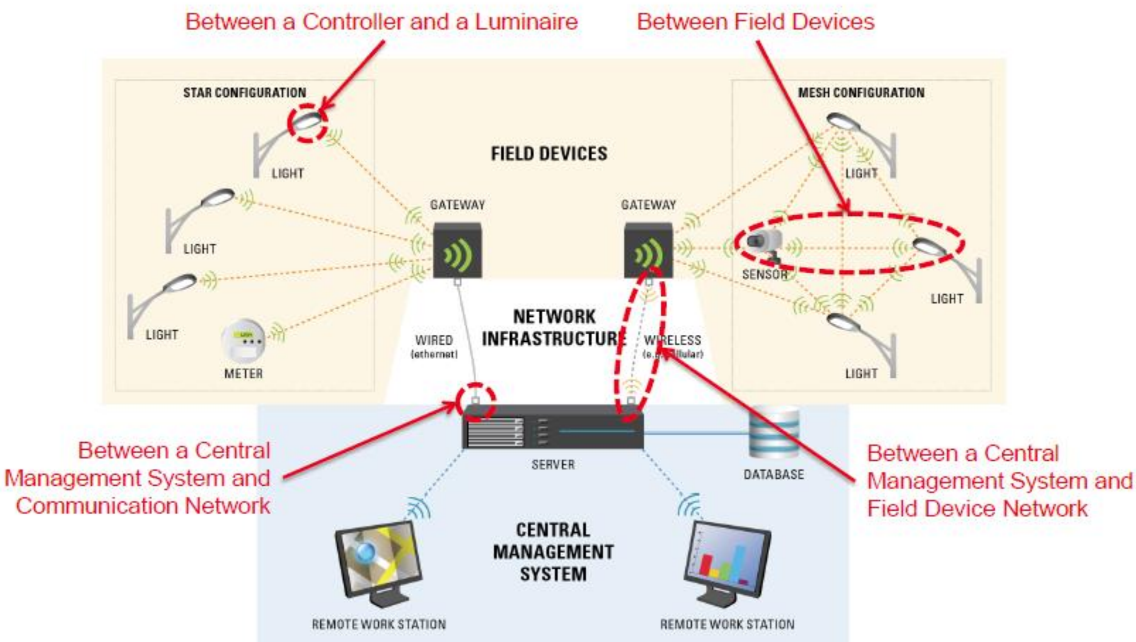

Figure 2.8 Lights, Sensors, Meters, Gateways, and Management Systems Working Together
Source: Michael Poplawski, DOE SSL Market Development Workshop, Detroit, MI, November 2014 [14]

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. Since 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 or 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.

Many lighting controls are marketed as complying with one or more standards. However, the level to which these standards will ensure commonality between SSL products is not always clear. For example, when two luminaires from different manufacturers are presented with the same dimming control signal, one may go to a low lighting level while the other turns off completely. Similarly, the DALI standard has not historically required compliance testing, leading to different manufacturers developing different versions of DALI products, which are often not interoperable.

Open standards with improved definition can help ensure interoperability, future-proof technology, and offer simpler integration. Such standards can lead to vendor independence, which minimizes risk for the customer and benefits all players in the ecosystem. Efforts to bring more interoperability to the lighting control market are already underway within the ZigBee Alliance, LonMark International, the TALQ Consortium, the Connected Lighting Alliance, and others. 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.

Interoperability in home energy management systems also remains a key hurdle, along with the cost of the systems. Home management integration through ecosystems like Wink or Belkin's WeMo allow for the control of most home devices using one simple interface. 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 the user to monitor and control energy usage for the devices within their home. Most of the connected lighting products available today require a bridge or hub for communication with the smart bulbs (e.g. Philips Hue, GE Link, TCP Connected, OSRAM Lightify bulbs), however some have the interface embedded in the bulb itself, such as Cree Connected bulbs or LIFX bulbs. Figure 2.9 shows some of the products available for use with home energy management platforms. Interoperability between home automation systems could simplify the use and promote the acceptance of advanced lighting controls and home energy management systems.[d]

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[d]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/
TCP Connected: http://go.tcpi.com/GetConnected
OSRAM Lightify: http://www.osram.com/osram_com/tools-and-services/tools/lightify---smart-connected-light/
Cree Connected: http://creebulb.com/products/standard-a-type/connected-60-watt-replacement-soft-white-led-bulb
LIFX: http://www.lifx.com/

Figure 2.9 Residential Smart Lighting Products: Cree Connected & GE Link Bulbs with Wink Hub & App.
Source: Wink [15]

Security

As more and more devices are becoming part of a connected world, the many benefits come with security risks, as demonstrated by a few publicized cases where firewalls have been breached by hacking into the lighting products [16]. An internet-connected lighting system can provide hackers an entry points to everything else 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 such as passwords, and the use of default passwords in customer environments [16]. Securing user data, 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. Manufacturers should take on the responsibility of delivering secure devices to their customers and make it easy for customers to maintain the security of their devices over time.

2.5.3 Visible Light Communication

Visible Light Communication (VLC) is a technology where information can be bundled with light to provide services such as indoor location or communication through the connection of wireless devices. VLC transmits data by switching, or modulating, LEDs on and off faster than the eye can perceive.

The opportunity to provide new sources of bandwidth using Li-Fi communications may be important in the future to help cope with the continuing rise of global mobile data traffic, which grew 69% in 2014. Cisco projects that global mobile data traffic will increase nearly tenfold between 2014 and 2019, growing at a compound annual growth rate (CAGR) of 57% from 2014 to 2019, as shown in Figure 2.10 [17]. The increasing number of wireless devices that are accessing mobile networks worldwide is one of the primary contributors to global mobile traffic growth.

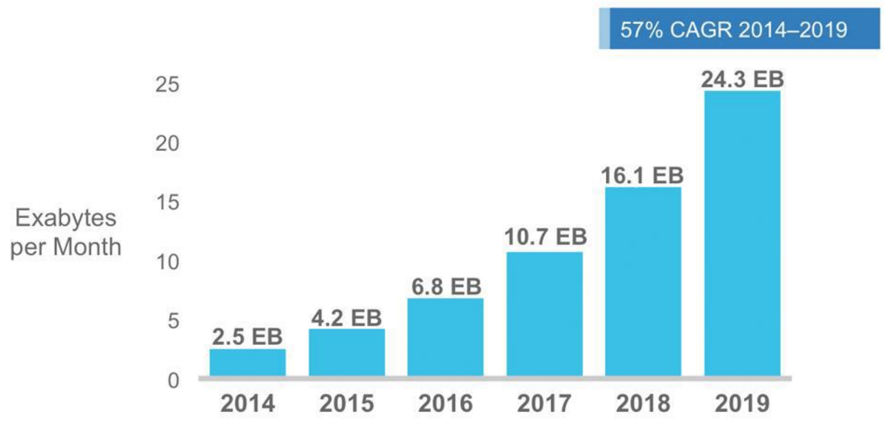


Figure 2.10 Cisco Forecasts 24.3 Exabytes per Month of Mobile Data Traffic by 2019
Source: Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update 2014–2019 White Paper, February 2015 [17]

R&D is being performed in the area of VLC to enhance communication bandwidth, though products providing this feature are not currently available. On the other hand, VLC embedded in LED light dixtures is being successfully used for indoor location services. This new application can deliver value to retailers by allowing them to track the precise location of shoppers who have chosen to participate via their smartphone, shown schematically in Figure 2.11. The shopper 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.

Figure 2.11 VLC + BLE – Turn Lightings into Indoor Location Beacons
Source: Dan Ryan, ByteLight, SSL R&D Workshop, San Francisco, CA, January 2015 [18]

2.5.4 Spectral Control and Tuning

LED lighting products can be designed to emit almost any spectrum of visible light. Newer commercial products such as the Philips Hue[d] and specialty products such as the Telelumen Light Replicator[e] can provide active control of the emitted spectrum with varying degrees of spectral resolution. It should be made clear that 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 whole host of value added features for SSL lighting beyond energy savings. Some new applications that are enabled by LED color tunability include horticultural lighting, lighting for human health and productivity, dynamic theatrical and entertainment lighting, and spectral replication.

Horticultural Lighting

Horticultural lighting represents an increasingly important application that takes advantage of the spectral tailoring and tuning ability of SSL sources. Changes in the spectrum of light influence various aspects of plant growth such as the size of the plant, germination process, flowering, and vegetation. The blue and red regions of the spectrum are the key regions for photosynthetic activity, as seen in Figure 2.12. 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. The use of tailored wavelength lighting for horticulture can enable energy efficient indoor farms, and 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 has led to the following exemplary results described by GE at the 2015 DOE SSL R&D Workshop [19]:

- 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

[e] For more information on the Telelumen Light Replicator please see: http://telelumen.com/products.html

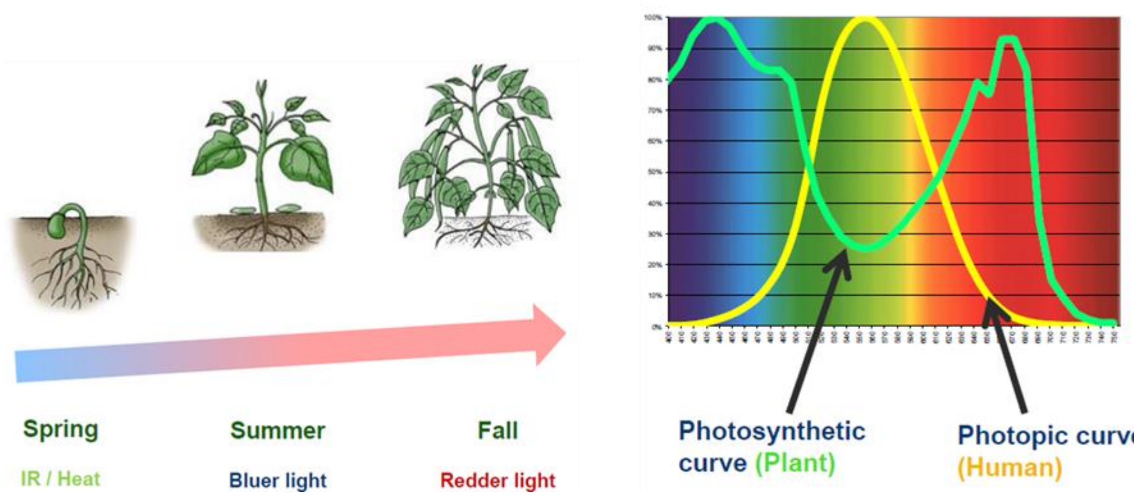


Figure 2.12 Effect of Light on Plant Growth
Source: Robert Spivock, GE, SSL R&D Workshop, San Francisco, CA, January 2015 [19]

Human Health

Humans are exposed to a substantial amount of artificial lighting, all of which has some effect on our physiology, regardless of the light source type. Recent research has greatly advanced the understanding that light not only enables vision, but is also a critical signal to our biological systems, affecting circadian rhythms, pupillary response, alertness, and more, as illustrated in Figure 2.13 [20]. Light has even been shown to be an effective treatment for a variety of conditions, such as Seasonal Affective Disorder (SAD) and dementia [21].

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.

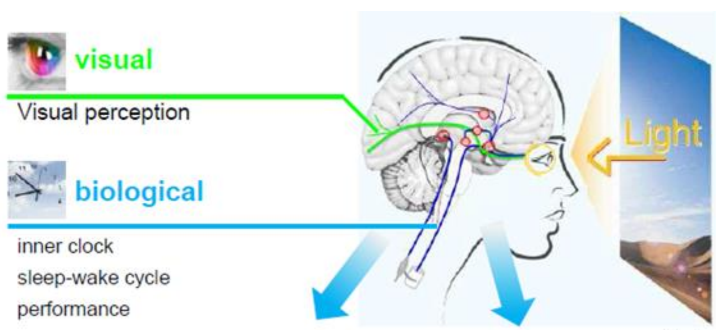


Figure 2.13 How Light Affects a Biological Systems
Source: Andreas Wojtysiak, OSRAM, SSL R&D Workshop, San Francisco, CA, January 2015 [21]

A number of case studies have shown that tuning the spectrum of the lighting throughout the day can lead to improved alertness and productivity, as well as 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 2.14. During the evening, it is desirable to reduce the amount of blue light in the spectrum since it suppresses the production of melatonin and makes falling asleep more difficult.

Studies using spectral tuning have shown the following results [21]:

- Improvements in classroom alertness for students
- Significant improvement in daytime activity, alertness, and better sleep at night for the elderly (nursing homes)
- Improvements in chronic pain therapy through structuring the day and stabilizing sleep/wake cycles
- Better evening and nocturnal relaxation and morning activation for passengers in an aircraft cabin
- Reduction in the duration of therapy to relieve unipolar depression

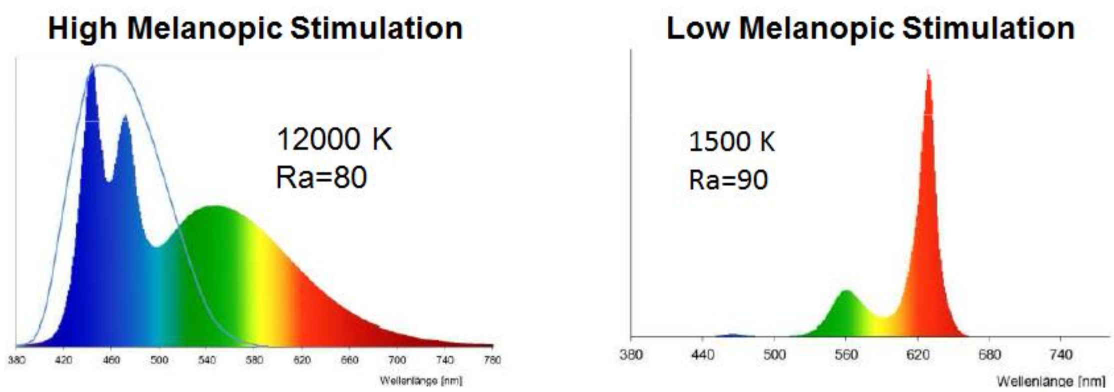


Figure 2.14 Daytime Activation by Light (left) and Less Circadian Light Effects in the Evening and Night (right)

Source: Andreas Wojtysiak, OSRAM, SSL R&D Workshop, San Francisco, CA, January 2015 [21]

The physiological impacts described above could be harnessed to improve labor force productivity. Spectral tuning based on the work task and individualized control of lighting could also improve work output. 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 productivity in educational settings. LED technology can enable the required control of the light output, spectrum, and light distribution to implement such a system.

2.5.5 Conclusion

While energy savings has been the primary motivation to pursue LED lighting, the incorporation of new features can change the way we use lighting, which in turn will help drive LED adoption. The ability to tailor the spectrum is leading to a better understanding of the most appropriate light for performing a specific task, optimizing horticulture, positively impacting 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. The semiconductor nature of LEDs can also enable communication that is invisible to humans through the light that is all around us. These new features could provide value beyond simple energy savings such as health benefits, productivity improvements, improved agricultural output, simplified building energy management systems integration, and enhanced control and communication between lighting, home automation, and users. These are just a few of the new applications and benefits that will be enabled by SSL. Ongoing improvements to SSL building blocks are required to fully enable and optimize the features proposed in this chapter. For example, improvements to green and amber LED efficiency will improve the performance of color tunable systems, and improvements to the underlying blue LED and phosphors will reduce cost and improve efficiency in these systems. In addition, R&D on lighting control and home automation system interoperability is required to fully implement these concepts.

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 significant additional research is necessary to fully understand these biological responses. LED technology will play its part 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.

2.6 Improved Environmental Sustainability

SSL technology provides 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, enable reduced 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. SSL technology also offers additional environmental benefits such as a reduced use of toxic, scarce, critical, or energy intensive materials [22]. In addition, new levels of control of the spectrum and the optical distribution of the emitted light can minimize the impact of lighting on the ecosystem. The DOE-sponsored life-cycle assessment (LCA) shows 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 lifecycle energy consumption from LED products 4 years ago, as shown in Figure 2.15 [22].

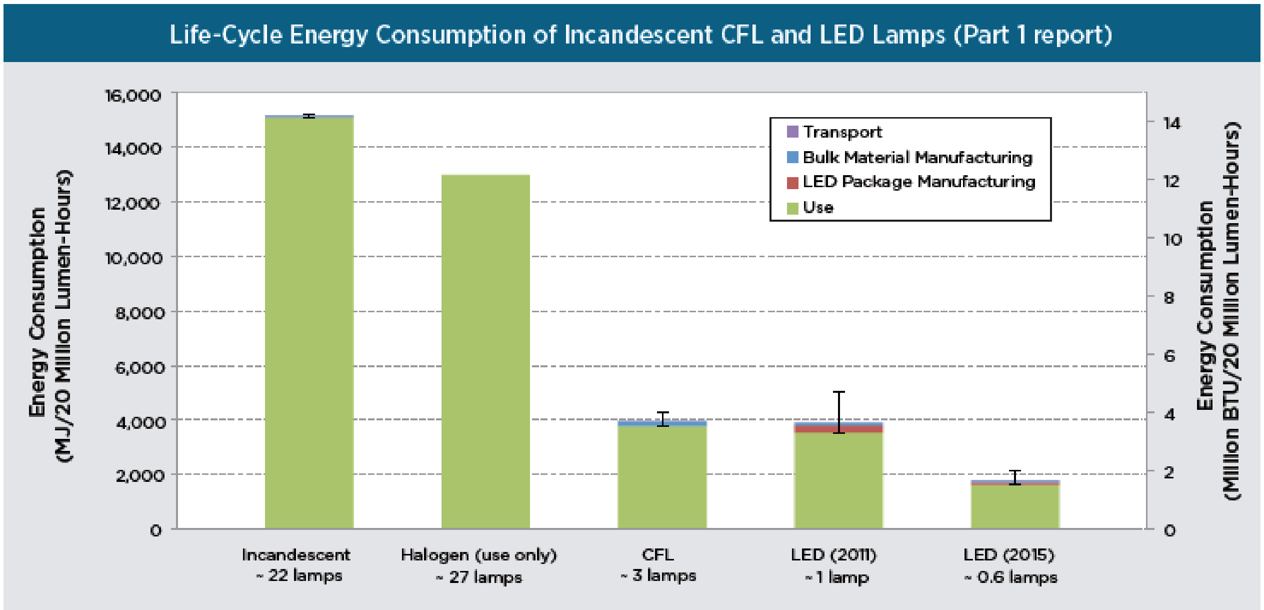


Figure 2.15 Energy Consumption Comparison from DOE LCA Study

Source: DOE SSL Program, "Life-Cycle Assessment of Energy and Environmental Impacts of LED Lighting Product", April 2013 [22].

The DOE-sponsored LCA study has shown that SSL can reduce energy use from lighting and maintain performance levels without using large amounts of toxic or scarce materials[f]. 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 has 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 [22].

[f] 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

Although LED-based SSL products are already demonstrating exceptional 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, such as outdoor lighting which provides a spectrum designed to minimize disruption of sea turtle hatching[g].
- Minimizing light pollution from streetlights. The International Dark-Sky Association[h] suggests guidelines to reduce the amount of unusable upward emitted light at night. LED lighting products with their improved optical distribution can significantly reduce the amount of light wasted upward into the atmosphere.
- "De-materializing" 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 or the Cree 4-flow lamp (shown in Figure 2.16), 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.
- Improving manufacturing efficiency through yield improvements, material utilization, and equipment energy usage.

(a) (b)

Figure 2.16 Lamps without Aluminum Heat Sinks: (a) the Philips SlimStyle and (b)Cree 4-flow
Source: (a) Philips Website, May 2015 [23]*; (b) Cree Website, May 2015* [24]

[g] For more information on approved Sea Turtle Lighting please see: http://www.myfwc.com/wildlifehabitats/managed/sea-turtles/lighting/
[h] For more information on the International Dark-Sky Association and their guidelines please see: http://www.darksky.org/

3.0 Barriers to Adoption

There are profound energy, economic, performance, and application benefits enabled by advancements in SSL technology. Despite the many benefits and additional functionality that can be achieved with SSL, there remains a number of barriers to the adoption of SSL products. These include first cost, reliability and compatibility issues, which can limit adoption of these energy saving light sources. An overview of each of these aspects are discussed in the following sections, but more detailed information on reliability can be found in Section 5.2.4 Reliability and Color Shift.

3.1 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. Yet, despite the large cost reductions, SSL products remain more expensive than incumbent sources based on first cost and are still sold on a TCO basis, as described in Section 2.3. The adoption of LED-based products in many commercial and industrial applications has accelerated as the payback period reaches the one to two year level, but lighting sold at the consumer level will tend 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.

LED replacement lamp prices will continue to decline as LED package prices come down and manufacturers continue to innovate. Ultimately it will not be necessary for SSL to reach cost parity with incumbent sources since it offers many additional benefits such as higher efficiency, longer lifetimes, and value added-features such as tailored spectra and connectivity (see Section 2.5 for more about new functionality in lighting).

One risk to ever dropping prices is that product quality could become a concern. As thermal management materials, such as aluminum heat sinks, are being shrunk or eliminated to save cost, the efficiency, lifetime, and color shift of LED lamps may be impacted. As 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 may lead to a compromise in quality and an increased early mortality rate. It is important that the drive for lower first cost does not cause performance or lifetime deficiencies or it will reduce consumer confidence in LED technology, reduce adoption, and limit the total energy saved.

3.2 Reliability

In addition to high energy efficiency, LEDs have the promise of extremely 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, even decades, failures may be very slow to appear under normal operation. Therefore, detecting these failures in the laboratory or factory is very difficult, but it is important to understand and to be able to estimate useful product life. Since LED products are generally more expensive than their traditional predecessors, the ability to recover the first cost over the life of the product is important to consumers.

LED lamps typically do not fail catastrophically (i.e., 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 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 would determine 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. Optics degradation, power supply failure, and solder detachment may occur under normal operation well before the LED light source fails. In addition, catastrophic random short term failures may be observed due to assembly or material defects. Studies to date have shown that component and manufacturing failures in the power supply are responsible for many luminaire failures. Overheating caused by poor luminaire design can also reduce the life of an LED package dramatically, and moisture incursion can be an important mechanism of failure and determinant of life for an outdoor luminaire.

More work is required to understand the various mechanisms and enable the development of new reliability models so that system reliability can be confidently understood and communicated. The DOE SSL Program has funded specific R&D in this area and supported the creation of an industry consortium to coordinate activities and foster improved understanding. 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.

3.3 Color Stability

Lumen maintenance has dominated discussions about LED package lifetime, but color shift is another important performance attribute that can cause an LED lamp or luminaire to fail in its application and discourage their use. The color stability of LED lamps and luminaires varies between 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 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 all 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, like plastics, glues, or epoxies, may discolor over time. Temperature fluctuations, which are not included in standardized test procedures, may also exacerbate degradation mechanisms for some LED products.

Unlike for LED package lumen maintenance, there is no currently available standard methodology for projecting future color stability using standard test procedures. 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 currently working on this issue.

3.4 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 and lumen, as a metric defining light output. These compatibility issues can exist between nominally identical products from different manufacturers, as well as between 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.

For linear fluorescent replacement products there is an added level of complexity. LED linear fluorescent replacement tubes will either be compatible with the existing fluorescent ballast, have their own LED-based power supply, or must be wired directly to mains. Each approach has its pros and cons, but this choice 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 a 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 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.

4.0 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. Through the en.lighten initiative[i], the United Nations Environmental Program (UNEP) estimated that in 2010 the use of lighting energy had risen to 2,815 terawatt-hours (TWh), corresponding to 15% of total global electricity use [25]. UNEP predicted that, in the absence of further measures, consumption would increase to 3,575 TWh by 2030, and, as a result, has urged governments to set minimum energy performance standards to ensure the efficiency and quality of energy-saving lighting products and to remove obsolete technologies from the market. They suggest that slow implementation of new regulations will lead to a lighting energy demand of 2,743 TWh in 2030, but implementation of the accelerated lighting programs suggested by the Sustainable Energy for All Program of the UN Secretary-General would reduce that demand to 2,366 TWh [25].

In most regions of the world, even with government policy support, less than 10% of existing lighting installations use SSL products, showing that further R&D is essential to accelerate its adoption. At this time, the global market for SSL is dominated by LED-based lighting products, while OLED lighting is currently confined to decorative luminaires and custom-built fittings. OLED lighting is also expected to contribute to energy savings, but at this early stage of development it is difficult to quantify their total market opportunity. For these reasons, the remainder of this section will focus on the market impact for LED-based lighting.

4.1 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 LEDs are more expensive than traditional technologies, market share of sales will be greater in terms of revenue than for units. LED penetration of the installed base will follow increasing market share more slowly, as LEDs become the majority of sales and are used for replacing existing installations.

Strategies Unlimited estimates that in 2014, LED lamps comprised 5% of unit sales, 41% of total lighting revenue, and achieved 3% penetration of the installed base [26]. By 2020 Strategies Unlimited expected these figures to rise to 42% of unit sales, 76% of revenue, and capture approximately one-third of the installed base. Most major suppliers including Acuity, Osram, Philips, and Zumtobel are now reporting that LED products (i.e. lamps and luminaires) account for over 40% of total revenues. Despite these successes, LED Inside has estimated that for the global industry as a whole, LED revenues in 2014 were $20 billion, representing only 26% of total lighting revenues [27]. Table 4.1 compares multiple forecasts of the LED share of global lighting revenues. Despite differences, all market research companies predict significant growth in LED share.

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

Table 4.1 Global Market Share of LED Lighting Measured as a Percent of Total Lighting Revenue

Source	Scope	2014	2016	2018	2020	2022
IHS [28]	Lamps	31%	42%	52%	61%	67%
Strategies Unlimited [26]	Lamps	41%	56%	68%	76%	80%
Strategies Unlimited [26]	Luminaires	33%	44%	53%	61%	69%
LED Inside [27]	Lamps & Luminaires	26%	34%	54%	-	-

The global adoption of LEDs, shown in Figure 4.1, is only just beginning. Strategies Unlimited forecasts that SSL penetration of the global installed base will grow rapidly from below 5% in 2014 to over 30% by 2020 [26].

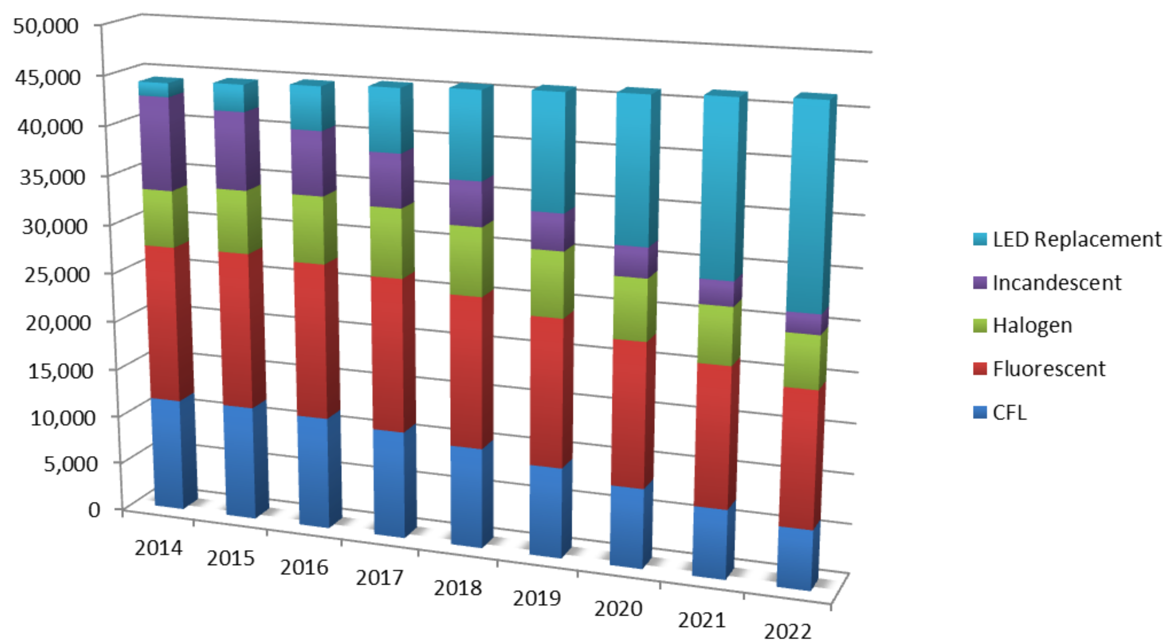


Figure 4.1 Evolution of the Global Installed Lamp Base by Lighting Technology

Source: Philip Smallwood, Strategies in Light Conference, Las Vegas, NV, February 2015 [26]

4.1.1 United States

Forecasts of LED adoption in the U.S. are similar to global forecasts, in that LEDs account for a small but increasing share of the lighting market. DOE's 2014 study, "Energy Savings Forecast of Solid-State Lighting in General Illumination Applications," (hereafter referred to as the DOE SSL Forecast) suggests that SSL could account for nearly half of all lighting shipments in the U.S. (measured in terms of light production capacity in lumen-hours) and approximately 40% of the installed base (in lumen-hours) by the year 2020 [2].

Adoption

The forecasted shift in technologies used in U.S. lighting installations is shown in Figure 4.2. In 2014, LEDs made up less than 4% of the installed base (in lumen-hours). To date the U.S. installed base has been dominated by linear fluorescent and HID lighting, both of which have high operating hours, high lumen output per lamp, and large numbers of installations. However, as the prices decrease and efficiency increases, LED lighting is predicted to nearly eliminate the use of HID sources and reduce the installed base of linear fluorescent lamps to one-third of its current share. By 2030, LED lighting is forecasted to account for the majority of installations, equivalent to 88% of all lumen-hours being produced for general illumination [2].

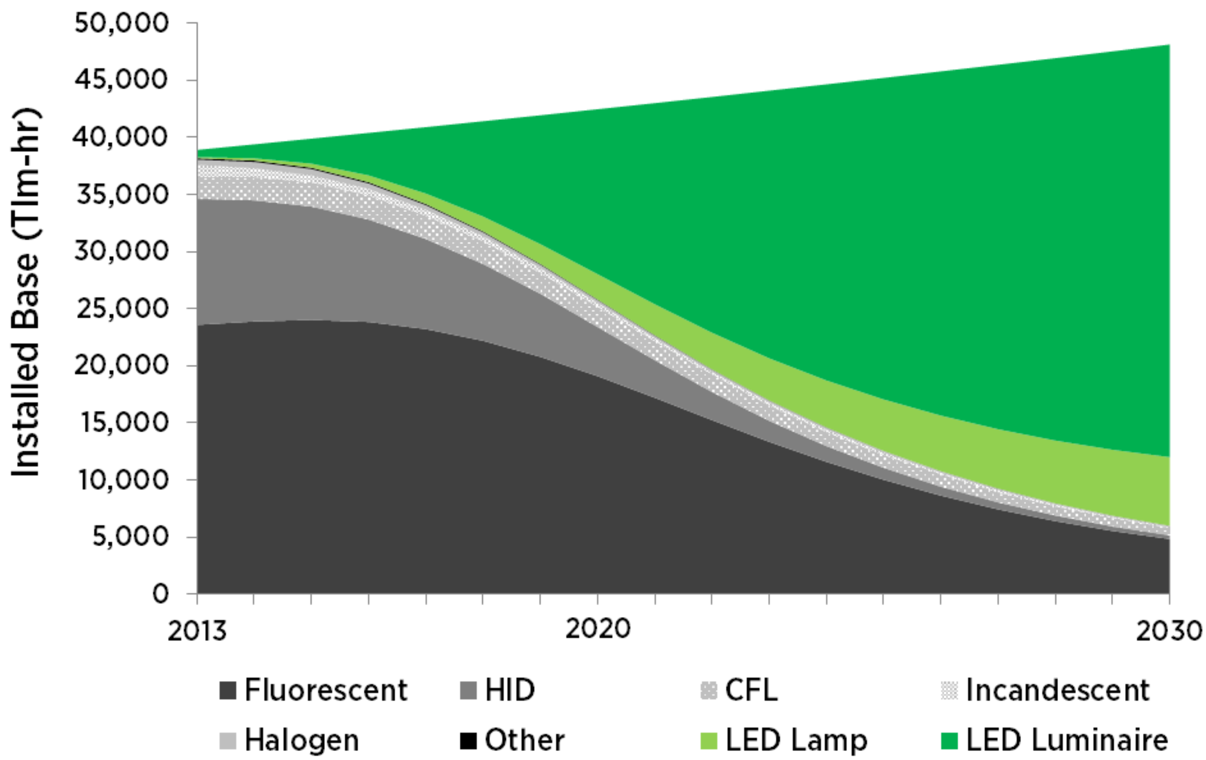


Figure 4.2 U.S. Lighting Service Forecast, 2013 to 2030

Source: DOE SSL Program, "Energy Savings Forecast of Solid-State Lighting in General Illumination Applications", August 2014 [2]

Table 4.2 provides the 2014, 2020, and 2030 forecasted market share of LED lighting shipments in terms of lumen-hours for nine common lighting applications. The following observations can be drawn from this data:

- To date, LEDs have a much larger market penetration in the outdoor sector than the indoor sector, although the difference decreases with time.

- The highest level of market penetration for LED lighting in 2014 is in the street and roadway submarket at 21%. LED lighting is predicted to reach an 83% market share in this submarket by 2020 and nearly 100% by 2030.
- Parking garages have the smallest market share of the outdoor markets at 8%, but this is still greater than that of the most successful indoor submarket.
- The directional submarket has the largest market share of the indoor markets at 6%, led in part by the early success of small directional MR16 replacement lamps.
- Projections show that LED lighting will make up nearly half of all lighting shipments by 2020, and 84% by 2030.

Table 4.2 Forecasted U.S. LED Market Share of Lighting Shipments (lumen-hour) [2]

Application[1]	2014	2020	2030
General Service	4%	55%	>99%
Directional	6%	26%	74%
Decorative	1%	31%	94%
Linear Fixture	4%	44%	83%
Low/High Bay	3%	36%	73%
Total Indoor	3%	42%	81%
Street/Roadway	21%	83%	99%
Parking Lot	12%	74%	99%
Garage	8%	67%	>99%
Building Exterior	11%	71%	99%
Total Outdoor	**14%**	**75%**	99%
Total All	**6%**	**48%**	**84%**

1. See Appendix 8.1 for definitions of SSL Lighting Applications and products within each category.

Energy Savings

The DOE SSL Forecast report discusses multiple sensitivity scenarios considering the impact of several factors on the future of the lighting market and resulting energy savings. The forecast model is available publically as an online interactive tool[j] where users are able to investigate for themselves the impact of manipulating various key input parameters.

Two scenarios presented in the 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 the DOE SSL

[j] Readers are invited to examine the different sensitivity scenarios in the DOE SSL Program's lighting market model for themselves at http://energy.gov/eere/ssl/led-lighting-forecast.

program goals. A comparison of the results is used to determine the additional energy savings that may be enabled by aggressive R&D.

The study found that by 2030, when considering the more conservative trajectory, LED technology offers the potential to save 261 terawatt-hours (TWh) annually, a 40% reduction in site electricity consumption from a counter-factual scenario without LEDs. This 261 TWh of savings in site electricity consumption corresponds to 3.0 quadrillion BTUs (quads) of primary source energy saved. Furthermore, DOE goals are realized, the total annual energy savings in 2030 would increase to 60%, an additional 130 TWh in site electricity or 1.5 quads of primary source energy savings [2].

Figure 4.3 shows the resulting energy savings for each of these scenarios and illustrates the importance of the SSL Program's R&D priorities and milestones (discussed in Section 7.2) to help realize aggressive price and performance improvements.

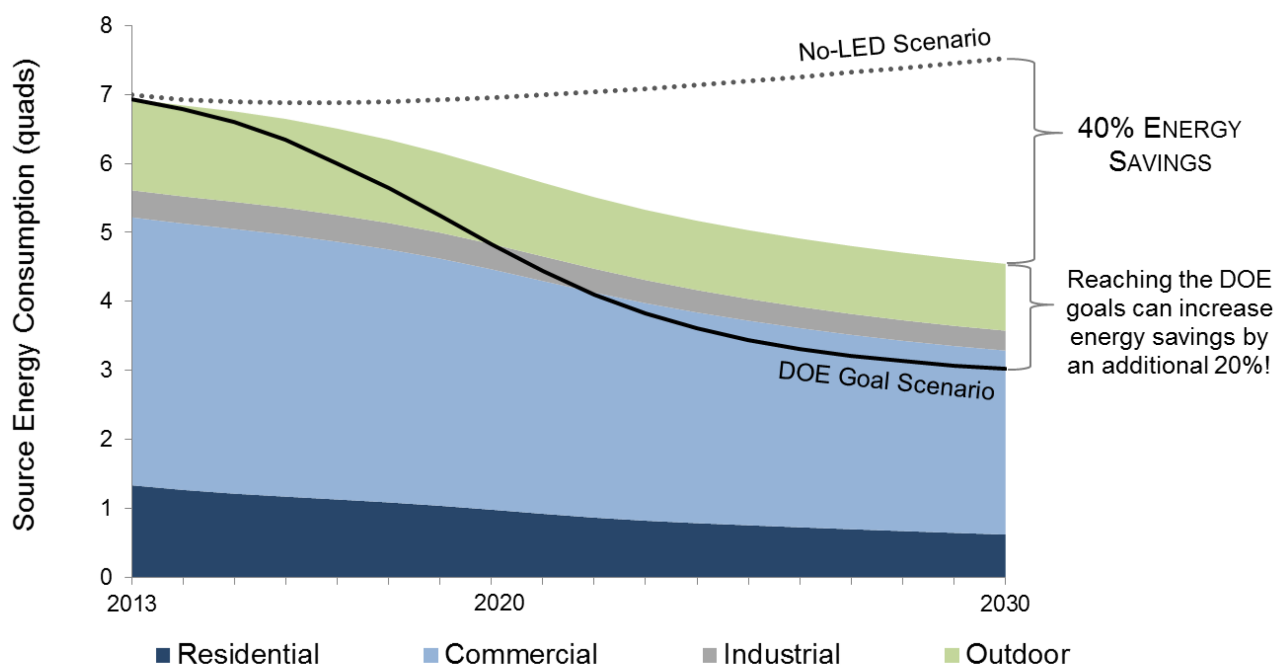


Figure 4.3 Forecasted U.S. Energy Savings if DOE SSL Program Goals are Realized
Source: DOE SSL Program, "Energy Savings Forecast of Solid-State Lighting in General Illumination Applications", August 2014 [2]

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 4.4). At an average price of $0.10/kilowatt-hour[k], this would correspond to an annual dollar savings of about $40 billion [2]. This demonstrates that

[k] 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

SSL provides an unprecedented opportunity to reduce electricity consumption, thereby improving domestic energy security, and reducing greenhouse gas emissions.

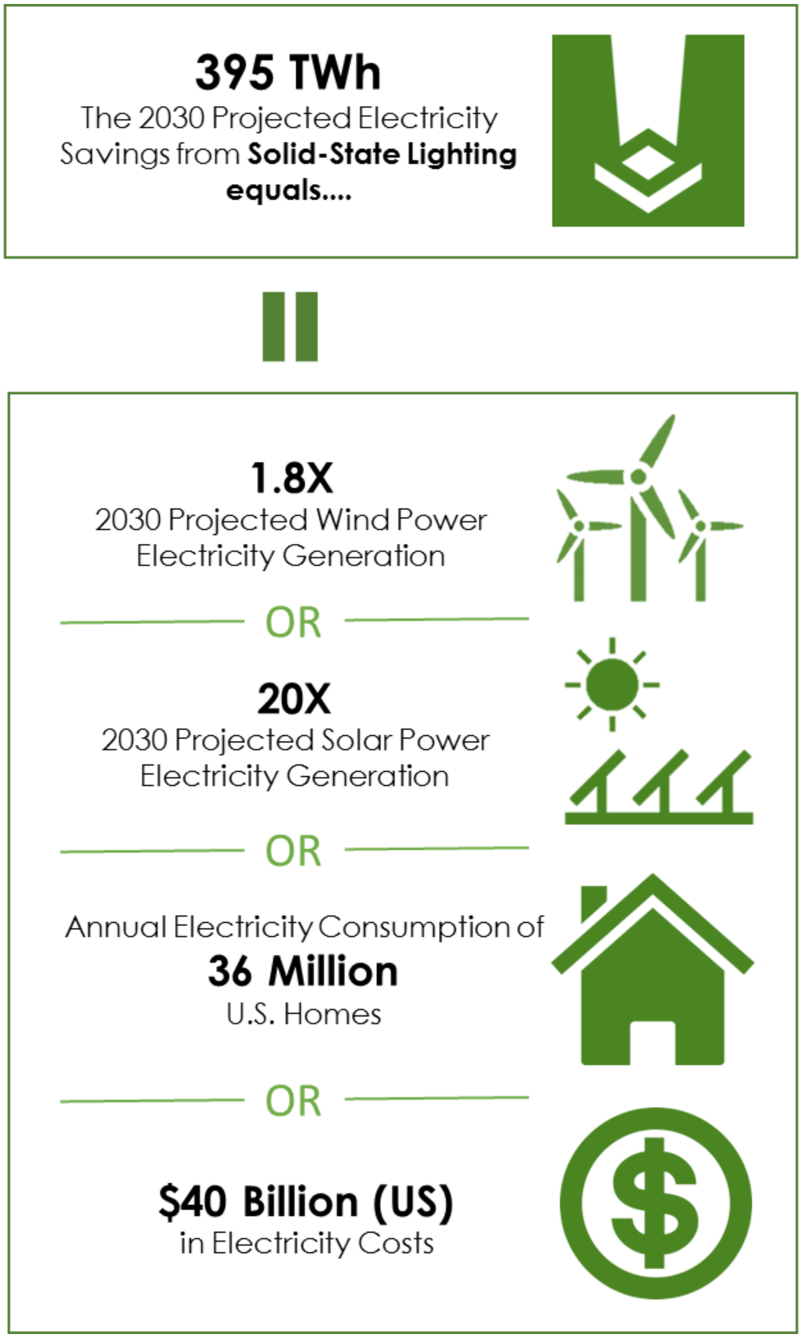


Figure 4.4 Projected U.S. Electricity Savings from SSL in 2030 Compared to Wind Power Generation, Solar Power Generation, or U.S. Household Annual Electricity Consumption

4.1.2 Asia

UNEP estimates that in the absence of new policies, 57% of the lighting energy demand in 2030 would come from Asia [25]. Therefore, developments in Asia will be critical with respect to reducing the global demand for electricity.

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. In 2013, LED bulbs accounted for over 30% of the unit sales of omnidirectional bulbs, with CFLs contributing 24%. In terms of sales revenues from lamps and luminaires, the LED share reached 72% in 2014, and is expected to rise to 79% in 2015 [29]. Panasonic has declared that in 2015 all of its residential lighting products will be LED-based [29]. In March 2015, the Japan Lighting Manufacturers Association presented its “Vision 2020 for Lighting Business”, which projects that 100% of shipments and 50% of the installed base of 950 million luminaires will be LED-based by 2020 [30].

China is now the largest market for SSL. In 2014, the sales of LED lamps and luminaires reached 750 million units, equivalent to 16.5% of all lighting products sold, and the China Solid-State Lighting Alliance expects the fraction of unit sales to rise to 31% in 2015 [31]. In terms of the installed base of almost 10 billion lights, LED penetration increased from 2.4% in 2013 to 10% in 2014. The national goal for 2020 is to raise SSL penetration to 70%, thereby saving 340 TWh of energy, equivalent to 80% of the UNEP global savings target of 420 TWh [32].

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, the development of industrial parks, and establishment of standards programs. Over 50% of the SSL products produced in China are exported, and are looking to diversify from previous emphasis on European and North American markets to include South East Asia, Brazil, India, Russia and South Africa through vigorous promotion [33].

Although the population of India is similar to that of China, the installed lighting base is only 2 billion units. This is likely to increase substantially over the next fifteen years and the government is keen to meet the demand with energy efficient lamps. In the past, the emphasis has been on the promotion of CFLs, with annual production rising from 35 million to 450 million between 2003 and 2013. The focus has shifted to LED products, primarily on retrofit lamps, downlights and streetlights. The goal for LED sales revenues in 2015 is $1.25 billion, which would represent over 80% of total lighting sales [34].

4.1.3 Europe

Per-capita consumption of lighting energy in Europe is less than half of that of North America, but there are still substantial savings to be achieved through the introduction of SSL [35]. UNEP reported that lighting energy use in the European Union was 480 TWh in 2010 [36]. Philips has estimated that complete replacement of the installed base by SSL sources could lead to savings of 280 TWh [37].

Within the European market, the share of tungsten-filament incandescent light bulbs has fallen from 59% in 2009 to 12% in 2013 (measured in unit sales). However, these have been mostly replaced by halogen light bulbs, so that the total market share of incandescent lamps has hardly changed, reducing from 80% to 79%. Although sales of LED lamps rose from 0.6% to 4.8% between 2009 and 2013, this was mostly due to replacement of CFLs, whose market share dropped from 18% to 15%. As a result, the average efficacy of domestic lamp sales has risen only modestly, from 16 lm/W to 18.3 lm/W [38]. These levels fall short in comparison to that of global leaders, such as South Korea (44 lm/W) and Australia (27.5 lm/W) [39].

This situation has led to intense debate about the implementation of Stage 6 of the European Commission Regulation 244/2009, which would impose a minimum efficacy on most clear non-directional lamps using a sliding scale which requires 17.9 lm/W for 400 lm bulbs and 20.8 lm/W for 800 lm bulbs. This stage was due to come into effect in September 2016, but pressure from the European lighting industry led to the introduction of these limits being postponed until 2018 [40].

For the commercial and industrial sectors, the energy-efficiency organization, CLASP, has estimated the effect of replacing fluorescent and HID lamps with LEDs, using U.S. DOE models for efficacy improvements and adoption rates. They concluded that electricity consumption can be reduced from 219 TWh in 2010 to 199 TWh in 2020 and to 148 TWh in 2030, even though the light output is expected to rise by 35% over this period. The share of lumen-hours produced by LED lighting is forecast to be 12% in 2020 and 67% in 2030 [41].

As in the U.S., the need for local authorities to reduce electricity bills and maintenance costs is driving the installation of LEDs to replace mercury vapor, metal halide and sodium street lights. This has been facilitated by the encouragement of energy performance contracting and the Smart City movement [42]. For example, the European Innovation Partnership has set a goal of replacing 10 million of the 60 million existing streetlights by 2017 [43].

4.1.4 Off-grid Communities in the Developing World

Reductions in lighting electricity use through SSL adoption are expected to provide substantial relief from the pressure for additional power generation in almost all developed economies. In the rest of the world, 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 development of SSL sources and photovoltaic technology offers a far more affordable solution for electric light sources than developing the grid to deliver electricity.

Approximately 1.3 billion people throughout the developing world do not have access to the electrical grid and, instead, spend over $30 billion each year on fuel for lighting, such as kerosene. In comparison, replacing this source with solar lanterns would reduce these costs by a factor of 10, to an estimated $2.7 billion annually [44].

In addition to the financial savings, solar 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 per annum. The use of these light sources is also dangerous due to the risk of fires and toxicity of the fuel, which contains a high proportion of heavy particulates [45].

The rapid growth of the solar lantern market, which rose from $200 million in 2013 to $500 million in 2014, would have been impossible without LED sources. The increased efficacy leads to substantial reduction in the cost of solar panels and storage batteries, far outweighing the added cost of the LEDs. Moreover, the small size of LEDs enables the design of rugged devices with more effective optics in a wide range of form factors [46].

On a community level, the availability of highly efficient lights that can be driven easily by low voltage DC current is leading to affordable solar-powered streetlights and enabling evening classes in schools, extended operation of health clinics, and other social activities in rural communities that were previously impractical.

SSL will allow many countries to provide more adequate lighting with minimal additional energy requirements. Nevertheless, the latent demand for good lighting is so great in the developing world that the increased energy consumption may offset energy savings that are made through increased efficacies. In particular, demand for lighting in Africa and certain parts of Asia is likely to increase over the next decade as these economies grow. This scenario provides even greater motivation for the development of higher efficacy SSL sources, the more efficient utilization of light, and the increased adoption of controls to minimize unnecessary light production.

4.2 Economic Impact

The impact of lighting on the global economy, as estimated by the International Solid State Lighting Alliance (ISA) is shown in Figure 4.5 [35].

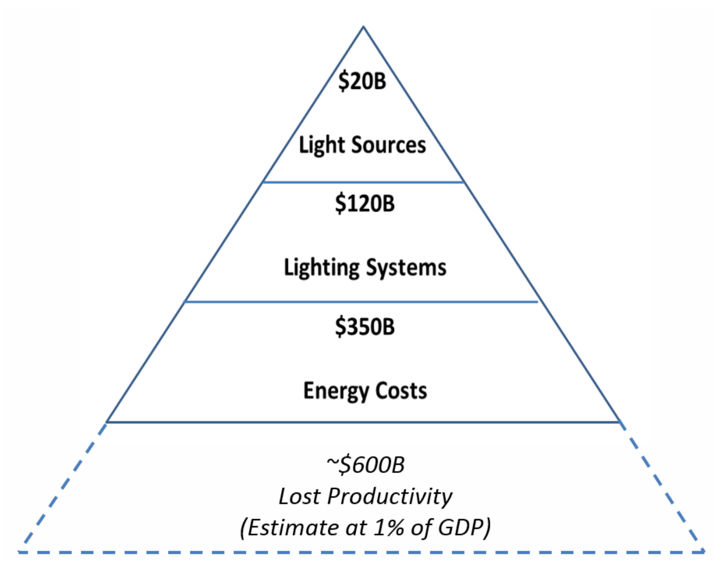


Figure 4.5 Impact of Lighting on the Global Economy in 2014
Source: ISA, Global Solid State Lighting Industry Status Report and Market Trends 2014, 2014 [35]

Figure 4.5 shows that expenditures on energy are far greater than the costs of buying and installing lighting systems. Without the introduction of energy saving lamps and more effective controls, the expanding global demand for artificial light and increasing costs of electricity could drive the energy bill towards $1 trillion by 2030 [35]. But with the increases in efficacy and a widespread adoption of lighting controls described in previous sections, future energy bills could be reduced substantially.

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 (as discussed in Section 2.5.4) or indirectly, for example, by facilitating access to education and healthcare in developing countries.

In rural communities of Africa and Asia, the introduction of solid-state lamps powered by solar panels is having a broader economic impact, enabling the first step on the ladder of access to lower cost electrical power. The funds that were previously used to buy kerosene or candles are often used to purchase larger solar power systems, providing opportunities to start small businesses as well as improving the quality of family life.

Impact on the Lighting Industry

The advent of SSL has already transformed the lighting industry. The traditional global dominance by large vertically integrated companies, such as GE, Osram, Panasonic and Philips is being challenged by many new companies. Some of these new companies, including Nichia, Seoul Semiconductor, Epistar and Sanan Optoelectronics, produce LED chips and packages only, whereas others, such as Cree, are expanding from these initial areas of strength to supply complete lighting solutions. Meanwhile, Osram and Philips are splitting their businesses into several units to provide greater flexibility in adapting to new markets. GE and Panasonic purchase most of their LEDs from other companies for integration into their lamps and luminaires.

The willingness of Asian companies and governments to make major investments in manufacturing equipment and the development of a local supply structure is leading to a wider geographical distribution of the industry. For example, U.S. LED manufacturers may perform the LED wafer growth and processing in the U.S., after which LED chips are sent to China for packaging and then returned to the U.S. to be integrated into streetlights. The small size and weight of LED chips and packages makes inter-continental transfers economical, but there is greater incentive to manufacture large LED luminaires and OLED panels close to the customer.

Manufacturers are reacting in several ways to the changing market dynamics. Most companies in China have aggressively expanded their capacity to gain maximum market share while the demand is strong and prices relatively high. European and U.S. companies are diversifying with emphasis on the added value of SSL and the opportunities to provide lighting as a service.

The design, manufacture, and installation of SSL lighting requires many new skills. Associations such as the Illumination Engineering Society provide distance learning, while universities such as Rensselaer Polytechnic Institute and the University of California at Davis have set up special programs to support undergraduate and graduate courses, as well as research in SSL. Many utilities have educational activities to promote understanding and effective application of SSL, as does the DOE SSL program.

5.0 LED Technology Status

LED lighting technology performance has improved dramatically over the past 10 years leading to the development of one of the highest efficiency light sources available. While much success has been achieved, more work is needed to realize the adoption rates required for substantial energy savings for the nation. Various technologies contribute to the development of high performance LED packages and luminaires, and their subsequent manufacturing. Understanding the factors affecting performance in the LED packages and luminaires and their practical limits of current solutions is critical to developing breakthroughs that can surpass some of the performance-cost paradigms that exist in LED lighting today. The following sections explores prospects for technological advances and the impacts of these on future performance. Ultimately the practical realization of products depends on the development of high quality, low cost, manufacturing technologies and the establishment of an efficient manufacturing supply chain. Therefore, the current status of manufacturing technologies and costs is also discussed.

5.1 Technology Status

5.1.1 LED Package Efficacy

Much progress has been made in LED package efficacy values since the DOE SSL Program began. Today's commercial LED packages can achieve efficacies of 200 lm/W. However, these very high efficacies are not achievable in practical operating conditions, as the LED must be operated at very low drive currents resulting in less overall luminous flux being generated in the package. Increasing drive current, warmer correlated color temperature (CCT), and increasing color rendering index (CRI) also comes with efficacy penalties in typical phosphor-conversion. The evolution of LED package efficacy over time at a typical current density of 35 amperes per square centimeter (A/cm^2) is shown in Figure 5.1. At this current density, the measured commercial products reach 160 lm/W for cool white and 130 lm/W for warm white. Further R&D is required to achieve 200 lm/W and beyond at high current densities and low cost. Various source architectures and their performance potential and light quality levels are discussed below.

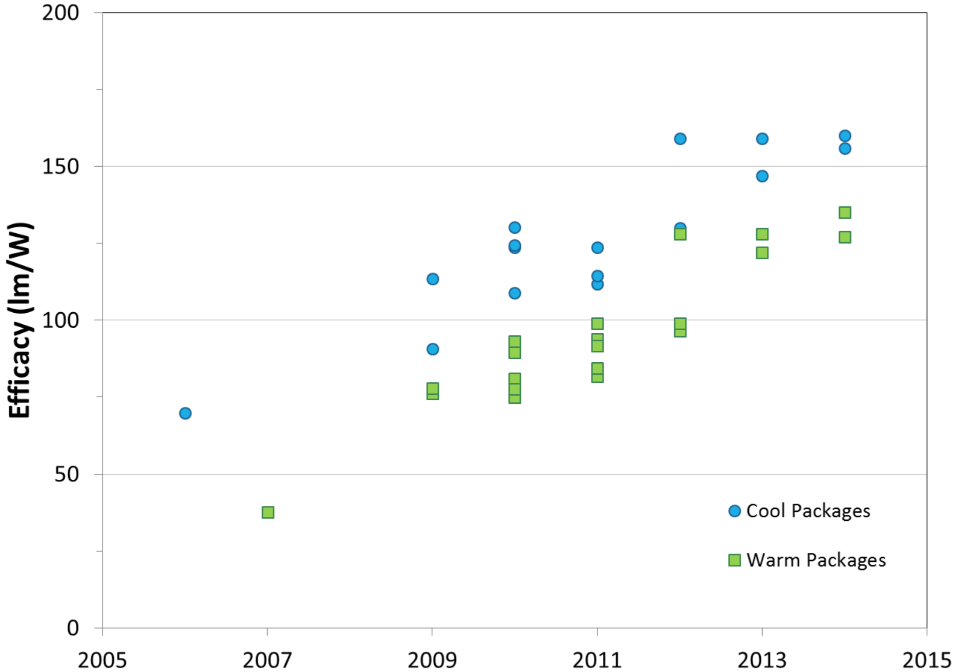
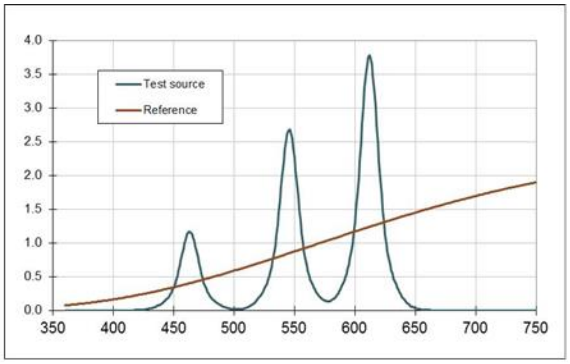


Figure 5.1 LED Package Efficacy Data for Commercial Packages Measured at 25°C & 35 A/cm² current Density

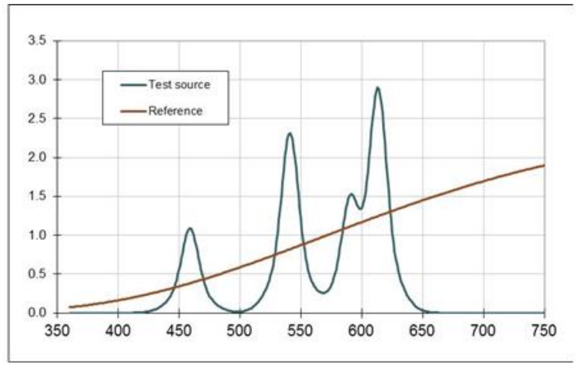
The theoretical maximum efficacy of an SSL product given perfect conversion of electricity to light is characterized by the luminous efficacy of radiation (LER), which is the amount of light obtained from a given spectrum per optical watt. Simulation work by Yoshi Ohno and Wendy Davis at the National Institute of Standards and Technology (NIST) has shown that LED emission spectra with good color quality and LER values in the range of 350 to 450 lm/$W_{optical}$ can be achieved [47, 48, 49]. If the theoretical best value is LER_{max} and LER is the practically achieved result from a light source, then LER/LER_{max} is the spectral efficiency of a given source. NIST's simulation model (version 7.5) was used to estimate efficacies for a number of CCT/CRI combinations, both for narrow-band monochromatic LEDs (color-mixed) and phosphor-converted LEDs, the latter simulated by using a combination of broadband LEDs and a narrow-band pump. The model will be used to explore the practical limits of LED package efficacy.

The performance of white-light LED packages depends on the basic LED architecture, but also on the CCT of the package, the CRI objective, and the spectral power density. Efficacy projections and program targets have been grouped into main categories: one for cooler CCT (5700K) with CRI equal to 70 and the other for warmer CCT (3000K) with CRI equal to 80.

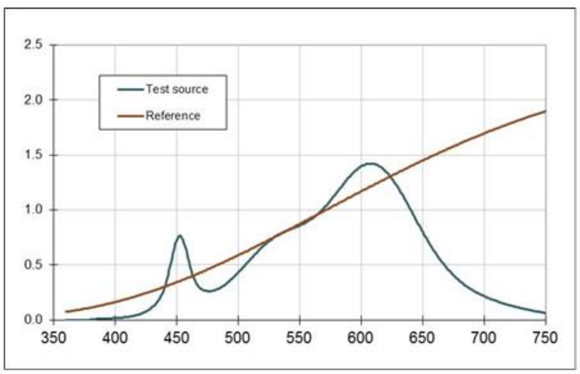
To analyze the potential efficacy of a white LED package, the theoretical limits are identified and the various sources of efficiency loss for the principal types of LED package are separately analyzed. Three categories are considered: (i) the color-mixed LED (cm-LED), (ii) the phosphor-converted LED (pc-LED), and (iii) the hybrid LED. The hybrid LED combines one or more monochromatic LED sources with a pc-LED.



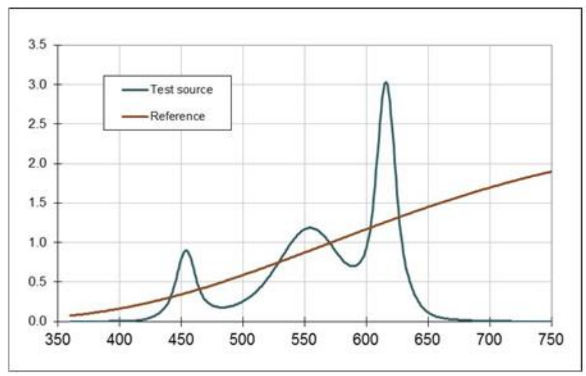
Typical Color-Mixed RGB LED Spectrum



Typical Color-Mixed RGBA LED Spectrum



Typical Phosphor-Converted LED Spectrum



Typical Hybrid LED Spectrum

Figure 5.2 Typical Simulated Optical Spectra for Each Approach Compared to Black-Body Curve (3000K, 85 CRI, R_9>0)

Typical simulated optical spectra for a warm white cm-LED (red-green-blue [RGB] and red-green-blue-amber [RGBA]), pc-LED, and hybrid (phosphor-converted plus monochromatic red source) LED are shown in Figure 5.2. The spectrum from a conventional incandescent black-body source is included as a reference for comparison. For each spectrum the peak wavelengths, spectral widths, and intensities can be optimized in order to determine LER_{max} for any given CCT and CRI.

In the following analysis, a CRI of 80 (R_9 greater than zero) was targeted for the warm white LED package and CRI of 70 (R_9 greater than zero where possible) for the cool white LED package. CRI reflects the ability of the source to accurately render a set of eight standard color samples R_1 to R_8 (CIE 1995) but fails to reflect 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 specification[l] 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 specification[m] calling for R_9 greater than or equal to 50. Relaxing the criterion for CRI or R_9 would result in a higher LER_{max} but would compromise the quality of light. The analysis assumes an operating current density of 35 A/cm^2 and a temperature of 25°C. Performance data discussed later has been obtained for packages with the same CCT and CRI combinations under equivalent operating conditions.

The theoretical maximum luminous efficacy of the LED can be calculated once the optimum spectrum and corresponding LER have been determined. For monochromatic sources the efficacy is determined by multiplying the contribution to LER from each peak in the spectrum by the power conversion efficiency (PCE) of that source. For the phosphor-converted source, it is necessary to integrate over the envelope of the phosphor spectrum with each point multiplied by the down-conversion efficiency and Stokes loss[n]. However, in order to simplify the analysis, the phosphor is represented by a simple Gaussian emission spectrum with a single overriding conversion efficiency and a single value for Stokes loss based on the peak of the emission spectrum. This is an imprecise assumption because the actual emission is rather broad and asymmetrical, particularly for the green phosphor; however it should provide a reasonable estimate. For the hybrid LED, both methods are combined to determine LED efficacy. Table 5.1 summarizes the parameter values used in the analysis.

Table 5.1 Key Parameter Values Used in the Analysis for LEDs (upper table) and Phosphors (lower table) in 2015 and 2020

LED Source	Wavelength Range (nm)	2015		2020	
		Power Conversion Efficiency (%)	Linewidth/ FWHM (nm)	Power Conversion Efficiency (%)	Linewidth/ FWHM (nm)
Blue	440-460	60	20	80	20
Green	520-540	22	20	35	20
Amber	580-595	8	20	20	20
Red	610-620	44	20	55	20

Phosphor Source	Wavelength Range (nm)	2015		2020	
		Quantum Yield (%)	Linewidth/ FWHM (nm)	Quantum Yield (%)	Linewidth/ FWHM (nm)
Green	530-560	95	100	99	70
Red	620-650	90	100	95	30

[l] For more information on the Energy Star specification requirements please see: http://www.energystar.gov/sites/default/files/ENERGY%20STAR%20Lamps%20V1%201_Specification.pdf
[m] For more information on the California Energy Commission voluntary specification requirements please see: http://www.energy.ca.gov/appliances/led_lamp_spec/documents/2014-12-10_Resolution_Voluntary_California_Quality_Led_Lamp_Specification_Resolution_No_14-1210-09_TN-74289.pdf
[n] Stokes loss arises from the difference in energy between the absorbed and emitted photons of the phosphor material.

The results of the analysis for the various LED architectures (i.e., RGB cm-LED, RGBA cm-LED, pc-LED, and hybrid LED), are summarized in Table 5.2. More details regarding the analysis methodology can be found in the 2014 MYPP [50].[o] Note: the projections for the color-mixed architectures do not include any additional losses for color-mixing.

Table 5.2 Summary of LER and Efficacy Performance at 2015 and 2020 for Various LED Package Architectures

Architecture	Warm White				Cool White			
	2015		2020		2015		2020	
	LER (lm/W)	Efficacy (lm/W)	LER (lm/W)	Efficacy (lm/W)	LER (lm/W)	Efficacy (lm/W)	LER (lm/W)	Efficacy (lm/W)
RGB cm-LED	397	134	397	189	367	124	367	180
RGBA cm-LED	388	81	388	146	-	-	-	-
PC-LED	331	143	387	242	331	158	352	236
Hybrid LED	368	171	392	244	-	-	-	-

The highest LER values are achieved for the cm-LED architectures; however, the practical efficacy is limited by low PCE values for amber and to a lesser extent for the green LEDs. If the PCE for both could be raised to 55%, approaching the target for the red LED, then the efficacy for both configurations would increase to around 230 lm/W. In order to achieve a target value closer to 250 lm/W, it will be necessary to increase PCE for red, green, and amber LEDs to around 60% each.

The configuration with the next highest LER is the hybrid LED which marries a narrowband red LED source with a phosphor-converted blue source. This configuration takes advantage of the high efficiency of green phosphors and current blue and red LEDs to achieve the highest efficacy performance. The efficacy is anticipated to increase to around 250 lm/W as these components are further improved. The obvious advantages offered by this approach are tempered by the poorer thermal stability of the conventional aluminum indium gallium phosphide (AlInGaP)-based red LEDs. Their very different thermal behavior compared with gallium nitride (GaN)-based blue LEDs requires control system to maintain a consistent color point, which adds complexity and cost.

The phosphor-converted approach offers similar LER values for both warm and cool white LEDs using current broad linewidth phosphors. As the red phosphor linewidth is reduced and approaches the red LED linewidth, the performance of the warm white pc-LED approaches the performance of the hybrid LED. The situation for the cool white LED is slightly different since there is a much smaller component of red light in the spectrum. To achieve a CRI of 70 and maintain a reasonable R_9 value, it is necessary to compromise the LER value, but ultimately there will be little difference between the efficacy of cool and warm white pc-LED sources.

The above analysis for warm-white LEDs has been performed at 3000K and a CRI of 80, however some sectors of the market are increasingly demanding higher color quality. Therefore, it is interesting to

[o] The 2014 MYPP is available at:
http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_mypp2014_web.pdf

consider the impact of CRI on efficacy. Using the simple model we estimate that increasing CRI from 80 to 90 will produce a drop in efficacy of around 10%, however practical data suggest the drop to be significantly higher, in the range of 15 to 25%. Therefore, the drive for higher CRI will have a significant impact on efficacy.

A more detailed analysis of the various losses for pc- and cm-LED packages is included in Table 5.3 and Table 5.4 respectively, along with the 2020 target.

Table 5.3 Summary of Warm-White pc-LED Package Efficiencies and Efficacies

Metric		2015 Status	2020 Target
LER (lm/W)		331	387
Blue LED	Internal Quantum Efficiency	89%	95%
	Extraction Efficiency	85%	90%
	Electrical Efficiency	93%	95%
	Package Efficiency	85%	99%
	Power Conversion Efficiency	60%	80%
Green Phosphor	Quantum Efficiency	95%	99%
	Stokes Efficiency	84%	
	Conversion Efficiency	80%	83%
Red Phosphor	Quantum Efficiency	90%	95%
	Stokes Efficiency	74%	
	Conversion Efficiency	67%	71%
Overall Source Efficiency		43%	63%
PC-LED Efficacy (lm/W)		143	242

Table 5.4 Summary of Warm-White RGB cm-LED Package Efficiencies and Efficacies

Metric		2015 Status	2020 Target
LER (lm/W)		397	
Blue LED	Power Conversion Efficiency[1]	60%	80%
Green LED	Power Conversion Efficiency	22%	35%
Red LED	Power Conversion Efficiency	44%	55%
Weighted Power Conversion Efficiancy[2]		34%	48%
CM-LED Efficacy (lm/W)		134	189

[1] See Table 5.3 for a detailed breakdown of efficiency channels.

[2] The weighted power conversion efficiency reflects the individual source power conversion efficiencies weighted by the proportion of each source in the final spectrum.

Conclusions

Comparing the color-mixed, phosphor-converted, and hybrid approaches, we can draw the following key conclusions:

- The hybrid approach offers the highest efficacy in the short term due to the ready availability of narrow red LED sources, but high thermal sensitivity of the red LED creates additional complexity.
- The phosphor-converted approach can match the hybrid approach, provided that efficient narrow-band red and green phosphors can be developed.
- The color-mixed approach will only realize its efficacy potential advantage over the phosphor-converted or hybrid alternatives when green and amber LEDs can be achieved with power conversion efficiencies in the 60% range.
- The hybrid approach does not offer a significant advantage over the phosphor-converted approach for cool white LEDs.
- The maximum projected LED efficacy at 35 A/cm^2 and 25°C is around 250 lm/W.
- Increasing CRI from 80 to 90 at 3000K results in a significant reduction in efficacy for a pc-LED of between 15 and 25%.

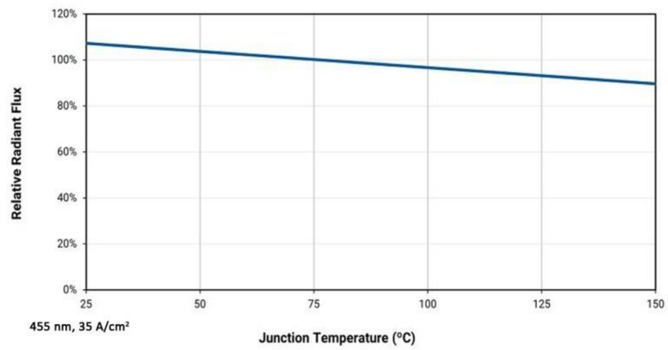
In a practical application, the current density and operating temperature will most likely deviate from the values used to perform the above analyses, impacting the efficacy. Reducing the operating current to minimize current efficiency droop can create a 15 to 20% increase in efficacy. Increasing the operating temperature, as typically experienced in a lamp or luminaire, will reduce the lumen output and produce a corresponding reduction in efficacy. Many LED packages are now routinely measured at a junction temperature of 85°C to be closer to the final device operating temperature and typically exhibit a 10 to 13% reduction in efficacy compared to a junction temperature of 25°C. Reducing the sensitivity of internal quantum efficiency (IQE) to current density (i.e., current droop) and temperature (i.e., thermal droop) remains a significant opportunity for improved efficacy and cost reduction. These and other loss channels are described in more detail in the next section.

5.1.2 Future Prospects

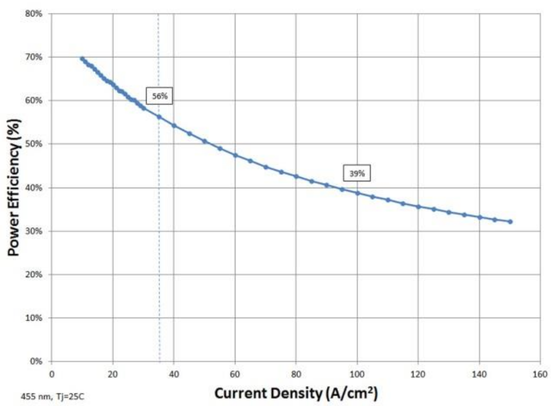
Phosphor-Converted LEDs

The vast majority of white LEDs currently used in SSL applications employ the phosphor-conversion approach. The performance of such devices is controlled by the efficiency of the pump LED source and the conversion efficiency of the phosphor material.

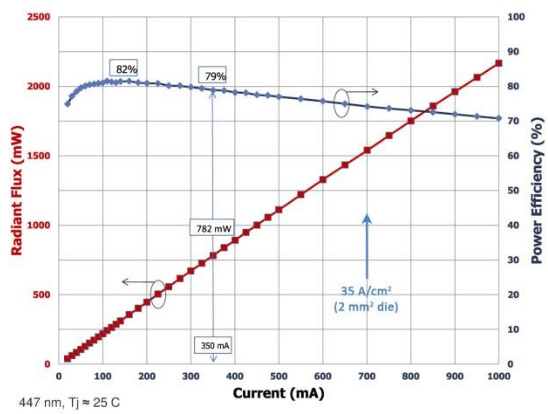
Current blue LEDs are already very efficient. The maximum internal quantum efficiency can be as high as 95% at low current densities. At typical operating current densities of 35 A/cm^2 the IQE drops to around 89% and the PCE (incorporating additional losses due to light extraction efficiency and electrical efficiency) is around 60%. The reduction in IQE as the operating current is increased is referred to as current efficiency droop and remains one of the critical performance limiting effects for typical operating conditions. A similar phenomenon known as thermal droop refers to a reduction in luminous flux as the operating temperature is increased. Figure 5.3 provides examples of droop behavior.



(a) Typical thermal droop (Cree XT-E)



(b) Typical current efficiency droop (Cree XT-E)



(c) State-of-the-art current efficiency droop

Figure 5.3 Examples of Thermal and Current Efficiency Droop Behavior
Source: (a)(b) Cree XLamp XT-E datasheet [51]*; (c) John Edmond, 2015 DOE SSL R&D Workshop* [9]

The origins of current density droop continue to be debated, but the general consensus is that Auger recombination is primarily responsible in conjunction with carrier transport issues associated with the presence of piezoelectric fields and asymmetrical electron and hole injection [52]. In order to realize the 2020 targets of IQE equal to 95% and PCE equal to 80% (at 35 A/cm^2), a significant reduction in current density droop will be required. Today's typical commercial blue LED devices exhibit PCE values in the 60% range at 35 A/cm^2; however, recent state-of-the-art laboratory results (see Figure 5.3c) have demonstrated a PCE of 75% at 35 A/cm^2 (700 mA), suggesting this target should be possible [9].

Another critical component in the pc-LED is the phosphor down-converter, which must exhibit high quantum yield in conjunction with a high optical flux saturation, excellent thermal stability, and narrow emission linewidth. Current phosphors possess high quantum yields in excess of 90% but exhibit relatively wide emission spectra (100 nanometer [nm] full width at half maximum [FWHM]) and suffer from saturation effects at high optical flux densities and temperatures. Work is required to identify new down-converter materials which maintain high quantum efficiency while offering improvements in linewidth, especially in the red spectral region where the target is 30 nm FWHM, and the saturation target is less than 5% quantum yield reduction at 1 watts per square millimeter (W/mm^2) compared to peak.

Color-Mixed LEDs

White LEDs comprising multiple monochromatic sources would, in theory, offer the highest efficacies, as discussed in Section 5.1.1. Current attempts to demonstrate these benefits have been impacted by the low efficiencies of green and amber LED sources, and thermal stability of red and amber AlInGaP based LED sources.

Improving performance for red and amber LEDs based on the AlInGaP materials system will present a significant challenge. This materials system is well understood, and the epitaxial growth technology is mature. Red LEDs in the 650 to 660 nm range can be very efficient but there is a rapid drop in efficiency as the wavelength is shortened into the range optimized for SSL applications (approximately 620 nm). This drop in efficiency is due to an increasing lack of carrier confinement as the energy difference between the active region material and barrier region material decreases. Unfortunately, little can be done to increase the barrier energy by changing the composition of the AlInGaP active region material due to a transition to indirect semiconductor at a bandgap energy of around 2.23 electron volts (555 nm). The indirect energy gap is virtually independent of material composition and provides a bottom limit to the emission wavelength, essentially ruling out its use for green LEDs. The maximum energy gap for the barrier material is similarly defined resulting in a shallower energy barrier and increasing lack of carrier confinement as the wavelength shifts from red to amber. This shallow energy barrier results in reduced quantum efficiency and extreme sensitivity to operating temperature due to the thermally-activated escape of carriers.

Despite these limitations, red AlInGaP LEDs have been very successfully employed in very efficient hybrid white LED sources in combination with a greenish-white pc-LED (white LED shifted off the black body curve toward the green), for example, Cree TrueWhite® technology. Such systems offer high efficiency and high color quality. The main drawback with implementing such an approach is dealing with the large difference in thermal stability behavior between the blue indium gallium nitride (InGaN) LED used in white pc-LED and the red AlInGaP LED. Typically, the hybrid white source incorporates a control system to maintain a consistent color point as the operating temperature changes but this adds cost and complexity.

The realization of an efficient green LED remains a unique technical challenge. There is a rapid reduction in efficiency as the green emission wavelengths are approached, both from the short wavelength side and long wavelength side, resulting in the so-called “green gap”. While performance of InGaN-based blue and violet LEDs has advanced rapidly over the past couple of decades with internal quantum efficiencies in excess of 90%, 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 of PCE. There are a number of physical phenomena underlying the drop in efficiency at longer wavelengths for InGaN-based materials, but solutions have proven elusive. High among the issues to be resolved is the growth of high quality InGaN with increasingly high indium content and increasing lattice mismatch strain. As a consequence, the PCE for 530 nm green LEDs based on InGaN quantum well active regions is limited to around 25%.

Amber and red LEDs based on the InGaN materials system require even higher levels of indium and suffer higher lattice mismatch strains. Therefore, the material problems impacting green InGaN LEDs are further compounded for amber and red LEDs. Work to improve the efficiency of green LEDs may suggest avenues to extend the useful operating range of InGaN LEDs to these longer wavelengths. Recent work suggests that further performance gains are possible using conventional planar device geometries, and that it is possible to extend the operation of such devices into the amber and red portions of the spectrum [53, 54]. The use of nanostructures, such as the growth on nano-patterned substrates or the growth of nanowires or nanorods, could offer a way to grow high quality layers of InGaN at the higher Indium content required for amber and red emission. Another research direction would be the use of engineered substrates with lattice parameters designed to have a closer match to the active region material in order to reduce the lattice mismatch strain during growth and reduce the dislocation density. An example of such a substrate is SCAM ($ScAlMgO_4$) which has the same lattice constant as $In_{0.17}Ga_{0.83}N$ for which the emission wavelength is around 505 nm [55].

Another 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 LEDs is included in Table 5.5.

Table 5.5 Comparison Between Direct and Phosphor-converted LEDs

Color	Approach	$\lambda_{peak}/\lambda_{central}$ (nm)	$\lambda_{dominant}$ (nm)	Efficacy (lm/W)	Conversion Efficiency (%)	Source
Green	Direct	530	-	147	25	OSRAM [56]
Green	Phosphor converted	540	-	209	32	OSRAM [56]
Lime Green	Phosphor converted	543	568	192	29	Lumileds [57]
Amber	Direct	-	590	60	12	Lumileds [57]
Amber	Phosphor converted	592	591	105	20	Lumileds [57]

Notes:

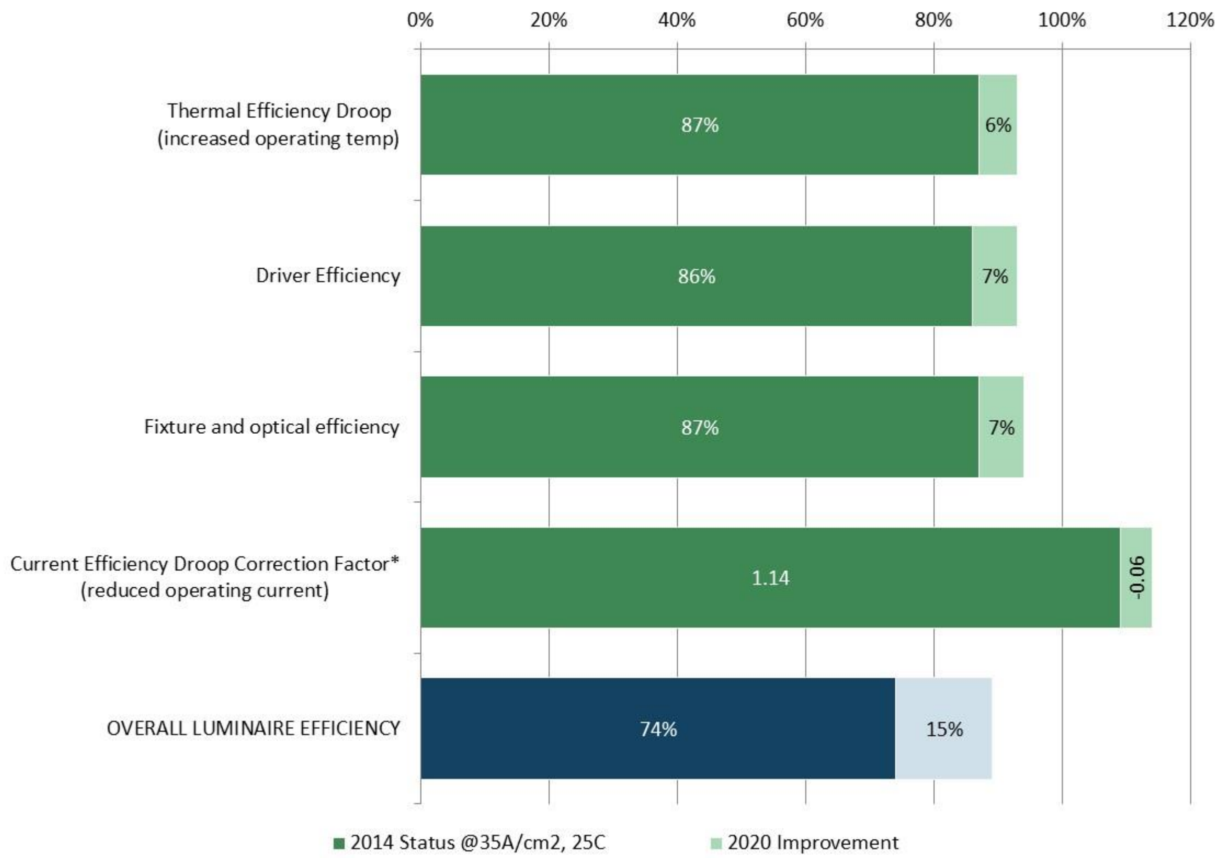
1. Devices are measured at 350 mA and 25°C (1 mm2 die size).
2. Conversion efficiency is calculated with reference to the theoretical maximum efficacy at the emission.

The phosphor-converted approach seems particularly well suited to green and amber LEDs where the fundamental semiconductor material challenges, greatly limit the efficacies of direct emitters. The relatively broad emission spectra associated with these sources will negatively impact LER, but can positively impact CRI. The future development of efficient narrow band down-converter materials to improve the performance of white pc-LEDs would therefore also enhance the prospects for separate narrow-band red, amber and green pc-LEDs. Combining individual narrow-band phosphor-converted red, amber and green LEDs with a blue LED would create an efficient RGBA white light source with enhanced color point stability and controllability.

5.1.3 LED Luminaire Efficacy

The efficacy performance of an LED luminaire is, to a significant degree, determined by the efficacy performance of the LED package. Integrating the LED package into a luminaire will result in additional efficiency losses, because power supply efficiency, optical efficiency, and thermal losses are included in the full luminaire performance characterization. Therefore, the efficacy of the LED package at a given operating current and temperature represents the upper limit for SSL luminaire efficacy.

In reality, the luminaire efficacy will depend on how the overall luminaire system comprising these various elements is optimized for a particular application. There are many different system design options to be considered when creating the optimum trade-off between cost and performance. Figure 5.4 and Table 5.6 help illustrate how these various components impact system efficiency. The overall system can be particularly sensitive to thermal management issues. SSL sources do not radiate heat and so it must be dissipated through the luminaire itself, in contrast to the traditional lamp and fixture combination. Optical efficiency depends on the optical system in the luminaire. Lenses, reflectors, optical mixing chambers, remote phosphors, and diffusers can all be employed, 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. For example, some streetlight 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 current efficiency correction factor reflects the benefit obtained by driving the LED package at a lower current density to minimize current efficiency droop.

Figure 5.4 LED Luminaire Efficiency Factors

Table 5.6 Breakdown of Warm-White[1] LED Luminaire Efficiency Projections

Efficiency Channel	2014	2015	2020	Goal
Package Efficacy Projection[2] (lm/W)	146	162	220	250
Thermal Efficiency Droop (increased T_{op})	87%	88%	93%	95%
Driver Efficiency	86%	87%	93%	96%
Fixture/Optical Efficiency	87%	89%	94%	96%
Current Efficiency Droop Correction Factor (reduced I_{op})	1.14	1.13	1.09	1.05
Overall Luminaire Efficiency	74%	77%	89%	92%
Luminaire Efficacy[3] (lm/W)	108	125	196	230

Notes:

1. Warm-white packages and luminaires have CCT=3000K and CRI=80.
2. Package efficacy projections are for the warm-white pc-LED, per Table 5.8
3. Luminaire efficacy is obtained by multiplying the package efficacy by the overall luminaire efficiency.

The thermal handling design in a luminaire, the operating current of the LED package, and the ambient temperature will determine the practical operating temperature of the LED package. In Table 5.6, 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. Instead of mounting LED packages onto a circuit board that is mounted onto the heat sink, luminaire developers are exploring mounting LED packages directly onto the heat sink whenever possible, removing thermal interfaces (and cost).

The driver efficiency of an LED luminaire describes the efficiency of the power supply in converting AC line power to an electrical input suitable for running the LED package(s). If a luminaire is dimmable, the power supply must also be able to convert the dimmed input into an appropriately dimmed LED output. The efficiency of the power supply is typically not constant during dimmed operation. Different lighting applications and products require a wide range of light outputs, requiring different numbers of LED packages in varied circuit architectures. The range of luminaire architectures has made it difficult to apply a standard power supply architecture or module. In new LED packages, some of the power supply functionality can be embedded in the package itself. AC LED packages are designed to run directly off of AC line power. High-voltage LEDs contain multiple LED electrical junctions in series to raise the operating voltage of the package closer to the line voltage and overcome some driver efficiency losses. Luminaire designers can take advantage of these products to reduce the cost and improve the efficiency of the power supply within the luminaire.

The correction factor for current efficiency droop reflects the benefit obtained by driving the LED package at a lower current density to minimize current efficiency droop. Reducing the operating current density below the nominal 35 A/cm^2 can improve efficacy by up to a factor of 1.14, although this factor will become smaller as current efficiency droop is gradually improved. Reducing the operating current can also facilitate lower operating temperatures which can reduce the impact of thermal droop and improve the efficiency of the luminaire, although the larger number of LED packages required generally has a cost implication. System-level optimization of the various trade-offs can lead to higher efficacies than those suggested in Table 5.6.

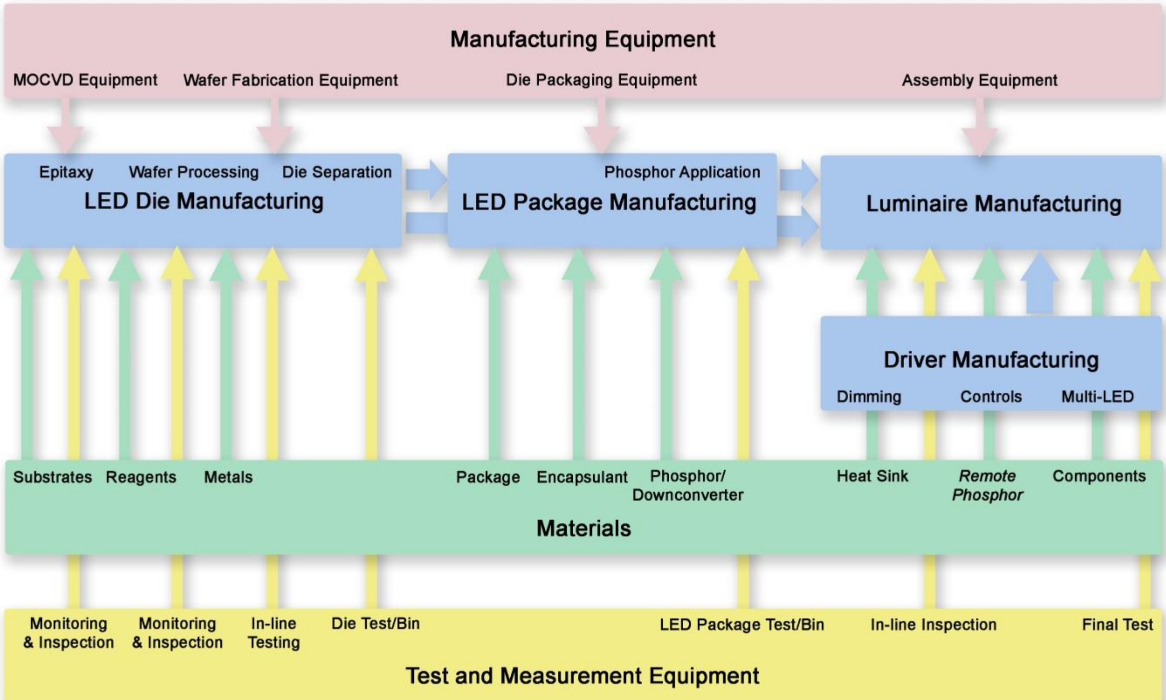
There are a number of practical examples of lamps and luminaires currently under development that highlight the kind of performance gains that can be achieved through careful system optimization. Philips first announced the realization of a prototype 200 lm/W TLED lamp in 2013 [58]. The lamp is designed to replace fluorescent tube lighting and uses a hybrid (white + red) LED architecture to achieve the high efficacy at a CCT in the 3000 to 4500K range with CRI and R_9 greater than 80 and 20, respectively. In January 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 American National Standards Institute (ANSI) color specification for 3000K [59]. In March 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 [60]. In all cases, these R&D products meet the 2020 target shown in Table 5.6 and serve to demonstrate that significantly better performance can be obtained from the same LEDs through careful system optimization. In particular, all three implementations take advantage of the hybrid approach to producing a white light source which currently offers the best performance (as discussed in section 5.1.1). Commercial products based on these prototype demonstrations are scheduled for release in 2015.

5.2 Manufacturing Status

5.2.1 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 5.5 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.



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 5.5 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.

5.2.2 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 25% in a replacement lamp to even 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 5.6. 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 allows you 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.

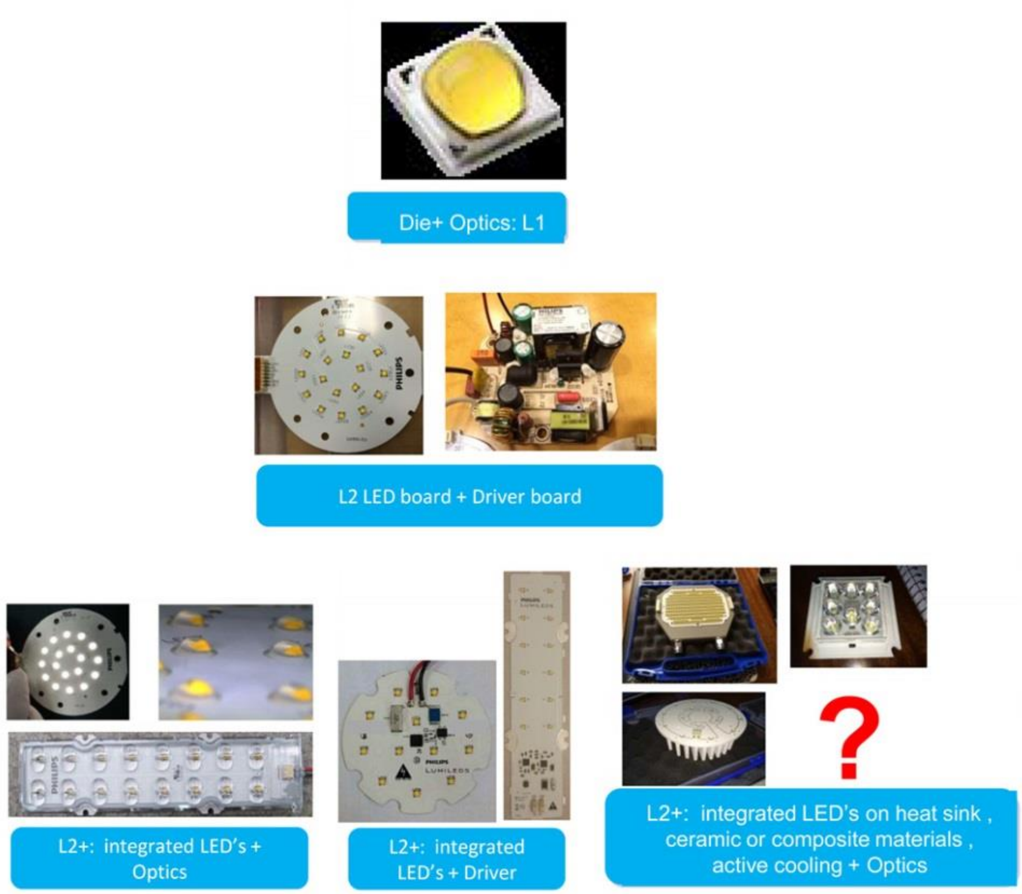


Figure 5.6 Integration Path for LED Components
Source: Ian Black, DOE SSL R&D Workshop, San Francisco, CA, January 2015 [61]

Package Diversity

The variety of LED packages for general illumination has exploded in recent years from a few types of 1 watt (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.

Three main LED package platforms (shown in Figure 5.7) 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 (0.1-0.5 W) typically used in products requiring omnidirectional emission (e.g. troffers, A-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).

a) **High-Power**: Ceramic substrate, molded lens

b) **Mid-Power**: Leadframe, Polymer

c) **Chip on Board**: MC-PCB, ceramic PCB

Figure 5.7 Examples of High-power, Mid-power, and Chip-on-board 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-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 covered with a phosphor mixed silicone encapsulant and resemble a fried egg. 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.

More recently, the chip scale package (CSP), also called a package-free LED or white chip, has gained attention as a compact, low cost alternative to the mid-power platform. In the semiconductor industry a CSP is defined as direct surface mountable package comprising a single die with a package area no greater than 1.2 times that of the die [62]. The development of CSPs for silicon ICs was driven by the need for miniaturization, improved thermal management, higher reliability, and ease of integration into Level 2 packaging. Recent examples of CSP LED products include the Samsung LH141A and Toshiba TL1WK shown in Figure 5.8(a).

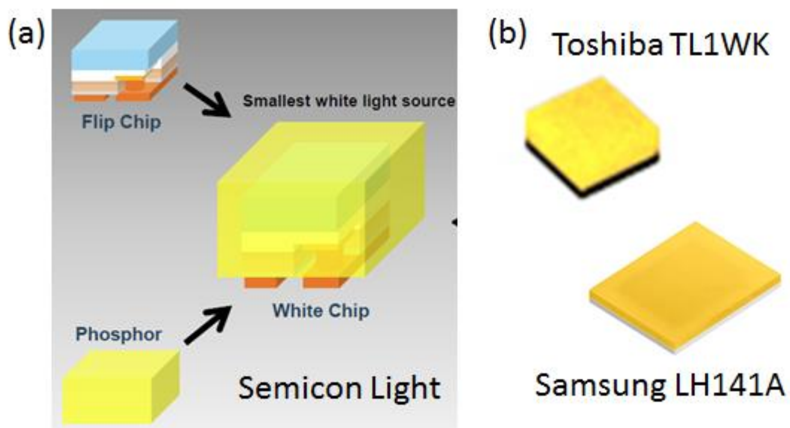


Figure 5.8 (a) Schematic Representation of a CSP Manufacturing Approach and (b) Recent Examples of Commercial CSPs.

Source: (a) Eun-Hyun Park, Strategies in Light 2015 [63]*, (b) Toshiba* [64] *& Samsung* [65] *Press Releases*

The majority of current CSP LED products use flip-chip die as a base, onto which the phosphor and encapsulant is applied. The CSP provides luminous flux on five sides and at wider angles. Eliminating wire bonding and removing the need for lead frames or ceramic substrates, allows for a more compact size and reduced cost. A recent trend in LED CSP manufacturing is to apply a conformal phosphor coating directly onto a blue flip-chip LED die, as shown schematically in Figure 5.8(b). Both Samsung and Toshiba have made recent product announcements based on this newer technology [65, 64].

While CSPs offer the potential for significant system cost savings, there are various performance trade-offs 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.
- Handling of packages must be optimized in order to avoid destroying the phosphor layer, because direct handling of the phosphor layer is unavoidable.
- Increased levels of electrostatic discharge (ESD) protection is required, because CSP devices do not have integrated Zener diodes for ESD protection.

LED Package Costs

The typical cost breakdown for a high-power and mid-power LED package is shown in Figure 5.9. 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 0.1 mm^2 die packaged in a plastic leaded chip carrier package of similar dimensions. In both cases, the analysis was performed using the LEDCOM modular cost model [66]. The cost breakdown for the high-power LED package is largely unchanged compared with 2013, 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.

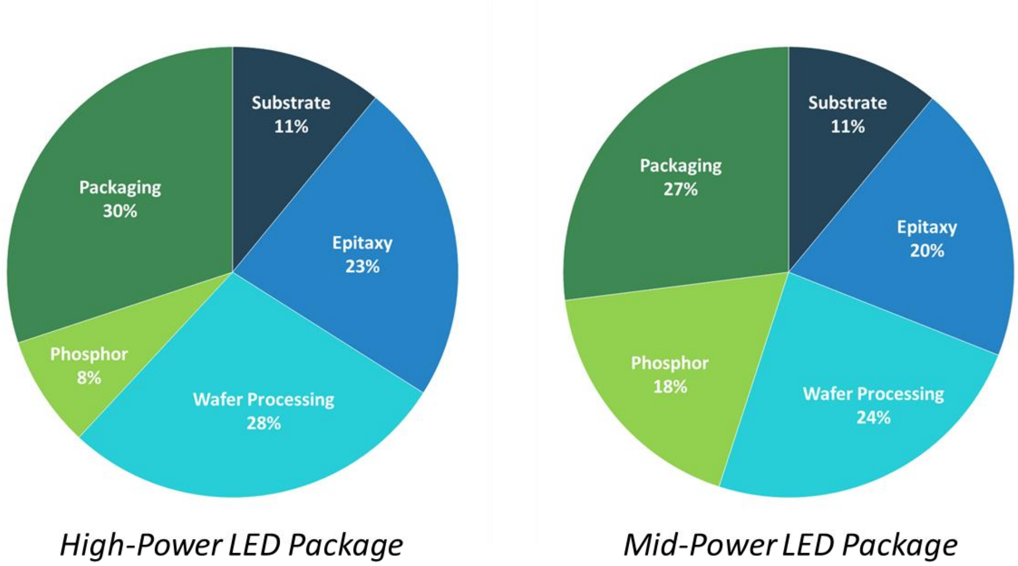


Figure 5.9 Typical Cost Breakdowns for High-Power and Mid-Power LED Packages
Source: Inputs from DOE SSL Roundtable and Workshop attendees

Figure 5.9indicates 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. Substrate and phosphor costs are a smaller proportion of the total cost for high-power devices although phosphor costs remain significant for mid-power devices. These breakdowns suggest the need for a more holistic approach to cost reduction. Figure 5.10 shows how the high-power LED package cost may change over time as volumes continue to ramp, falling to about 35% of 2014 values by 2020. It is anticipated that the relative contribution from substrate, epitaxy, and phosphor will rise over this period while the relative contribution from wafer processing and packaging will fall. The overall reduction in cost over this time period remains consistent with the price projections reported in the 2014 MYPP assuming general reductions in materials costs, a movement toward chip-scale packaging, and a continuing erosion of gross margins [50].

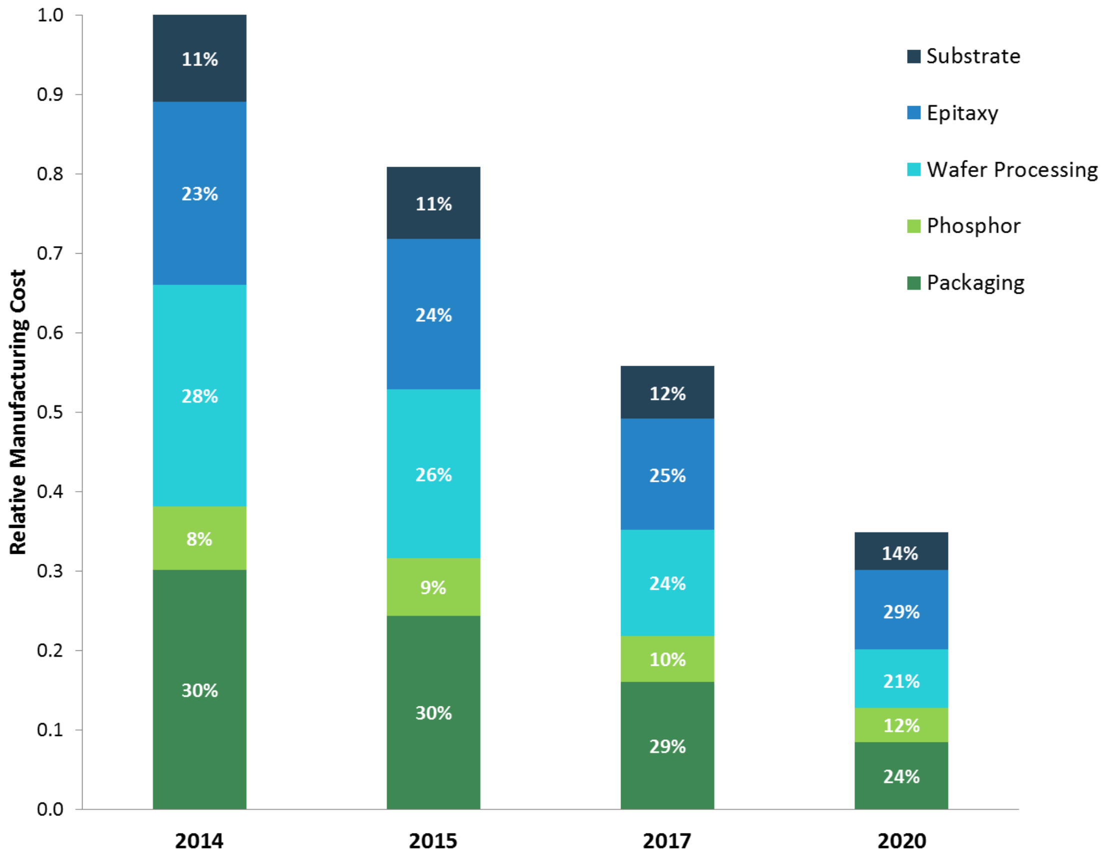


Figure 5.10 Projected High Power LED Package Cost Reduction
Source: Inputs from DOE SSL Roundtable and Workshop attendees

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

5.2.3 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.

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-bulb paradigm, with the manufacturing of each part handled completely separately, 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 5.11 shows a comparison of the cost breakdown for an outdoor area lamp, indoor residential downlight, and A19 replacement lamp (and has been revised from previous years based on inputs from the community). It is apparent that the relative costs for different form factors can vary considerably, especially the cost of the LED package(s). Overhead costs also represent a real cost element, especially for 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 30% plus.

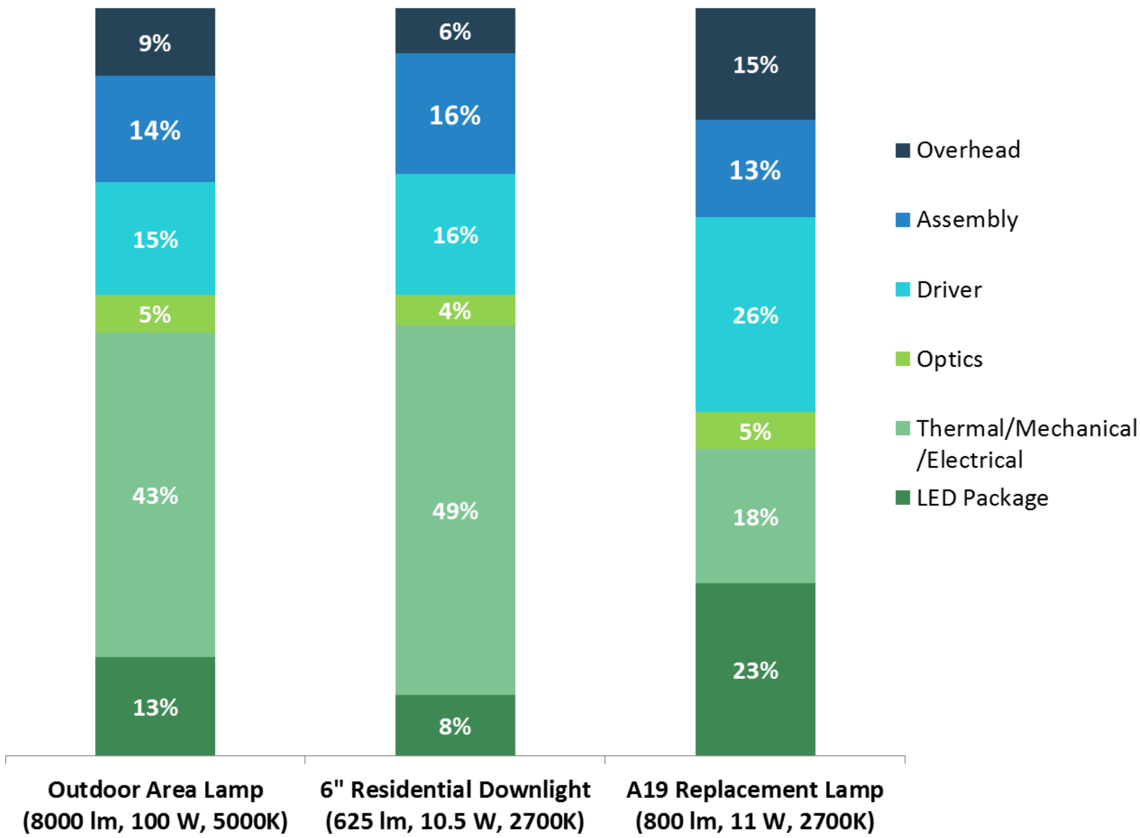


Figure 5.11 Comparison of Cost Breakdown for Different Lighting Applications
Source: DOE SSL Roundtable and Workshop attendees and industrial partners

For a specific product, it is useful to consider how the cost breakdown might change as a function of time. Figure 5.12 shows how the relative manufacturing cost for a common A19 60 W equivalent replacement lamp is expected to change between 2014 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 2014 to around 11% by 2020. As noted above, and shown in Figure 5.11, relative costs vary widely among specific luminaire and lamp types, so it is not possible to project a generic luminaire cost breakdown. Nonetheless, for most types, a factor of two to three times reduction in relative cost is not an unrealistic expectation.

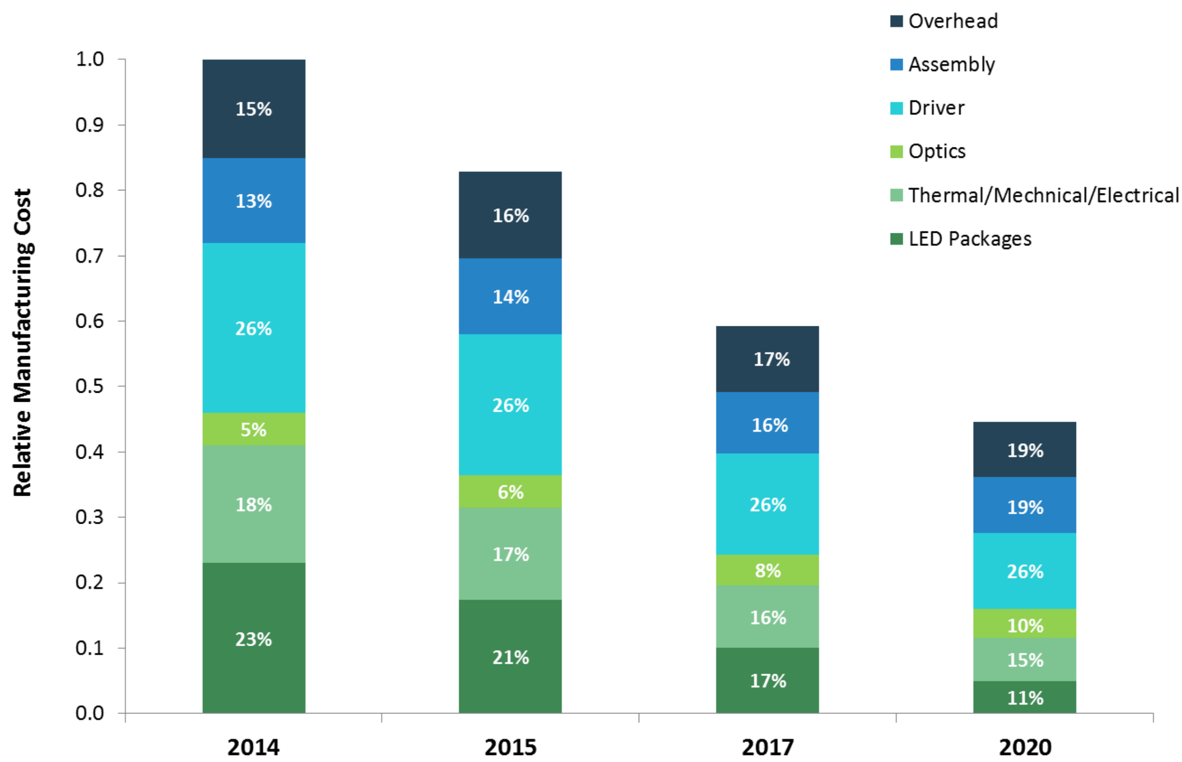


Figure 5.12 Cost Breakdown Projection for a Typical A19 Replacement Lamp
Source: DOE SSL Roundtable and Workshop attendees

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 products, no single cost element now dominates and cost reduction will be achieved by focusing on optimization of the complete system rather than focusing on any specific cost element.

The key cost drivers for each major element of the LED supply chain are summarized in Table 5.7.

Table 5.7 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

5.2.4 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 no longer understood to 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 [67]. 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, and IES has documented a forecasting procedure, IES TM-21 [68]. 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 simulate 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 LM-80 data from more than 100 different LED products was analyzed using this methodology and supplemented with new experimental data. 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. The study has determined that the materials of construction at the die and package level has a direct impact on long-term performance of LEDs.

Different LED package platforms (detailed in Section 5.2.2) 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.

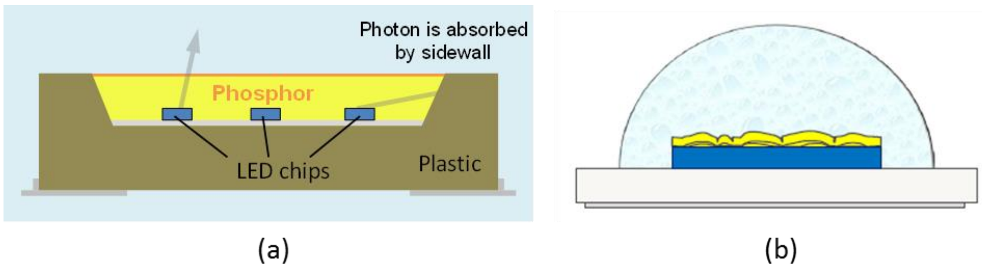


Figure 5.13 LED Package Schematics Showing (a) Sidewall Discoloration and (b) Phosphor Delamination.
Source: Monica Hansen, Strategies in Light 2015 [69]

Different grades of plastic resin have different lumen degradation behavior as seen in Figure 5.14. 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 5.14 compares the lumen degradation performance of mid-power packages using PPA and EMC plastic resins with high power packages using ceramic substrates. A more recent package material, silicone molding compound (SMC), has been shown to provide even better thermal stability than EMC. The number of LED products using SMC is limited today but are expected to grow in the next couple of years.

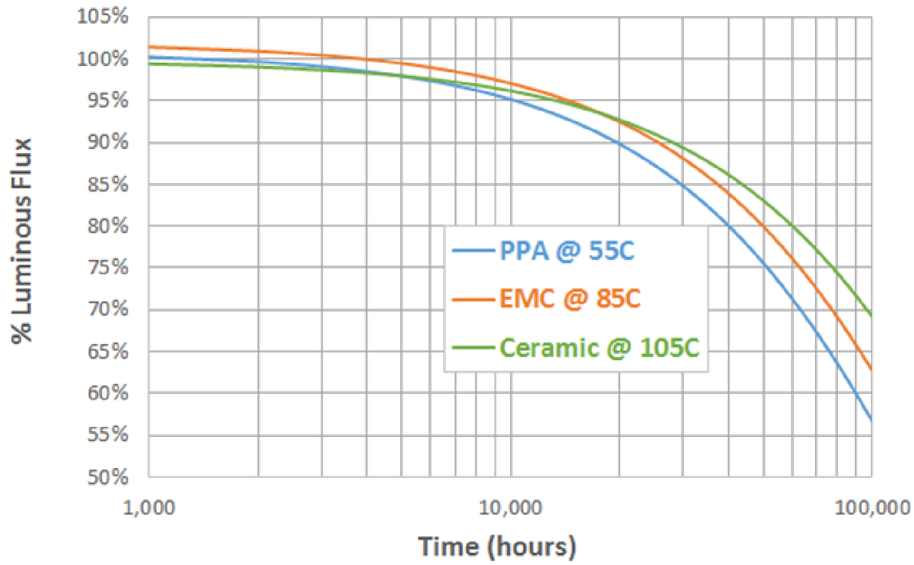


Figure 5.14 Lumen Degradation Performance of Mid-Power Packages (PPA and EMC Plastic Resins) and High Power Packages (Ceramic Substrates).
Source: Monica Hansen, Strategies in Light 2015 [69]

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. For this reason it has received less attention than lumen depreciation. 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 as demonstrated in Figure 5.15, but the magnitude of the color shift as a function of temperature will vary with packaging materials and manufacturing processes.

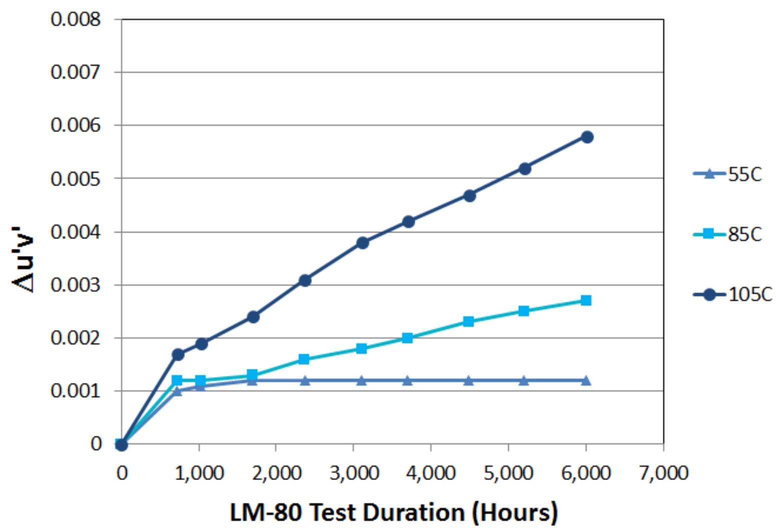


Figure 5.15 Color Shift of LED Package as a Function of Temperature
Source: Monica Hansen, Strategies in Light 2015 [69]

The resulting direction of color shift depends on the dominant degradation mechanisms occurring in the package. Phosphor cracking and delamination can occur (as shown in Figure 5.13b), and if severe enough, it can lead to a yellow shift in the spectrum due to an increase in the distance the blue photons travel through the phosphor. Discoloration of the plastic resin in the mid-power LED package (illustrated in Figure 5.13a) 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.

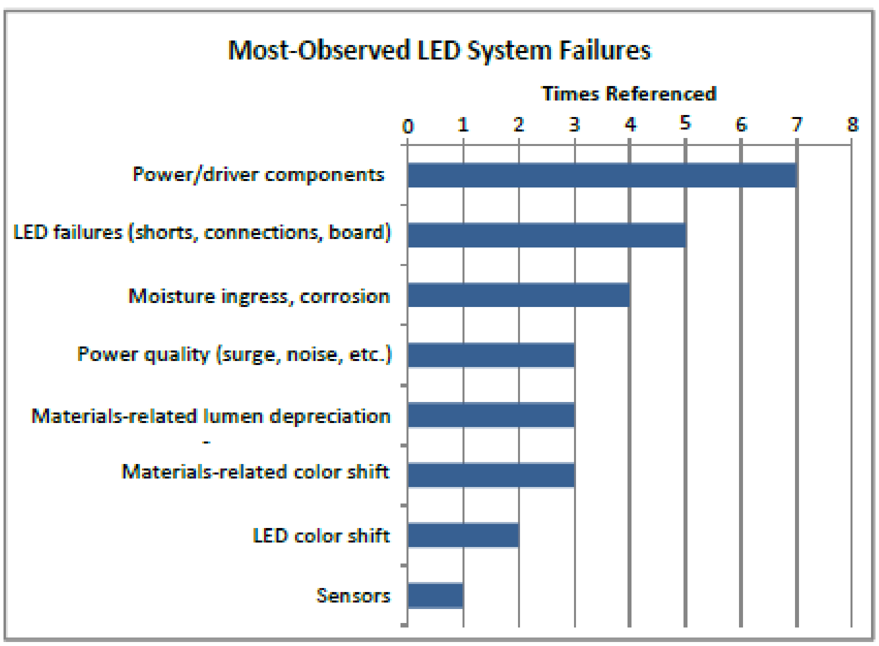
Experimental studies utilizing accelerated life tests (ALT) performed by RTI International have also provided insights into the impact of LED package materials on color point stability. Wet high temperature operating life (WHTOL) testing has been performed on individual high-power LEDs at 85/85 temperature/relative humidity settings. A color shift was seen in the warm white LEDs after 4000 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. 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.

Luminaire Reliability

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.

The LED Systems Reliability Consortium (LSRC), sponsored by DOE and the Next Generation Lighting Industry Alliance (NGLIA), is a group of industry, academic, and government representatives with the objective of advancing our knowledge of the failure and lifetime of LED systems (e.g., luminaire, lamp, and light engine). In 2014, the consortium 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 [70].

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-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 5.16.



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

Figure 5.16 The Most Commonly Observed Failures from LSRC Member Survey
Source: Next Generation Lighting Industry Alliance LED Systems Reliability Consortium, 2014 [70]

While color shift has not been identified as the largest reliability concern in this survey, it remains a real challenge since color shift is unique to the LED lighting industry and does 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.

5.2.5 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 $/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.

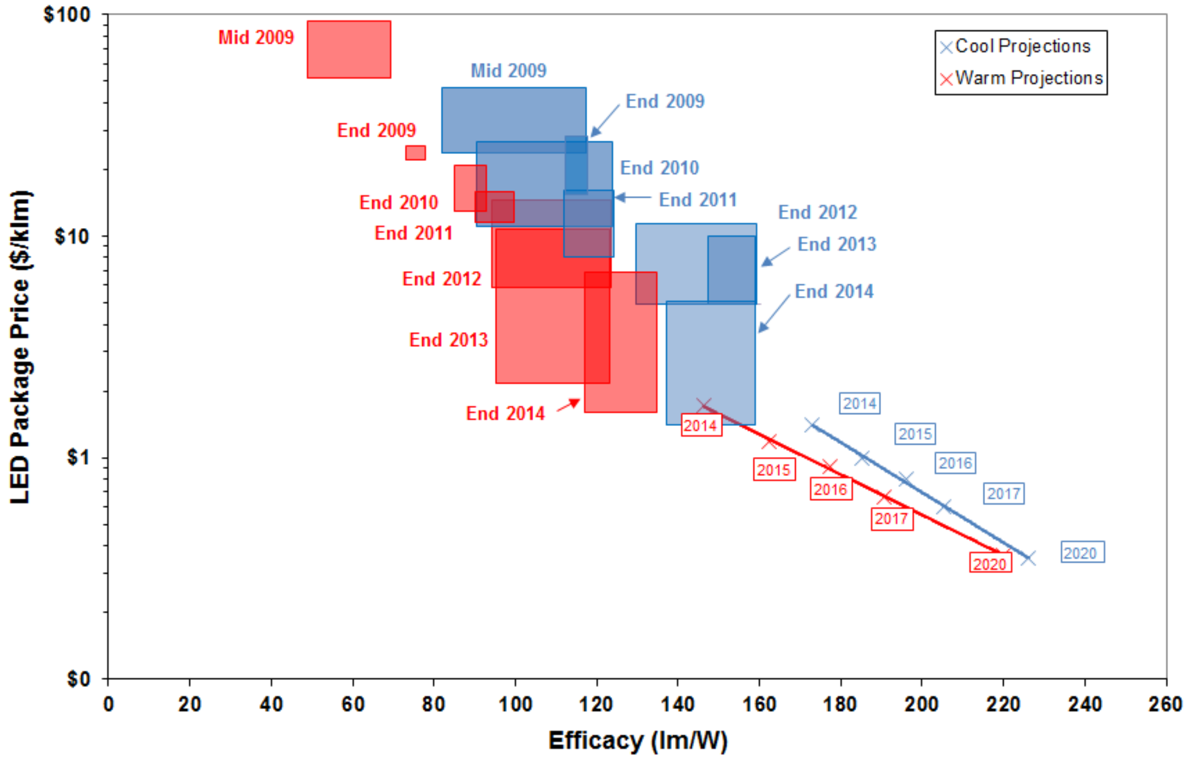


Figure 5.17 Price-Efficacy Trade-off for LED Packages at 1 W/mm^2 (equiv. 35 A/cm^2) and 25°C

Notes:

3. Cool-white packages assume CCT=5700K and CRI=70; warm-white packages assume CCT=3000K and CR=80.
4. Rectangles represent region mapped by maximum efficacy and lowest price for each time period.

The evolution of LED package efficacy and price is illustrated in Figure 5.17. Each time period is characterized by a rectangle with an area bound by the highest efficacy and lowest price products. Efficacies as high as 159 lm/W (cool white) and 135 lm/W (warm white) have been reported during 2014 as well as prices as low as $1.4/klm (cool white) and $1.6/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 5.17 for comparison purposes and are summarized in Table 5.8. 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 5.8 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)	173	185	205	226	250
Cool-White Price ($/klm)	1.4	1.0	0.6	0.35	0.3
Warm-White Efficacy (lm/W)	146	162	190	220	250
Warm-White Price ($/klm)	1.7	1.2	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 $/klm price once the total internal die area is known. Most major manufacturers have indicated that they will be prepared to share die area information with the 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.

LED Lamp and Luminaire Prices

LED lamp and luminaire prices vary widely depending on the application (see for example Table 2.1). To validate the progress on price reductions for LED-based lighting, a comparison of replacement lamps is both practical and appropriate. The most aggressive pricing has been associated with residential lamps, and consequently, the analysis will focus on the ubiquitous dimmable A19 60W-equivalent (800 lumen) replacement lamp.

Figure 5.18 demonstrates how the lowest retail price for the A19 lamp (neglecting subsidies and fire sales) has dropped over the past five years and how it compares to a typical conventional 13W CFL. The retail price is now below $10, corresponding to a normalized price in the $11/klm to $12/klm range, which remains in good agreement with the DOE projection (also shown in the figure). Furthermore, price reductions have continued unabated during the early part of 2015 with retail prices dropping below $8, corresponding to a normalized price below the $10/klm barrier.

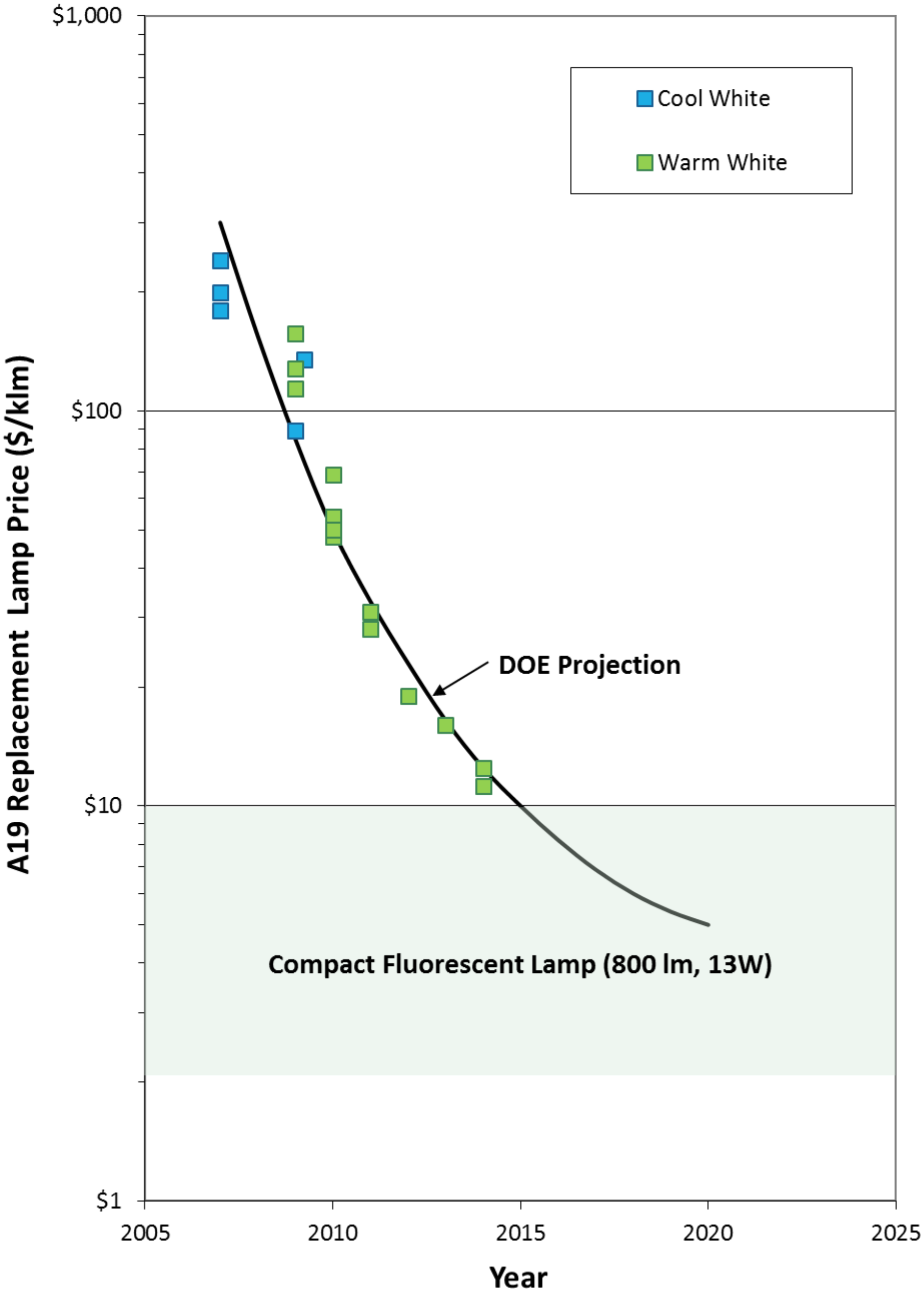


Figure 5.18 A19 Replacement Lamp Price Projection (60W Equivalent; Dimmable)
Note: The shaded region illustrates the price range for a typical equivalent performance CFL (13W, self-ballasted CFL, non-dimmable at bottom, and dimmable at top).

Retail prices for LED replacement lamps that appear in the Lighting Facts database have continued to fall, with reductions of 20 to 30% over the past year for most lamp types. For example, A19 60W equivalent lamps have fallen from $16/klm to $11/klm, PAR38 lamps have fallen from $37/klm to $23/klm, and 6” residential downlights have fallen from $43/klm to $30/klm. The main exception is the

MR16 lamp, which has only fallen slightly in price, consistent with the greater emphasis currently being placed on improving CRI performance. For existing product designs, it will become increasingly difficult to achieve further price reductions; therefore, new designs are constantly being introduced to realize lower prices while minimizing performance compromises.

Further rapid price reductions are expected for LED-based lamps and luminaires as the manufacturing technology matures, production volumes increase, and competition intensifies. Price reductions will continue to spur the adoption of energy efficient lighting products and contribute to energy savings.

6.0 OLED Technology Status

OLED lighting technology has reached a stage where successful commercialization of products is feasible. The performance, in terms of efficacy, lifetime and color, is competitive with other energy efficient lighting technologies such as fluorescent lamps and LED luminaires. Luminaires with exciting new form factors are moving from concept studies to the market-place. The key obstacle to adoption of OLED lighting remains cost, but substantial progress has been reported in the past year. It is possible that near term adoption of OLED lighting products will generate sufficient interest and revenue to support the development of manufacturing technology to enable further cost reductions.

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 in this section. The performance goals are compared to recent data which illustrate the efficacy trade-offs that are made to realize desirable lifetime and color quality as well as unique form factors.

For OLED lighting, the integration of a panel into a luminaire does not typically alter the performance specifications significantly, but some deviations in cost and performance are expected and discussed. 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 pricing is given and trends for upcoming luminaires are explored in the following sections as well.

6.1 Technology Status

6.1.1 OLED Panel Efficacy

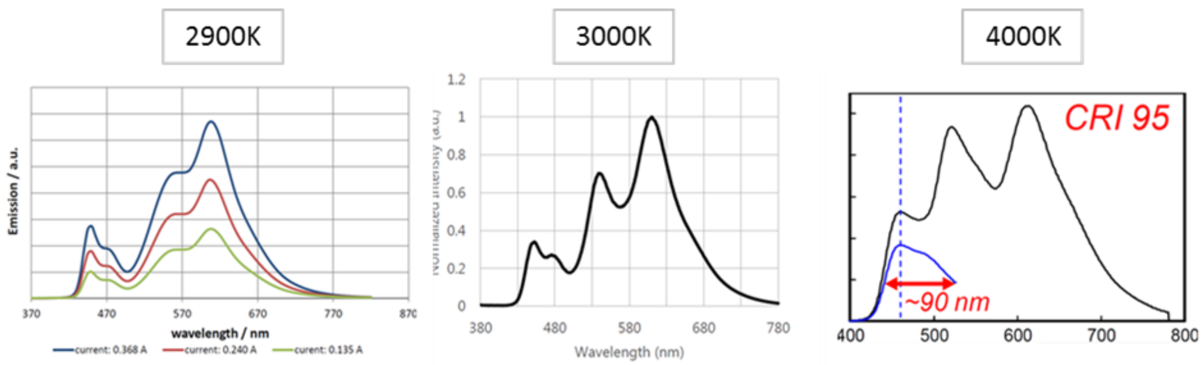
The laboratory-demonstrated efficacy in white OLED panels is continually rising. Most recently, Konica Minolta has shown a 15 cm^2 panel with an efficacy of 139 lm/W at 1,000 candelas per square meter (cd/m^2) and 126 lm/W at 3,000 cd/m^2 [71]. This represents an 8 lm/W improvement over the 2013 panel efficacy. Lumen maintenance (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 lumen maintenance (L_{50}) of over 100,000 hours when operated at 1,000 cd/m^2. Although this is an impressive number, it corresponds to an L_{70} lifetime of only 10,000 hours for a luminance of 3000 cd/m^2.

Though many companies made strides in their efficacies in 2014, no commercial panel product has yet surpassed the 60 lm/W efficacy that was produced in 2013 by LG Chem. This is due in part to delays in the implementation of internal light extraction solutions and a stronger focus being placed on balancing maximum efficacy against other important characteristics including color quality, lifetime, and form factor. For instance, in the past year, LG Chem has ratcheted the lifetime from L_{70} at 3,000 cd/m^2 of 20,000 hours to 40,000 hours while maintaining efficacy of 60 lm/W. With better control over these parameters the attention has again turned to efficacy, and LG Chem is targeting the commercialization of panels producing 100 lm/W and lumen maintenance L_{70} of 40,000 hours in 2015 [72].

This section provides a breakdown of OLED efficacy and provides likely practical limits for OLED panels.

Spectral Efficiency

The white light emitted by OLEDs is generated by two or three different colored emitters. The relative densities of the several emitters must be chosen to give good color quality and high efficacy. During the last two years much development work has been focused upon improvements in color quality. Figure 6.1 shows the spectra for two commercial panels from Philips and LG Chem and one laboratory panel from Panasonic. This comparison illustrates that there may be a penalty in LER of the order of 10% in assuring excellent color with vivid reds (high value of R_9). Given the relatively broad spectra of organic emitters, 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
LG Chem: CRI 89; R9 31; LER 328 lm/W
Panasonic: CRI 95; R9 77; LER 300 lm/W

Figure 6.1 Spectra of Commercial and Laboratory OLED Panels

Source: Philips Brite FL300 Data Sheet [73]*; LG Chem OLED Light User Guide* [74]*; C.T. Komoda "Overview of White OLED Technologies for Lighting Application", Printed Electronics USA, November 2014* [75]

The relatively broad line-width of red emission from OLEDs makes it difficult to achieve excellent color quality and high efficacy simultaneously. Thus, the LER in each of these examples is similar to that of pc-LEDs, which also contain broad emitters. The Panasonic panel shown in Figure 6.1 has a blue emitter with a peak at 460 nm and a full-width half-maximum linewidth of 90 nm.

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 in 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 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 mA/cm^2 for a single-stack device.

High electrical efficiencies of around 80% are observed with the use of stacked devices. However, there are trade-offs 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 interfaces lead to resistive losses across the device. Thus, careful design and materials selection is needed to realize improvements. Figure 6.2 compares the luminance vs. voltage characteristics of two panels from LG Chem, showing how losses are reduced with a tandem device operated at higher voltage and lower current. The left-hand plot is for a 2-stage tandem device at a CCT of 4000K, while the right-hand plot is for a 3-stage panel at 3000K. Note that the extra voltage required to produce the third photon is only around 2.5 V. At a luminance of 3,000 cd/m^2, the electrical efficacy is close to 80%.

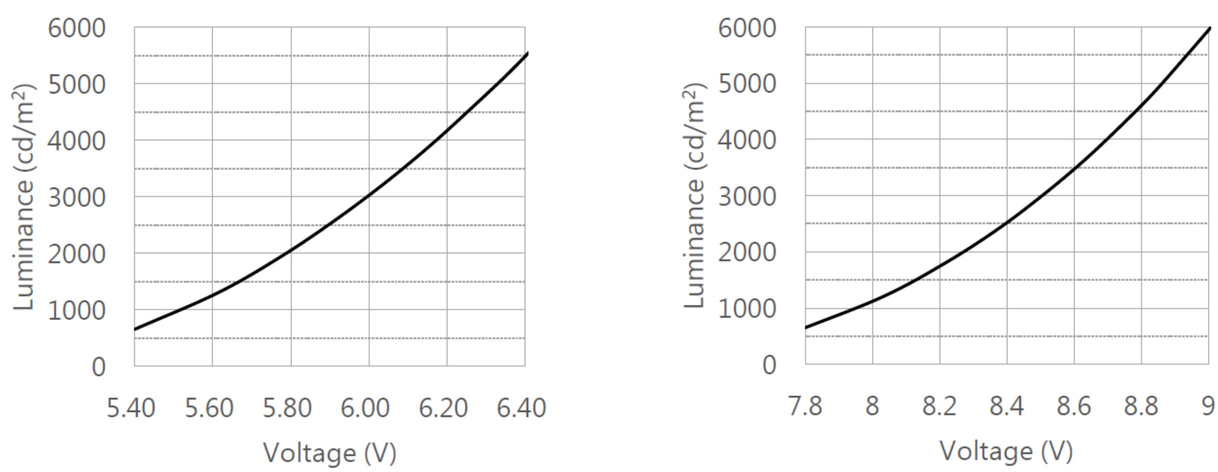
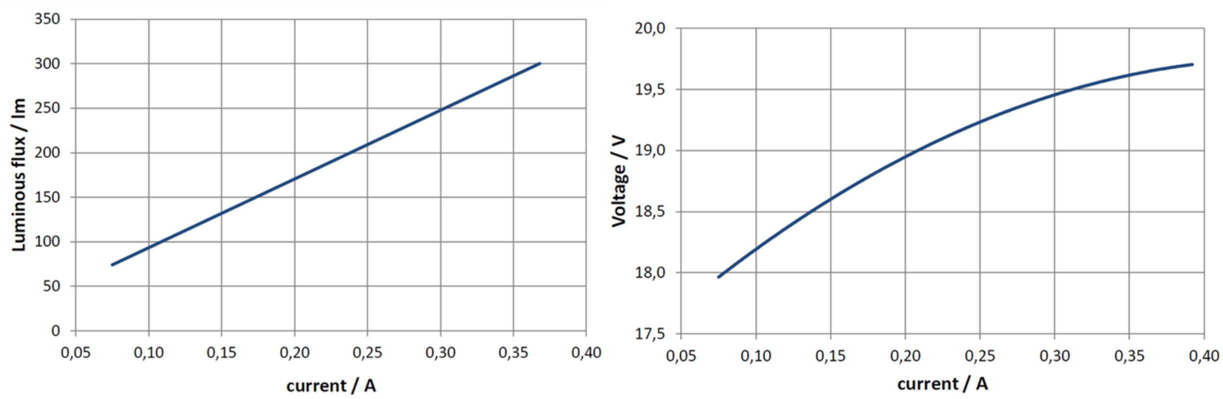


Figure 6.2 Luminance vs Voltage for a 2-stage Panel (left) and 3-stage Panel (right) from LG Chem
Source: LG Chem OLED Light User Guide [74]

Data on the Philips FL300 panel, which has a 6-stage structure with an emissive area of 105 cm^2, provides further insight into the dependence of luminance on current and voltage. Figure 6.3(a) shows that the luminous flux varies linearly with current, but there is a small effective threshold so that the efficacy decreases with increasing current. Output of 10 klm/m^2 can be attained at a current below 0.12 A. Figure 6.3(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%.



(a) (b)

Figure 6.3 Dependence of Luminous Flux and Drive Voltage on Current
Source: Philips FL300 Datasheet, 2014 [73]

The Philips FL300 is designed to operate at very high brightness, producing 300 lumen at a current of 0.368 A [73]. The increase from 100 lumen to 300 lumen leads to a 12% decrease in efficacy. The required drive voltage increases from 18.2 V 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 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, though triplet-triplet annihilation can result in additional singlet emission such that IQE as high as 40% has been observed [76]. On the other hand, phosphorescent molecules have demonstrated near 100% IQE. The major problem in exploiting phosphorescent molecules is that their excitation energy is held for a much longer time than in fluorescent systems (typically microseconds rather than nanoseconds). This energy can be diverted to other processes that reduce the IQE and can cause damage to the system. Thus, phosphorescent systems typically exhibit 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 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. Recent laboratory experiments have suggested that this can lead to an IQE of about 75%. As a practical example, for the Philips FL300 panel operating at full brightness, the IQE for the red and green emitters is estimated to be 80%, while that of the blue emitter is only 25%, giving an overall IQE of 62%.

In fluorescent emitters with small singlet-triplet separations, thermally activated up-conversion of triplet to singlet states may yield delayed fluorescence resulting in higher IQE, but it is too early to know whether this phenomenon can be exploited to give systems higher efficacy and long lifetime.

Extraction Efficiency

Extraction efficiency is the ratio of visible photons emitted from the panel to the photons generated in the emissive region. Absorption and trapping of photons in the electrodes, transparent substrate and inner layers lead to reductions in light extraction efficiency and account for the largest efficiency losses in OLED panels. For simple OLEDs, the extraction efficiency is typically in the range of 20 to 25%. This is due to a mismatch in the index of refraction between the organic materials, anode, substrate, encapsulation layers (for flexible substrates), and air, limiting the cone of incidence where light can be extracted. However, light extraction enhancement strategies can be applied to improve the light extraction efficiency.

There are several ways to increase the amount of extracted light:

- Bend the light towards the normal through the inclusion of micro-lens arrays or patterned interfaces between layers of different refractive index.
- Add scattering centers or rough interfaces so that light makes many attempts to escape, each time at a different angle.
- Reduce surface plasmonic losses at the metal/organic interface by reducing the coupling of light into surface plasmon modes (e.g. increasing the distance between the emitter and the metal electrode, horizontally oriented dipoles), making metal-free devices, or Bragg scattering the surface plasmon polariton modes into visible light with texturing at the interface.
- Reduce Fresnel reflections by using graded refractive index schemes.
- Use directionalized emitters, aligning the emitting molecules so that the emitted light is accordingly oriented.

Research in these areas has led to many of the improvements achieved in laboratory devices during the past two years, but many of the proposed solutions do not appear to be compatible with low cost manufacturing of large panels.

One promising approach being developed by Pixelligent (with funding support from the DOE) is the use of scattering particles embedded in an acrylic nanocomposite. They have demonstrated twice the extraction enhancement with this internal extraction layer approach and are working to optimize the technology to create a graded index layer through the incorporation of nanoparticles in a bilayer slot die processed film. Similarly, PPG is working on a low cost method to improve light extraction by integrating scattering particles into the glass substrate using an online process during glass manufacture. Preliminary results are encouraging, though not yet more effective than a typical external extraction layer approach yielding a 1.3 to 1.5 times the extraction enhancement.

Table 6.1 below compares common light extraction techniques. It should be noted that solutions comprising multiple approaches (e.g. a combination of internal and external extraction schemes) do not always work in concert with the same effectiveness.

Table 6.1 Table of Light Extraction Techniques

Source: Corning, DOE SSL R&D Workshop, San Francisco, CA, January 2015 [77]

Approach	Mode	Examples	Net Light Extraction	Manufacturing Probability
No modification	-	-	17-20%	-
Substrate modification	External	Surface texturing plastic foil or glass -	30-40%	High
Micro-lenses	External	PDMS 10 micron lenses	30-40%	Medium
Enhanced scattering	Internal	Micro-spheres, zirconia particles, high index substrates	-	Medium
Micro-cavity	Internal	SiO_2/Si_xN_y/metal	30-40%	Low
Photonic crystals	Internal	300 nm period mesas in ITO	30-48%	Low
Surface plasmons	Internal	Corrugated thin metal films	40%	Low
Nano-structured interfaces	Internal	Gold nanoparticles in organic layers	50%	Low

Efficacy Breakdown and Goals

Table 6.2 provides estimates of the efficiency factors for four OLED devices, comparing the performance of commercial and laboratory panels. The first two columns refer to commercial panels from LG Chem and Philips, operated at a luminance of 3,000 cd/m^2. The third device is a laboratory panel from Panasonic at a luminance of 1,000 cd/m^2. These are all tandem stack devices. The fourth column describes a small test panel from CDT using solution processing of polymer emitters in a single stack structure.

Table 6.2 Components of OLED Panel Efficacy

Metric	LG Chem NGSA30[1]	Philips FL300[2]	Panasonic[3]	CDT/Sumitomo[4]
LER	328	330	300	335
Electrical Efficiency	80%	64%	83%	70%
Internal Quantum Efficiency	65%	62%	87%	72%
Extraction Efficiency	35%	32%	61%	39%
Panel Efficiency	18%	13%	44%	20%
Panel Efficacy (lm/W)	60	42	133	66

Note: All data provided in communications with the represented company.

1. A commercial panel utilizing a hybrid triple stack with fluorescent blue emitters and phosphorescent red and green.
2. A commercial panel utilizing a hybrid 6-stage stack with fluorescent blue emitters and phosphorescent red and green.
3. A laboratory panel utilizing a double stack with all phosphorescent emitters
4. A test panel utilizing a single stack with polymer/oligomer emitters.

This table illustrates two important points. First, the efficacy of the commercial panels is less than half of that attained in the laboratory, showing that further effort is needed to transfer R&D results into manufacturable products. Second, the efficacy obtained in the laboratory for panels using polymer emitters that are compatible with solution processing is close to that of the available commercial panels but falls well short of the best laboratory results obtained for panels using small molecules deposited in vapor form.

Figure 6.4 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 Chem NGSA30 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. The goal corresponds to an LER of 360 lm/W and a panel efficacy of 190 lm/W.

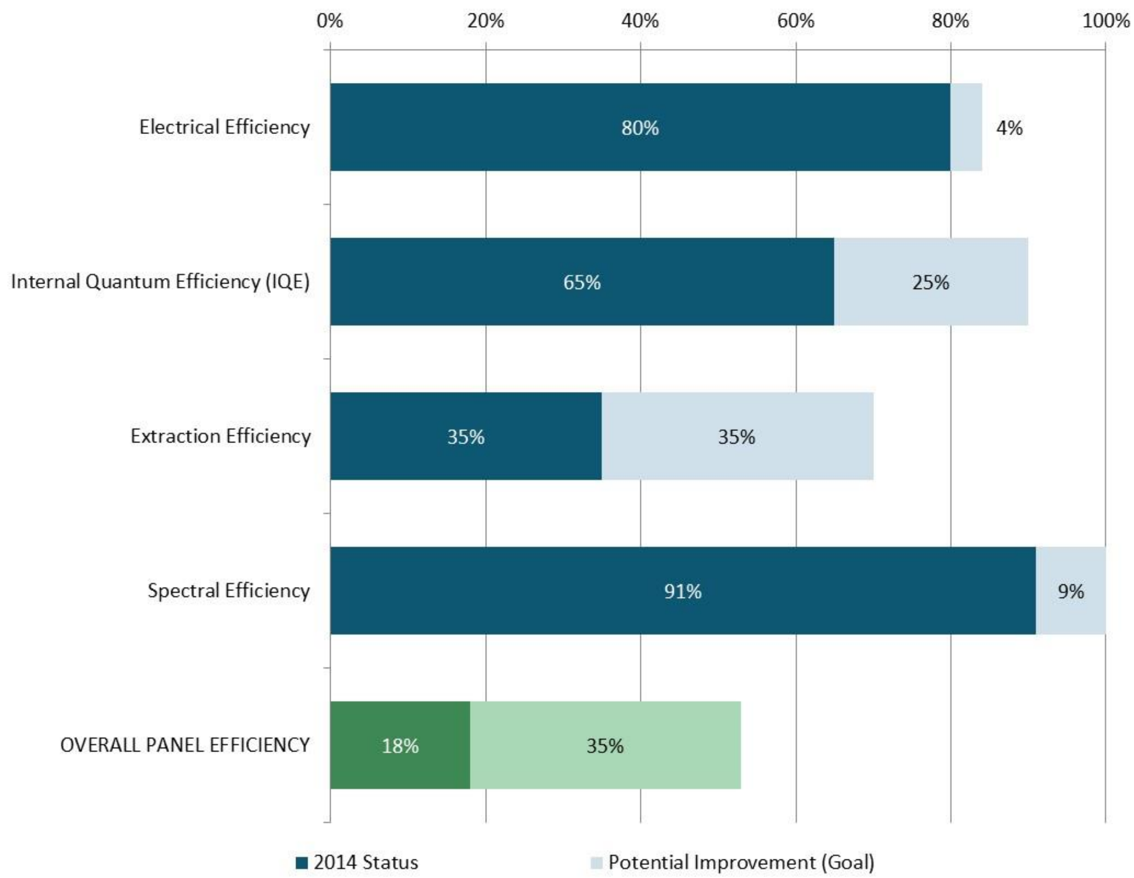


Figure 6.4 OLED Panel Loss Channels and Efficiencies

6.1.2 Panel Lifetime

In addition to efficacy, lifetime is another key performance metric for OLEDs. 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 (p) 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, it is important to note that 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. This “rated life” of OLED light sources is typically not reported since these measures require statistically significant sample sizes, whereas lumen maintenance is a durability measure with no sample size requirement. 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 ten years is expected under ambient conditions (temperature, 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 lifetimes:

- Developing new materials that offer the prospect of improved stability (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.
- 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 Philips, respectively. 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 anticipates luminous emittance of up to 4,000 cd/m^2 in 2018 [72]. However, these benefits require added complexity, which leads to lower yields and higher manufacturing costs.

Philips has provided some data on the dependence of L_{70} on current density for their FL300 panel. The nominal value of 50,000 hours corresponds to a current of 0.135 A at an ambient temperature of 25°C. The temperature of the organics is estimated to be 35°C under those conditions. When the current is raised to 0.368 A, producing a luminance of 8,300 cd/m^2, the organic temperature rises to 52°C and L_{70} falls to 10,000 hours [73].

6.1.3 Panel Color Quality

Over the past year, LG Chem (with the lead product efficacy of 60 lm/W) has been working on improvements in color quality alongside making strides in panel lifetime. They are now offering CRI of 89 or above, CCT at 3000K, and L_{70} at 40,000 hours from an initial luminance of 3000 cd/m^2. Progress has also been made on reducing panel-to-panel color variations to around ± 2 standard deviation color matching ellipses in luminaires with multiple panels.

Acuity Brands has reported that their market feedback suggests a need for better color quality for OLEDs to enable higher end lighting applications and feature lighting. OLED panel manufacturers have been responding, with most commercial panels demonstrating a CRI of at least 80 (e.g. Osram, Philips), and some manufacturers such as Lumiotec and LG Chem targeting a higher CRI of 90. 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} .

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 Philips FL300 panel, variations in color across a single panel are usually very small, with Δu'v' (distance between two color points in u'-v' colorspace) 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 ± 0.006, v' = 0.521 ± 0.005. 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 6.5). The angle of emission can lead to more substantial color shift, which is also illustrated in Figure 6.5. 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.

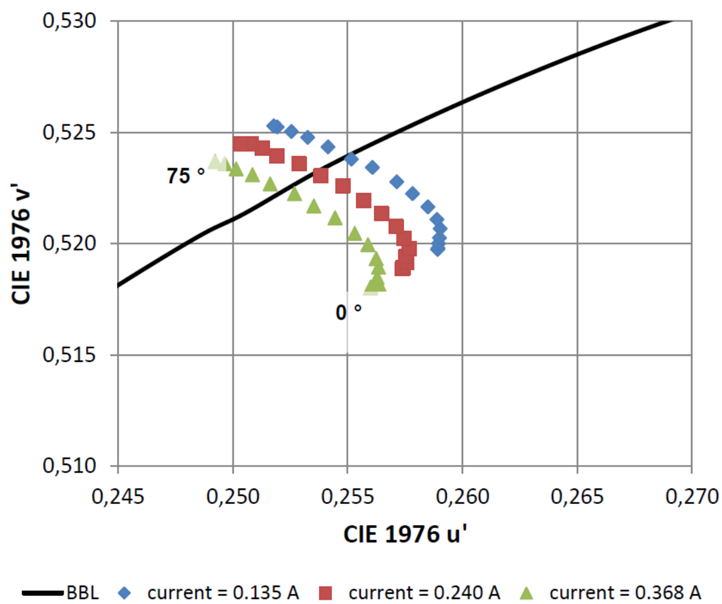


Figure 6.5 Variation of Color Point on CIE1976 (u',v') Diagram with Drive Current and Emission Angle

Source: Philips FL300 Datasheet [73]

6.1.4 Form Factor

Along with performance improvements, OLED developers have been working to enable the less expensive fabrication and improved form factor through the use of flexible or bendable substrates (e.g., metal foil, polymer, ultra-thin glass). Reduced manufacturing costs are anticipated through replacing replace incumbent vacuum deposition processes with roll-to-roll fabrication in conjunction with solution processing. However, this requires the development of new materials with improved efficacy and lifetime. Despite considerable effort in recent years by companies such as Sumitomo/CDT, DuPont, and Merck, there is still a performance gap between solution processed and vacuum deposited devices. The efficacy is lower, and although the lifetime of red and green emitters has reached impressive levels, the lifetime of phosphorescent blue emitters is still too short.

This shortfall in performance is holding up the introduction of OLEDs on flexible substrates and roll-to-roll manufacturing methods. Another 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 with cost, and more importantly, handling issues. A thin film encapsulant can be used in conjunction with ultra-thin glass substrates to retain flexibility. An alternate approach is to use ultra-thin glass as both the substrate and barrier material, 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 barrier material to create flexible and conformable panels. The substrate glass also includes Corning's light extraction technology.

Prototypes of ultra-light flexible panels have been shown for many years. For example, at the Light & Building Show in Frankfurt, Germany in 2014, Konica Minolta showed dual panels which flapped like the wings of birds and others which floated on a stream of air, as illustrated in Figure 6.6.

Figure 6.6 "Habataki" – Flexible Light-Weight OLED Lights
Source: Konica Minolta [78]

More significantly, bendable panels are now offered commercially by LG Chem. These are fabricated on ultra-thin glass. Face sealing is used on the top surface, backed by a thin metal foil, leading to a total thickness of around 1 mm. Engineering samples of their “true” flexible panels made on plastic substrates are also now available, though improvements in barrier technology are still being incorporated.

Figure 6.7 Acuity Nomi Curve Wall Sconce using LG Chem Bendable Panels
Source: Next Generation Luminaires Design Competition: Emerging Luminaires, May 2015 [79]

The appeal of flexible or bendable substrates lies in the reduced design constraints. 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. Figure 6.7 shows a panel conformed to a 3-D curve shape for use in a decorative wall sconce product.

6.1.5 OLED Luminaire

Efficacy

In luminaires that are available commercially at this time, 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%), most commercially available luminaires deliver an efficacy of just 66% or less, as compared to the panel. Improvements in luminaire design and drivers can help reduce losses. The projections in Table 6.3 assume that the efficiency of OLED drivers will improve along with that of LED drivers, but with a two year time lag since OLED specific drivers are required for optimal operation.

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, OLED 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 annoying 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 luminaire efficiency is shown in Table 6.3. The optical losses will depend on the application, so that the value in the table represents an average.

Table 6.3 Breakdown of OLED Luminaire Efficiency Projections

Metric	2014	2017	2020	Goal
Panel Efficacy[1] (lm/W)	60	125	160	190
Optical Efficiency of Luminaire	100%	100%	90%	90%
Efficiency of Driver	85%	85%	90%	95%
Total Efficiency from Device to Luminaire	85%	85%	81%	86%
Resulting Luminaire Efficacy[1] (lm/W)	51	106	130	162

Notes:
1. Efficacy projections assume CRI >80, CCT 3000 K

Luminaire Design

The OLED community is identifying key differentiating features of OLED lighting that are believed 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 which distinguishes OLEDs 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.

Advancements in driver technology to enable ease of panel installation are being sought to accelerate the integration of OLEDs into lighting designs. Figure 6.8(a) shows a novel connection scheme developed by LG Chem which magnetically connects panels to a rail that supplies current to the device. Each panel is encased and a DC-DC driver is integrated. The AC-DC driver supplies direct current to the conductor rail. Figure 6.8(b) depicts the Winona Modelo showing how modular tiling can be enabled.

Figure 6.8 User customizable lighting using (a) LG Chem magnetic connector rail and (b) Winona Modelo

Source: LG Chem OLED Light Brochure [80]*; Acuity Brands, 2013* [81]

The design possibilities for luminaire manufacturers would be increased by the commercial availability of color tunable and transparent panels. Color tunability can be achieved either by placing several emitters side by side, each with their 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 (COMEDD) among others, and prototype color-tunable panels have been offered by Verbatim and Konica Minolta [82, 83, 78, 84]. Konica Minolta intends to produce these panels in high volume from their roll-to-roll (R2R) line in 2015.

Transparent electrodes can be used for both cathode and anode, leading to devices that are transparent when turned off. Within the European Topaz project in 2012, Osram demonstrated flexible panels with transparency of over 57% and values of over 70% have been reported by UDC [85, 86]. However, the requirement of high transparency restricts the methods that can be used to enhance light extraction, so that the efficacy of transparent OLEDS may be limited. The addition of a highly reflective backing to a transparent panel enables the device to operate as a mirror when off, as demonstrated by Philips.[p] A similar effect could be attained by the use of one highly reflective electrode with a very smooth surface to enhance specular reflection.

6.1.6 OLED Product Availability

Although many proponents of OLED lighting envisage large luminous areas, such as OLED wallpaper or OLED curtains, OLED panels are currently not large enough to accomplish such designs. Currently, OLEDs are mostly being used in modular form, as arrays of small panels of area 100 cm^2 or less. These panels

[p] For more information on Philip's Living Shapes Interactive Mirror, please see: http://www.lumiblade-experience.com/livingshapes%3Fslide=1.html

can be configured either in 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. Figure 6.9 shows two examples of OLED Luminaires, the modular Acuity Brands' Trilia and First-O-Lite luminaires. Work on larger panel sizes has continued, with LG Chem now offering a 1,000 cm^2 panel. Eventually, lighting designers would like to see OLEDs in the form of large, customizable (any size, shape) sheets of light.

Figure 6.9 Acuity Brands' Trilia (left) and First-O-Lite (right) Luminaires
Source: Acuity Brands [87]*, First-O-Lite*

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 [88]. Such designs boost the light output and reduce cost per lumen while maintaining superior light quality and the aesthetic appeal of OLED luminaire designs.

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. Methods of shaping the OLED light distribution may be required for efficient light utilization at greater distances.

One of the largest installations of OLED lighting (shown in Figure 6.10) is in Seoul, Korea, where LG Chem supplied 1,100 reading lights to the Seoul National University library for energy efficiency and human health benefits based on the lack of UV light which can prevent eye fatigue and eye damage [89].

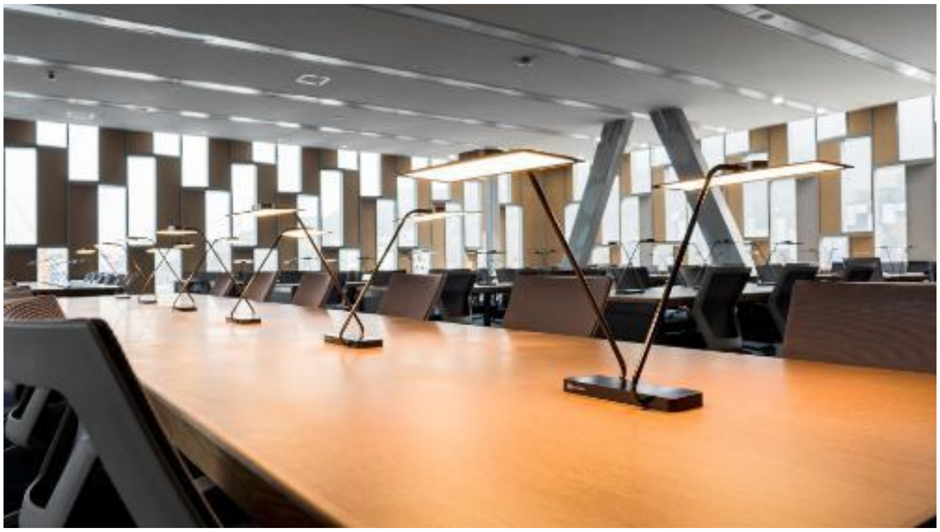


Figure 6.10 SNU Library with 110 OLED Panels Installed in Desk Lamps
Source: LG Chem [89]

Though many custom lighting solutions are available, the first products for residential use are just reaching the shelves. In November 2014, Acuity Brands released OLED pendant- and wall- mount products, the Chalina and Aedan, shown in Figure 6.11. These are available at Home Depot at prices of around $200 to $300, which translates to a lighting price in the range of $1,000/klm [90].

Figure 6.11 OLED Products Available at Home Depot.
Source: Home Depot website, March 2015 [90]

Rather than directly addressing the general illumination market, the first OLEDs are finding their way into niche lighting markets. U.S.-based OLED panel manufacturer OLEDWorks has developed panels for hospital marker lights that are used in OLEDWorks designs,shown in Figure 6.12(a), and in an Acuity Brands concept luminaire, shown in Figure 6.12(b). The lights are made with amber OLED panels to suit hospital settings where the lack of blue light is desired to prevent disturbances to the circadian rhythms of people exposed to these lights throughout the night.

Figure 6.12 Acuity Brands Marker Light Using Amber Panels from OLEDWorks
Source: DOE SSL R&D Program's 2014 OLED Stakeholder Meeting Report [91]*; Acuity Brands website: "Inspiration Through Concepts"* [92]

Another niche market for OLEDs is automotive lighting. Osram expects to have OLED products in cars by 2016, while LG Chem, working with BMW and Japanese automakers, hopes to capture 20% of the market by 2017. The applications for OLEDs in automotive lighting include rear lights, interior lighting, indicators, and accent lighting. Audi has also been working with OLEDs for several years. In 2012 they demonstrated lighting concepts including 3-D light clusters made of hundreds of triangular OLEDs whose light output can constantly be varied (Figure 6.13a) and the "swarm" concept which illuminates the rear of the car with hundreds of small light points mimicing the vehicle's motion (e.g. illuminating such that it appears the light points are swarming to the right when the vehicle turns right or are rushing forward upon deceleration). In 2013, they completed work with Philips, Merck, and the University of Cologne to make the first large area 3-D rear lighting panels which were installed in the Audi TT concept car [93]. BMW has similarly looked toward OLED technology when designing tail lights and indicators for the M4 concept car (Figure 6.13b).

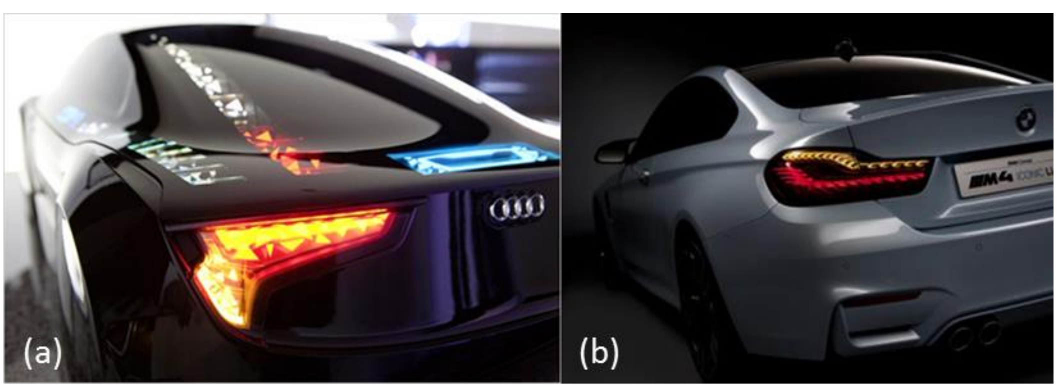


Figure 6.13 OLED Rear Lights on (a) Audi and (b) BMW Concept Cars
Source: EuroCar News 2012 [94]*; BMW 2015* [95]

OLED Panel and Luminaire Prices

While samples of OLED panels have been available since 2009, most have been produced on R&D lines and are very expensive on a $/klm basis. Fabrication lines designed specifically for higher volumes have been built by LG Chem and First-O-Lite, and the main R&D lines operated by OSRAM and Philips have been upgraded to enable commercial production. Konica Minolta has built a R2R line which should be ready for mass production in 2015.

In the spring of 2014, LG Chem announced that it was reducing the price guideline for high-volume panel sales from $600/klm to $200/klm [96]. This would mean that the price of their 100 mm x 100 mm panel, producing 75 lumen, would be about $15. However, recent offerings by the company of panels in low volumes have been much higher than is suggested by these guidelines. For example, the 320 mm x 320 mm rigid panel, with a maximum light output of 1,200 lumen, is priced at $680. Engineering samples of a flexible panel on a plastic substrate, producing 75 lumen, are offered at $250, although the price is expected to fall substantially when mass production begins later in 2015.

Acuity Brands has been offering luminaires using the LG Chem 100 mm x 100 mm panels to select customers at privately negotiated prices, but two pendant fixtures are available to the general public on-line through Home Depot. The 5-panel “Chalina” costs $299 and produces 343 lumen ($870/klm). The dual panel “Aedan” is less expensive at $199, but only gives 138 lumen ($1,440/klm) [5]. These prices confirm our rule-of-thumb that until sales volumes increase substantially, the retail price of luminaires will be at least 4 times the cost of the panel. However, although the prices seem high when expressed in $/klm, a comparison with similar stylish LED luminaires offered by Home Depot shows that the OLED products compete well on price.

Philips has chosen to target a lower price per kilolumen by designing its FL300 panels to operate at up to 8,300 cd/m^2. Panels with an output of 300 lumen have been offered in modest quantities at a price of around $60, corresponding to about $200/klm. However, further discounts might be expected for high-volume orders.

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[q].

Over the past three 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. Such lines have been commissioned by LG Chem in Korea, Osram and Philips in Germany, First O-Lite in China, Konica Minolta in Japan, and OLEDWorks in the U.S. These companies

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

join Astron Fiamm (in France) and Lumiotec (in Japan), who 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 their own set of issues, 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 recently released by Philips. Their process cycle time, often denoted by the German acronym TAKT, is currently three minutes and their yield of good panels is around 70%. Their substrate size is 400 mm x 500 mm. If we assume that the substrate utilization is 80% (leaving 20% for the edge exclusion zone and gaps between panels) 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 the Philips line will be close to 17,000 m^2, enabling the production of 1.7 million panels of size 100 mm x 100 mm.

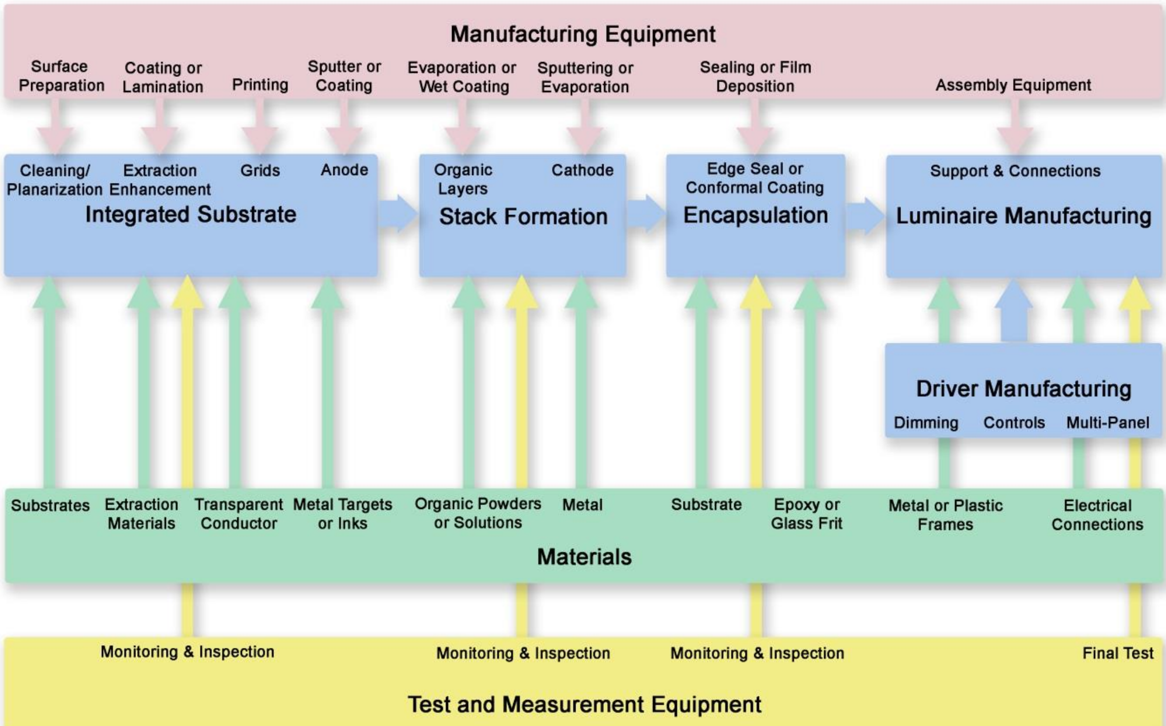
Konica Minolta has long been a proponent of R2R manufacturing on flexible substrates. In May of 2014, they announced the investment of ¥10 billion in an R2R production plant with a capacity of 1 million panels per month [97]. The schedule was to complete construction in the summer of 2014 and to begin production in the fall of 2014. In January 2015, it was 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 [98]. Although these lights are designed more for decoration than illumination, they could open a new era of innovation in light fixtures.

Limited panel production is also available from Kaneka and Mitsubishi-Pioneer in Japan, and from Visionox in China. In total, the global capacity in early 2015 is about 100,000 m^2, sufficient to produce 10 million panels of size 100 mm x 100 mm.

One of the factors that has been delaying mass adoption of OLED lighting has been the hesitancy of major luminaire manufacturers to incorporate OLED panels in their standard offerings. Acuity Brands and WAC Lighting have provided inspiring leadership, but adoption outside the U.S. has been led by lighting designers, entrepreneurs, and innovative customers, rather than by large luminaire manufacturers.

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 6.14. Appendix 8.3.2 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 6.14 OLED-Based SSL Manufacturing Supply Chain

6.2.2 OLED Panel Manufacturing

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.

Production of Rigid Panels

Early manufacturing lines for OLED panels on rigid substrates made use of a cluster configuration in which the tools were arranged in groups, each with several processing chambers fed from a common substrate handler. This allowed maximum flexibility, with different processing times for each step and the option for adding or removing modules.

Most current production lines use a form of in-line manufacturing, in which the substrate moves steadily from one process chamber to the next. This reduces handling time, but requires that the processing times are synchronized.

The layout of the Philips line in Aachen, Germany (shown in Figure 6.15) has been used to fabricate panels with six organic stacks. These complex structures can involve as many as 60 layers, with a combined thickness of only 400 nm. The panel fabrication yield is reported to be 70% which shows that significant progress has been made in the control of deposition of ultra-thin organic layers.

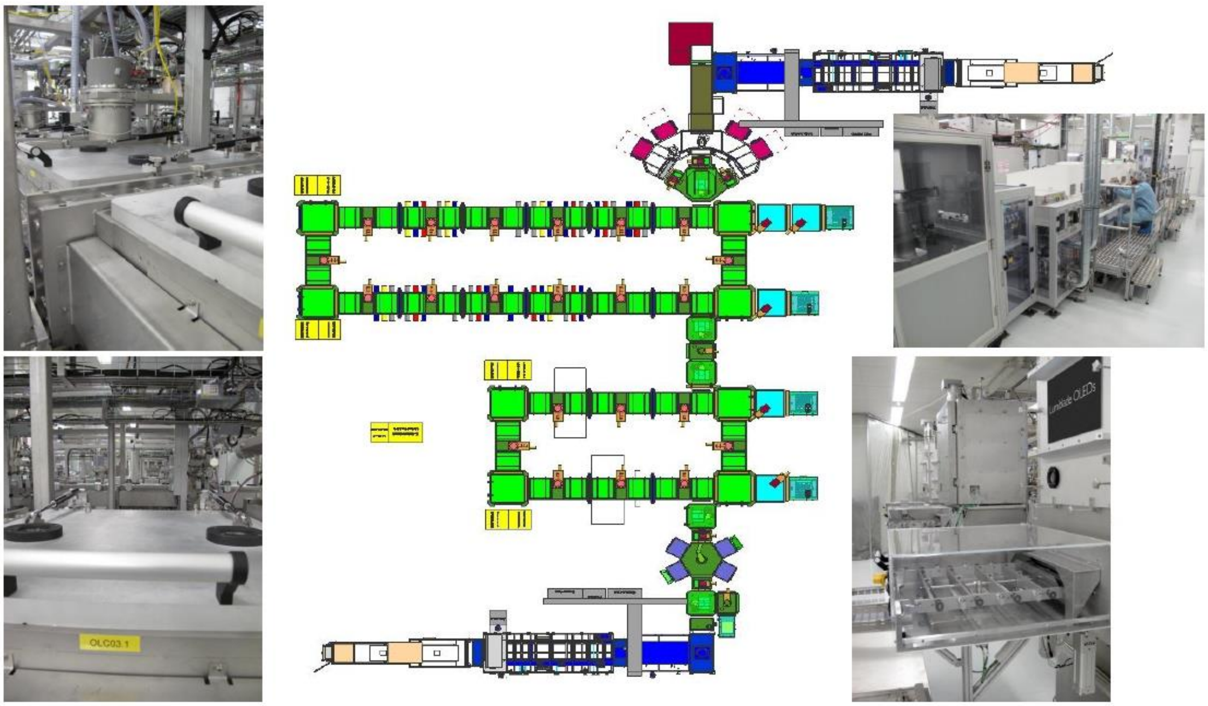


Figure 6.15 OLED Panel Production Line in Aachen Germany
Source: U. Hoffman, China International OLED Summit, Beijing, 2015 [99]

The line has four segments:

- Substrate preparation
- Organic deposition
- Metal deposition
- Encapsulation and connection

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.

Production of Flexible Panels

Conformable OLED lighting panels on ultra-thin glass are currently being produced by LG Chem, and the first samples on plastic are now available at an introductory price of $250 for a 75 lumen panel. These plastic-based panels maintain the same 60 lm/W efficacy and CRI greater than 85 performance of the glass-based panels. Production of flexible/conformable panels can be accomplished on traditional lines, either by using ultra-thin glass or by attaching polyimide substrates temporarily to glass. The required lift-off procedures have been developed by the display industry.

An alternative approach is to use roll-to-roll (R2R) processing but this comes with its own set of problems. When using plastic substrates, strict control of the web tension is necessary to assure alignment accuracy, and temperature increases must be kept within limits due to the high thermal expansion coefficients of plastic sheets. When using very thin glass substrates, handling is a key concern to avoid breakage.

The advantage of R2R processing is that it can reduce the time required to move the substrate from one tool to the next and may lead to lower cycle times. However, all the steps must be synchronized so that the cycle time is governed by the slowest process. It is often argued that R2R techniques will lead to lower costs in high-volume production, but such claims have yet to be verified in OLED manufacturing.

Figure 6.16 shows the layout of the vapor-deposition R2R pilot line at the Fraunhofer COMEDD Institute in Dresden, Germany. Note that this line also uses vapor deposition for the OLED materials and so is operated in vacuum. This unit is accompanied by a substrate cleaning system, a printing and lamination unit, and an inspection station.

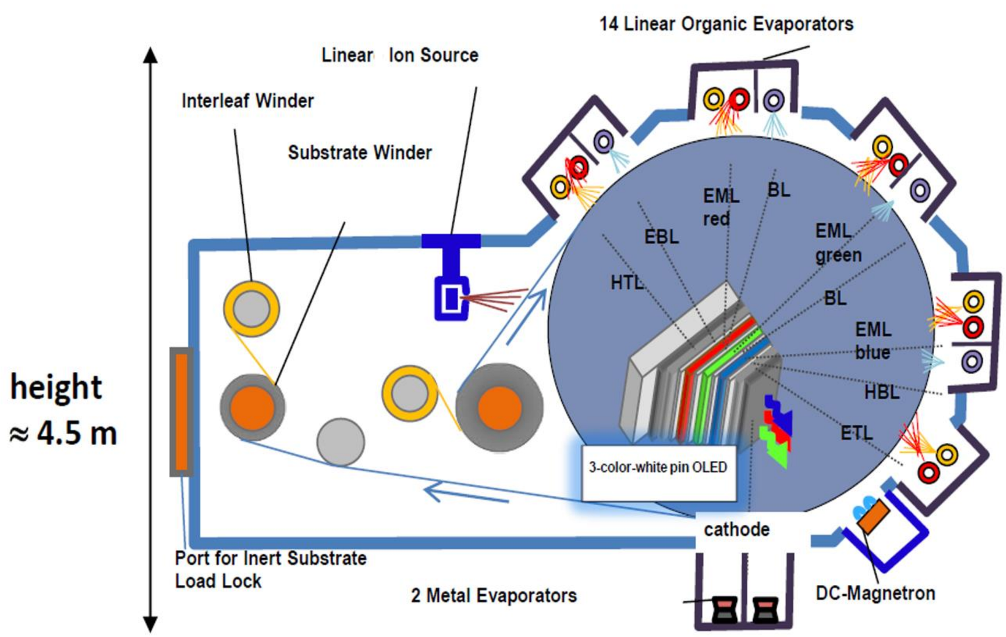


Figure 6.16 R2R OLED Deposition Line in Dresden
Source: Fraunhofer COMEDD [100]

Details of the Konica-Minolta high-volume commercial R2R production line have not been revealed and most experience has come from prototype production on pilot lines. R2R webs have been used by the

Holst Centre in Eindhoven for many valuable studies of barrier coatings and printing techniques for organic materials on both plastic and foil substrates [101]. Several U.S. companies have benefited from collaborations at the Centre. For example, slot-die coaters from nTact have been used to deposit organic materials onto polyethylene naphthalate (PEN) sheets from DuPont Teijin, and current spreading mesh grids have been created by applying photonic curing tools from Novacentrix PulseForge and silver inks from DuPont and PChem. Figure 6.17 illustrates that strict control of moisture and particulates is essential, even when processing is carried out in solution.

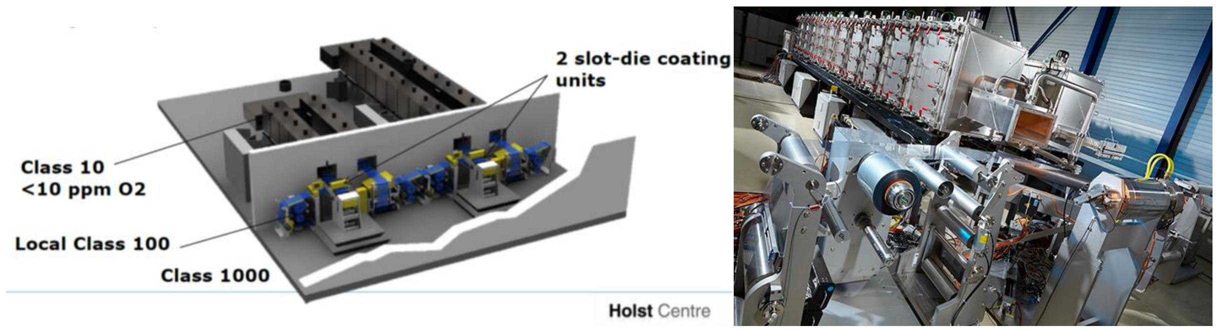


Figure 6.17 R2R Pilot Line for Organic Electronics at the Holst Centre in Eindhoven
Source: Pim Groen, DOE SSL Workshop 2015 [101]

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.[r] 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. 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. This high temperature capability is valuable in the fabrication of thin-film transistors with high performance, but is not necessary for OLED lighting panels. However, the cost of transparent polyimide with an effective moisture barrier layer is as high as (or 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. Surface roughness can be a serious problem with plastic materials not developed specifically for this application.

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[r] For more information on Corning glass, please see: http://www.corning.com/displaytechnologies/en/index.aspx

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 since 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 through the addition of 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.

Irrespective 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, since 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 and for web processing the inner surface should preferably not come into contact with any tool.

Electrode Structures

Anode and cathode structures need to be provided to distribute current uniformly across the panel and enable the efficient injection of electrons and holes into the organic stack. At least one of these structures must be optically transparent. The usual choice is to make the anode structure transparent with a semi-transparent or highly reflective cathode. In this case, spreading the current uniformly across the cathode is not too difficult, but accomplishing this for the anode is challenging, especially for large panels.

Achieving an effective anode structure requires a careful trade-off between sheet resistance and absorption of light. This trade-off becomes especially challenging if the drive voltage is low and current density is relatively high. The design and fabrication of anodes is simpler if multiple organic stacks are used. For example, in a 3-stack OLED, the drive voltage is increased by a factor of around 2.5 and the required current density is reduced by two-thirds relative to single-stack versions.

As shown in Figure 6.18, the uniformity of light emission across the panel can also be improved by increasing the panel efficacy and by driving from all four sides. These results were obtained with a two-stack OLED.

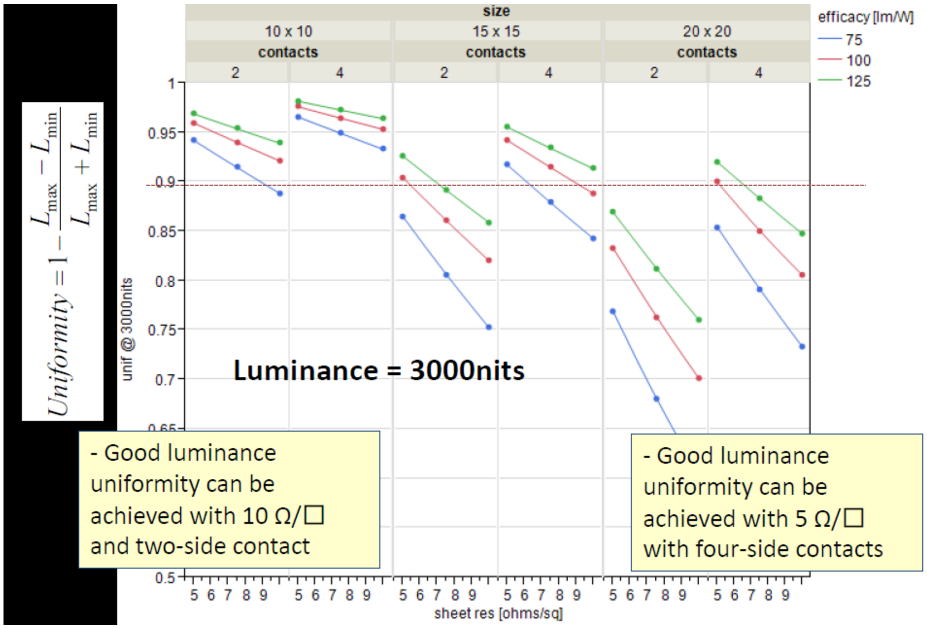

Figure 6.18 Luminance Uniformity as a Function of Anode Sheet Resistance
Source: Cambrios, OLED World Summit, Berkeley, CA, September 2014 [102]

This data suggests that a luminance uniformity of more than 85% may be achieved with a sheet resistance of around 5 Ω/□ for panels within the size range that is currently available, provided sufficient side contacts are employed. Unfortunately, it is difficult to attain such low sheet resistances with indium tin oxide (ITO) when processed at low temperature, or with most of the alternative transparent conductors that are currently under development. However, a sheet resistance of 5 resistivity per unit area (Ω/□). has been obtained by both Rolith and Cambrios using silver (Ag) nanowire coatings at an optical transparency of 90%, as shown in Figure 6.19 [103, 104].

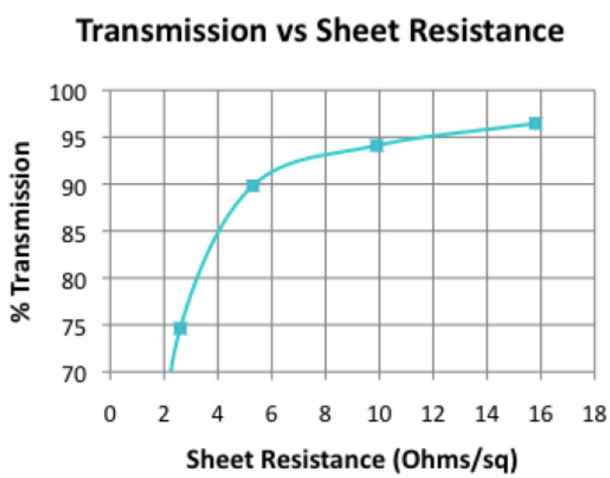

Figure 6.19 Optical Transmission vs Sheet Resistance for Ag Nanowire Coatings
Source: Rahul Gupta, Cambrios, DOE SSL R&D Workshop, San Francisco, CA, January 2015 [104]

An alternative approach, pioneered by Osram in their Orbeos panels, 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 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 Ω/□. 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 recent survey from the Holst Institute indicated that the typical resistivity of printed Ag lines is 7 to 10 times that of bulk Ag, while inks currently under development might reduce the resistivity deficit to 3 to 4 times the bulk value. 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 high temperatures of, for example, around 200°C. However, thermal curing is a relatively slow process, and attention is turning to photonic curing. Novacentrix has achieved a resistivity of 2.8×10^{-8} Ωm on coated PET using nano-Ag inks developed by PChem [105]. This is only two times the bulk Ag and could be used to create a grid with effective sheet resistance of less than 1 Ω/□ while blocking only 5% of the light. Grid lines can be patterned directly with such inks by using screen printing, flexography or ink-jet 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 of the order or 1 µm, and planarization layers may be required to avoid shorting across the organic stack.

On the cathode side, early OLEDs used metals such as barium or cadmium due to their extremely low work function which facilitates electron injection. However, current practice is to use metals with moderate work functions, such as aluminum or Ag, supplemented by an electron injection layer which often includes low work function elements such as lithium or cesium. The cathode can be made semi-transparent if the metal layer is very thin, but for standard opaque devices that emit light through the anode, the metal layer is made thicker and more reflective. Cathode deposition can be the rate limiting step for in-line systems. Thermal evaporation is the preferred method, but it is relatively slow. Sputtering is faster, but can damage the underlying organic layers.

Active Organic Layers

In an ideal OLED device, a single layer of organic material would be provide balanced flows of electrons and holes to create red, green, and blue photons from the recombining electron pairs, and the conversion from electrical energy to light would be so efficient that no energy would be left over to damage the organic molecules and shorten device lifetime. Such simple structures would be ideal for solution processing, but the high standards of efficacy, light quality, and reliability set by competing technologies have forced most developers of OLED lighting to move towards complex structures that can be formed most effectively by the vapor deposition techniques used in OLED displays. Separate emitting layers for red, green, and blue are often introduced. Special layers optimized for injection, transport or blocking of holes and electrons are placed between the emitting regions and the electrodes. Multiple sets of emitter layers are stacked, with charge generation layers in between, so that more photons can be created from the same current density. Many of these layers may contain multiple components, with mixtures that are graded to reduce damage and interface problems.

There has been steady progress in increasing the yield of the vapor deposition processes used to fabricate such complex structures. Yields are now reported to be above 50%, but need to improve to more than 95% if cost and reliability targets are to be met. Problems of device consistency still remain, particularly with respect to color control.

The formation of stacks with many layers has proved to be more difficult with solution processing techniques, primarily because solvents used in one layer can damage the underlying materials and the conventional curing and drying steps are time consuming. Therefore, most proponents of solution processing favor simpler structures in which additional functionality can be provided in each layer. However to date, this has proved to be difficult to implement, and substaintial performance penalties are incurred, both for solution-processed small molecules and polymer materials.

Improved manufacturing methods may resolve several critical performance issues. At the 2015 SSL R&D Workshop, it was suggested that the problem of degradation in blue phosphorescent emitting layers can be mitigated by grading the dopant concentration within the emission layer to broaden the recombination region and reduce exciton pile-up. Improved color consistency also requires tighter control over the relative density of dopant and host. Further development of sensors and flow controllers may be needed to meet these challenges.

The use of thicker charge injection or charge transport layers could help protect against shorting from roughness in the electrodes and minimize losses due to the excitation of surface plasmons. However, materials of higher conductivity may be needed so as not to increase the effective resistance of the transport layer.

Extraction Enhancement Structures

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. 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. An ambitious scheme to combine the benefits of both approaches and to introduce a graded index to reduce Fresnel back scattering is shown in Figure 6.20. The manufacturing problems associated with this approach are currently being investigated in a DOE-funded project.

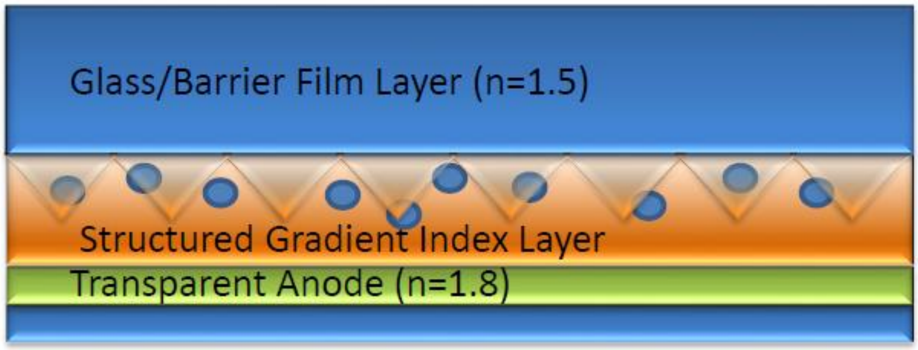

Figure 6.20 Hybrid Light Extraction Layer with Graded Index

Source: Gene Chen, Pixelligent, DOE SSL R&D Workshop, San Francisco, CA, January 2015 [106]

Encapsulation

Significant progress has been achieved globally in the application of new encapsulation techniques. LG Chem uses a Face Sealing Process[s] which combines a pressure-sensitive adhesive, an acrylic polymer, an epoxy resin, and a cationic photo-polymerization initiator to form a photo-curable layer. The composite layer may contain a moisture absorbant component which can be used to replace the traditional desiccant and air gap, filling the entire region between the OLED structures and the cover plate. This process appears to have been used with thin glass, metal, and polyimide covers.

Philips and Osram have both released products with thin-film multi-layer barrier coatings, reducing the panel thickness to less than 1 mm. Details of their processes have not been released, but considerable research into this approach has been carried out at the Holst Center in Eindhoven, and hints concerning the materials used can be found in patent applications. The basic approach, pioneered by Vitex and 3M, appears to be based on depositing multiple layers of dense silicon (or metal) nitrides or oxides, typically by plasma enhanced chemical vapor deposition (PECVD) or atomic layer deposition (ALD), interspersed with organic layers. The organic layers prevent the propagation of defects through the dense inorganic layers and may contain active moisture absorbers and oxygen scavengers. Figure 6.21 shows similar structures developed at the Holst Center that can be fabricated by R2R techniques.

[s]For more information on the Face Seal type OLED encapsulant see: http://www.lgchem.com/global/display/oled-encapsulation

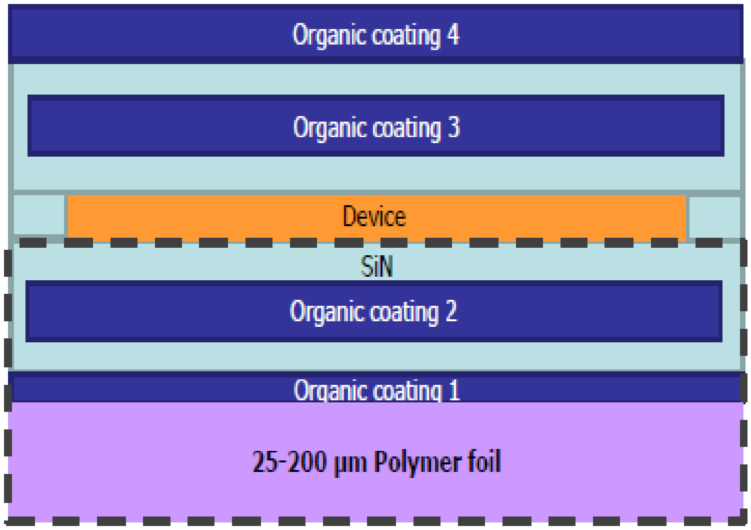

Figure 6.21 Multi-layer Barrier Coating to Prevent Ingress of Moisture and Oxygen
Source: Pim Groen, Holst Centre, DOE SSL R&D Workshop, San Francisco, CA, January 2015 [101]

Another significant development in the last 12 months has been the commercial availability of multi-layer barrier films and pressure sensitive adhesives from 3M [107]. Although the sales have been driven by quantum dot applications, for which the barrier properties are less demanding, there is evidence that the lamination of two such films will provide the protection needed for OLED lights and displays.

The cost of producing multi-layer barrier films is still on the same order as display-grade glass and does not yet meet 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 fast ALD deposition equipment for inorganic materials by Veeco, offers the prospect of lower prices in the future [108, 109].

Product consistency and reliability

Improved color consistency and the elimination of early failures during panel operation were two manufacturing challenges highlighted at the 2015 DOE SSL Workshop.

Color variations are caused primarily by differences in the number of emitting molecules. Color consistency therefore requires accurate control of layer thickness, and the density of dopants in each layer. Given the sensitivity of evaporation sources to variations in temperature and other operational parameters, in situ diagnostics and feed-back controls are needed.

The development of accurate flow models which can be checked by measurements during the installation of a deposition system means that in situ monitoring of the uniformity of deposition is not necessary. However, the density of the vapor emerging from the evaporation chamber must be measured in real time, usually through the use of quartz crystal micro-balances (QCM) [110]. The response of QCMs changes as the thickness of deposited material increases, so that they must be cleaned in situ or exchanged regularly.

Early failures usually result from the growth of undetected defects. These can arise from the presence of particulates or shorts due to roughness of the electrode structures. Miniature pinholes or cracks in the encapsulation may also lead to rapid deterioration.

Greater control over the creation of particulates is clearly required and more sensitive detection of defects would be helpful. Most manufacturers find it necessary to burn in all panels to identify those prone to early failure, but this is time-consuming and expensive. More rapid ways to accomplish this would be of great value.

6.2.3 OLED Luminaire Manufacturing

In current practice, the manufacture of an OLED luminaire involves the provision of a mechanical frame to hold the panels in place and electrical connections to the power supply. Sleek, lightweight materials are often preferred to complement the slim profile of the panel itself. Traditional manufacturing methods have been used so far, but there is ample opportunity to use 3-D-printing for rapid production of custom fixtures. Given the desire to incorporate panels produced in high volume into a wide variety of luminaires, standardization of connectors would be helpful.

One possible area for future R&D is the development of drivers that are especially suited to the electrical characteristics of OLEDs and enable effective dimming. Vendors currently provide single or multiple output drivers depending on the number of panels being driven. For example, Philips offers a 24 V DC driver for a single FL300 panel which is compatible with either DMX, DALI, analog or TouchDim protocols at a price of about €35. Alternatively, they can provide a multi-panel driver with 8 outputs for €108 [111].

As well as providing compatibility with dimmers and other controls, the driver needs to allow for variations in the current-voltage characteristics of the panels. Figure 6.22, shows that the voltage required to produce a desired current level for the Philips FL300 with its six-fold stack can vary with operating conditions and during the initial warm-up phase.

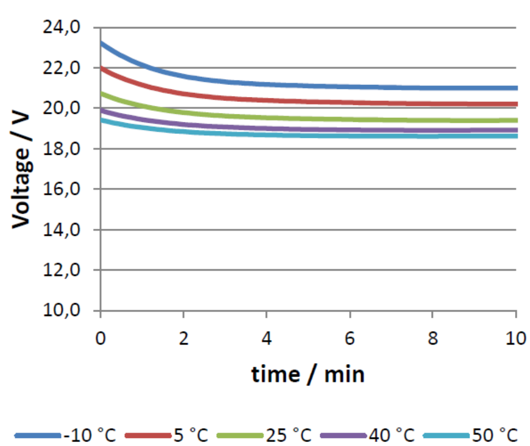

Figure 6.22 Variation of OLED Drive Voltage with Ambient Temperature During Warm-Up Phase
Source: Philips, Design-in Guide: Philips Lumiblade OLED Panel Brite Family [111]

6.2.4 OLED Cost Forecasts

At the component (e.g. substrate, encapsulation, electrode, and organic layers), panel and luminaire level, the cost of OLED production is strongly dependent on volume levels and yield. Although it seems likely that the panel efficacy targets of 100 lm/W set in the 2010 MYPP[t] will be met in commercial panels in 2015, the manufacturing costs are currently at least ten times higher than the goal of $\$90/m^2$.

The DOE cost targets have always been set by market expectations for general illumination. For certain niche markets, the price of OLED luminaires is already competitive with similar LED fixtures. But if OLEDs are to make a substantial contribution to SSL adoption rates and energy savings, it is essential that cost reduction continues.

Costs can be assessed either in terms of $\$/m^2$ or \$/klm. At this stage of development, the cost of both materials and processing scale more closely with panel area than with light output. Therefore, there has been pressure to increase the light emission per unit area (brightness) by increasing the complexity of device structures rather than making them larger. One critical factor in the evolution of OLED panel costs is the limit placed on brightness such that the light source remains pleasing to the eye and does not need to be hidden from view. Another factor that has led to considerable debate is the trade-off between cost and device complexity. Some argue that simpler devices that involve fewer layers are amenable to R2R processing and will prove most cost effective, while others cite experience in the microelectronics industry suggesting that increasing the complexity of devices and reducing their size leads to the most rapid cost reductions.

Materials Costs

Reducing raw materials costs is essential to commercial success. Although companies may be willing to forego the recovery of equipment depreciation and other fixed costs during the development phase, it is very unlikely that they will set prices below the added cost of producing each panel or luminaire. On a longer-term basis, the bill of materials often represents over half of the cost of similar electronic devices when produced in high volume.

In purchasing materials and components, panel makers often have to reimburse their suppliers for their development costs and other expenses, in addition to the cost of the raw materials. This is the case for two critical components of OLED panels, the phosphorescent emitters and the transparent conductors.

Universal Display Corporation has been developing phosphorescent emitters for over 20 years, spending a total of over $350 million on R&D and the acquisition of intellectual property. Established in 1994, UDC's first profitable year was 2011 [112]. Although sales have increased substantially in recent years, manufacturing costs have always been a small part of UDC's expenses, reaching around 30% only in 2014. Thus, the prices charged by UDC to panel manufacturers have been governed more by their fixed costs than the cost of manufacturing the phosphorescent materials. Due to success in supplying manufacturers of OLED displays, sales volume has risen so that the price of phosphorescent emitters has

[t] The 2010 SSL MYPP is available at:
http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_mypp2010_web.pdf

been kept to less than 2% of the price of the OLED panel. However, the cost per unit area is around $100/m^2, which is inconsistent with the cost goals for OLED lighting.

Almost all OLED display panels use ITO as the transparent conductor. The cost of the necessary raw materials is less than $0.50/m^2, but the cost of substrates with patterned ITO is often in the range of 20 to 30 $/m^2. This price is determined mostly by processing costs, particularly since the patterning is usually accomplished by expensive photolithography, and the fixed costs of the suppliers. Since the market for alternative transparent conductors with performance suited to OLED panels is very limited, their costs are more dependent on development rather than production costs.

While the market for OLED lighting remains small, substantial cost reduction is most likely to result from synergy with other applications. Success in the sales of OLED TVs should lead to reduced prices for organic materials, since the area of a typical TV is 100 times that of a smart phone, and the cost constraints are more severe. The development of alternative transparent conductors, such as silver nano-wires, has been driven by the touch screen market. Thin-film encapsulation is needed in flexible displays and to hold the quantum dots that are improving the color quality of many liquid crystal displays. However, the performance requirements of OLED lighting panels are often more extreme than those of other applications and further technology refinement is required.

Total Panel Costs

One possible scenario to reach the cost goal of $100/m^2 by 2025 is presented in Table 6.4. Depreciation is calculated on a five year straight-line basis.

Table 6.4 Estimated Cost of Panels Produced by Traditional Methods

	2014	2015	2017	2020	2025
Substrate Area (m^2)	0.17	0.17	1.38	2.7	5.5
Capital Cost ($M)	75	75	200	300	400
Cycle Time (minutes)	3	2	1.5	1	1
Capacity (1000m^2/year)	14	25	300	1,000	2,400
Depreciation ($/m^2)	1,050	600	125	60	35
Organic Materials	200	150	100	35	15
Inorganic Materials	200	200	120	50	30
Labor	150	100	20	10	5
Other Fixed Costs	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**

Much of the cost reduction is enabled by the anticipated rise in production volume. This scenario follows the route taken by display manufacturers, with substantial increases in substrate size while retaining the traditional batch processing line structure. This approach incurs high capital costs, which may limit the number of manufacturers. An alternative approach would be to focus more aggressively on reducing the cycle time while keeping substrate sizes relatively small, as done in the optical disk industry. However, it is yet unclear whether cycle times of much less than one minute can be achieved.

Proponents of R2R manufacturing often cite the potential for a substantial reduction in cycle time. However, this benefit has yet to be demonstrated. The successful production of OLED panels from the new Konica Minolta line will offer valuable insight to the practicality of R2R production. The goal is to produce one million panels per month, which would represent an annual capacity of the order of 100,000 m^2. At this level of production the depreciation cost per panel would be around \$200/m^2, which would represent a substantial reduction. Konica-Minolta has not released details of their R2R line, but if the web width is 600 mm, the required web speed would be at least 0.5 m/min.

Data from nTACT and the Holst Center has demonstrated that several of the critical process steps can be carried out at commensurate web speeds [113]. For example:

- Slot-die coating of patterned layers can be performed at 3 m/min
- Photonic sintering of nano-Ag inks can be achieved at up to 20 m/min
- Formation of multi-layer barrier films can occur at 4 m/min

Therefore, the major manufacturing challenge is to demonstrate that all the required processes can be accomplished sequentially with an acceptable yield.

Luminaire Costs

At the current sales volumes, the costs of converting an OLED panel into a luminaire are determined mainly by the fixed expenses associated with product design, tooling and driver development. As with decorative luminaires using LED sources or traditional lamps, expensive materials are often used to attract customer attention. Mechanical protection is essential, but thermal management is less challenging than with other technologies. The availability of modular connectors and adaptable drivers will help reduce these costs while retaining the capability to offer a wide variety of form factors.

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, more than 95% of its potential remains untapped. Continued innovation and breakthroughs in materials, processes, product designs, control systems, and manufacturing 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 with the additional benefit of fostering U.S. leadership in SSL manufacturing. Finally, Applied Technology 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 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 in order to promote further discussion on the key issues and assist in prioritizing necessary 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 Solid-State Lighting Program please see http://energy.gov/eere/ssl/about-solid-state-lighting-program

Figure 7.1 SSL Program Input Strategy
Source: James Brodrick, DOE SSL R&D Workshop, San Francisco, CA, January 2015 [114]

The DOE SSL Program continues to use the Funding Opportunity Announcement (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 that are shorter in duration (1 to 3 years) and has the goal of advancing applied scientific understanding or the global state of the art of the technology. In addition to the FOA process, the DOE has used different support mechanisms to fund R&D topics that are not suited for the FOA process in order to maximize the DOE SSL Program influence toward the objective of maximizing lighting energy savings.

The DOE SSL Program has worked with the DOE Office of Basic Energy Science, NIST, Pacific Northwest National Laboratory, and the 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[v]
- LED lighting reliability research through the LED System Reliability Consortium (LSRC) facilitated through the NGLIA
- A wide range of application R&D through Pacific Northwest National Laboratory
- OLED testing through competitively selected external laboratories

This year, through the course of the typical R&D prioritization discussions, several R&D topics arose that are better suited for non-FOA R&D support. These are further discussed in Section 7.6.

[v] For more information on color work at NIST please see: http://www.nist.gov/pml/div685/grp03/color.cfm

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), however, this section describes some expectations for progress towards DOE efficiency goals over time based on performance to date. For the most part, these projections have not changed since last year, as progress has been more or less 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 generally available products, which is necessary to achieve the energy savings promised by the technology.

Within each individual task, described later in this section, are a number of metrics specific to that task and individual goals that together will enable us to achieve the goals of the program.

Efficacy Projections for LEDs

Figure 7.2 and Table 7.1 provide a projection of 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 250 lm/W, as explained in Section 5.1.1. 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 or 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, allows 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 (lm/W)

Metric	Type	2014	2015	2016	2017	2018	2019	2020	2025	Goal
LED Package Efficacy	Cool White	173	185	196	205	214	220	226	242	250
	Warm White	146	162	177	190	202	212	220	242	250

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 ready availability of narrow line-width red LED sources. Pc-LEDs will approach the goal more gradually as the 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 power conversion efficiencies 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 these together while achieving further enhancement of light extraction. Figure 7.3 and Table 7.2 provide a projection of OLED panel efficacy based on past performance and anticipated progress. It should be noted that data on panels remains rather sparse and shows 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.

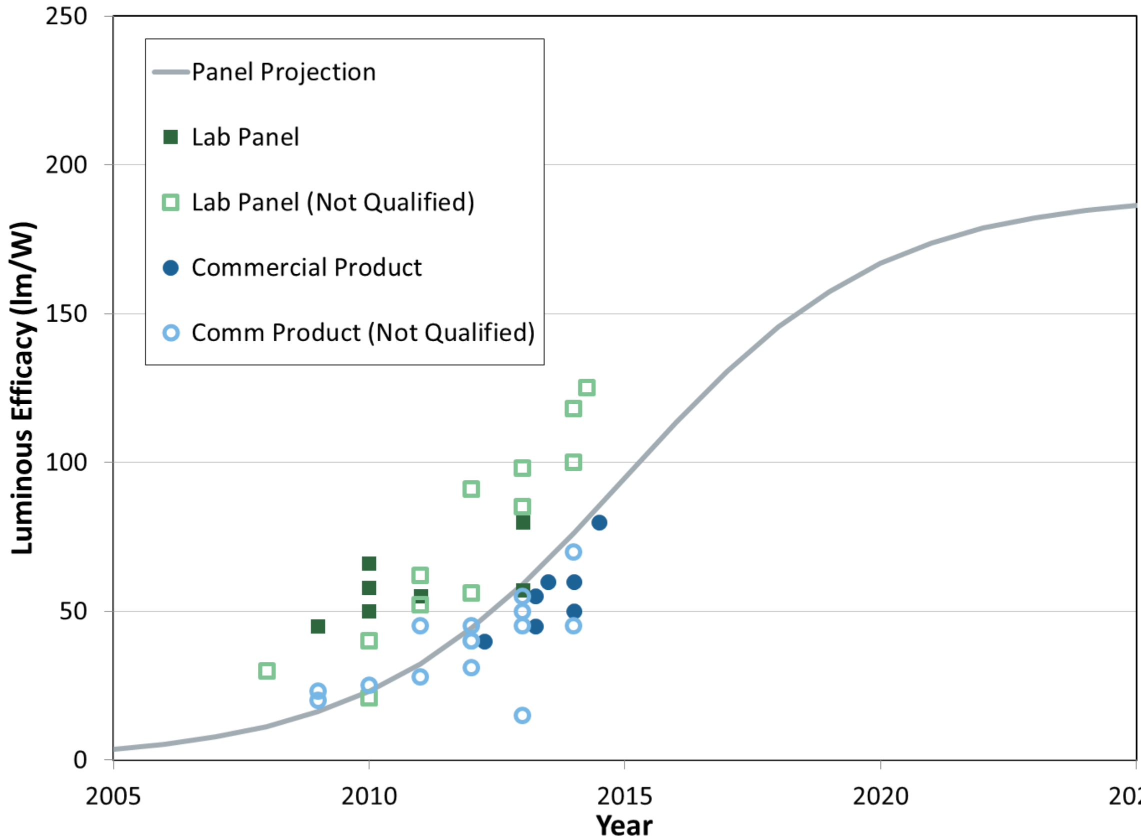

Figure 7.3 White-Light OLED Panel Efficacy Projections

Table 7.2 summarizes a path towards 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 (lm/W)

Metric	2014	2015	2017	2020	Goal
Panel Efficacy	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 lifetime 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. The FY 2012 milestone focused on the development of higher-efficiency luminaires. The SSL community successfully demonstrated the FY 2012 LED goal of a high-efficiency luminaire with an output of 1,000 lumen, efficacy of 100 lm/W, and warm-white color temperature. This performance level demonstrates advancements in efficacy, light output, and color quality to reach performance levels similar to linear fluorescent, the most efficient indoor conventional light source.

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 Smart troffer with integrated controls: <$85

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

By FY 2015, it is expected that prices for LED packages will fall below $1/klm while retaining the high efficacy of over 100 lm/W and 50,000 hours lumen maintenance. By 2017 (three years ahead of the original schedule), DOE expects the focus to shift toward realization of a commodity-grade luminaire product with output exceeding 3,500 lumens and price below $100, while maintaining reasonable efficacy. By 2020, DOE anticipates the introduction of cost-effective smart lighting in the form of troffers with integrated 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.

The LED package and luminaire milestones represent distinct steps in developing low-cost, high-performance SSL luminaires. The first step, completed a couple of years ago, was to develop a reasonably efficient white LED package that is sufficient for the lighting market. LED packages continue to improve efficiency while decreasing price in order to realize the best possible energy savings. The availability of LED packages with efficacies at and above 130 lm/W has shifted the focus toward the development of efficient luminaires. With progress made on developing efficient luminaires, with indoor fixtures realizing 120 lm/W, the next step in progress is to significantly reduce the cost of LED lighting to the point where it is competitive across the board. This work, currently underway, has been supported through the R&D manufacturing initiative.

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 Chem and Philips have indicated that they can meet the 2015 price target of $200/klm and the L_{70} lifetime of 40,000 hours from an initial luminance of 3000 cd/m^2. All panels from LG Chem now have CRI around 90 or higher, but most others are below this goal. The main challenge for manufacturers is to meet the efficacy milestone of 80 lm/W without compromise in other parameters.

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/klm Luminaire: 100 lm/W; CRI >90
FY20	High-Performance Panel: 150 lm/W
FY25	Commercial Panel: <$15/klm Luminaire: 150 lm/W; engineered light distribution

The only explicit panel milestone for FY 2017 is the price target of $100/klm, representing a 50% reduction in price. However, the panel efficacy will need to be increased to enable the production of luminaires with at least 120 lm/W. Further improvements in CRI or operating lifetime are deemed to be less important.

By 2020 it is anticipated that high-performance panels will be available with efficacy of 150 lm/W. The manufacture of simpler panels with lower efficacy may enable luminaire prices to drop, allowing OLEDs to play a role in high-volume markets. However, expressing price in terms of light output is not appropriate for many applications, so no quantitative target has been set for luminaire price.

The 10-year milestone for OLED development is to reach drastically reduced panel prices that hurdle the cost barrier to widespread adoption. To reach this stage of development, manufacturing issues will need to be resolved and materials costs and designs improved. Panel pricing of $15/klm and luminaire efficacy of 150 lm/W are targets that are believed to allow OLEDs competitive consideration in the general illumination market.

7.3 Key Issues & Challenges

While much progress has been made over the years in LED and OLED lighting performance, demonstrated by the many LED products available in the market and the introduction of commercial OLED luminaires, many challenges remain to meet the overarching DOE goals described above and maximize SSL energy savings. A number of key R&D issues were identified at the various DOE stakeholder meetings.

For LED lighting, the R&D issues identified include:

- Emitter Materials Research – targeting current density droop, thermal droop, green and efficiency and red thermal stability.
- Down-Converters – directed at the development of high efficiency, stable, narrow linewidth red and green phosphors or quantum dots.
- Encapsulation – targeting materials with improved thermal stability and high refractive index
- Novel Emitter Architectures – targeting improved performance through the use of advanced device architectures such as lasers, nanowires, superluminescent diodes, electroluminescent quantum dots, etc.
- Higher Integration Levels – for example, flexible integration of package, driver and optics (Level 2+) into an LED module, flexible manufacturing processes for customizable integration levels, etc.
- Improved Light Utilization – luminaire optics development, targeting new levels of control such as beam steering
- Smart Controls and Sensors – targeting simple and effective controls with interoperability in mind; compact, low-cost sensors; and integrated end-use device energy measurement system for luminaires

While there are many more technology challenges facing the LED industry, these topics were selected as the most pressing research topics to address the current performance shortcomings in LED lighting.

For OLEDs, steady progress continues to be made in terms of technical performance, and commercially viable lighting products continue to be introduced. Yet, a number of fundamental technical challenges remain that could be addressed through DOE supported R&D.

For OLED lighting the identified R&D issues include:

- Materials research – targeting 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 – focusing on cost-effective manufacturable solutions that will allow for substantial improvements in panel efficiency by extracting light trapped in organic/anode waveguided modes and/or reducing surface plasmonic losses. The ability to control the distribution of the emitted light would be an additional benefit
- Luminaire development – aiming 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 – directed towards improvements in 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 R2R manufacturing

These key R&D issues are centered 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 the DOE SSL R&D Workshop 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 their 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.

In the specific task tables that follow, there are references to 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	-
Green	520-540 nm	-
Amber	580-595 nm	-
Red	610-620 nm	-
Warm White	3000K	≥80
Cool White	5700K	≥70

The purpose of the task selection process is to identify those areas of work that need to be addressed to overcome the current critical technological barriers. With all of the tasks described below, it should be noted that the milestones provided represent the minimal descriptions for progress. All of these tasks will require some addition level of system level performance description, but the specifics of the system vary widely. It is expected that researchers in these areas have and can communicate a system level understanding of the role of the described research.

7.4.1 LED Core Technology Research 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 apparent 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, in addition to the light emitters, work on improvements in down-conversion materials remains a priority.

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. 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	**2014 Status**	**2020 Targets**
IQE at 35 A/cm^2	89% (Blue) 39% (Green) 75% (Red) 13% (Amber)	95% (Blue) 54% (Green) 87% (Red) 32% (Amber)
External Quantum Efficiency (EQE) at 35 A/cm^2, 25°C	76%(Blue) 32% (Green) 54% (Red) 10% (Amber)	86% (Blue) 46% (Green) 65% (Red) 24% (Amber)
Power conversion efficiency[w] at 35 A/cm^2	60% (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	77%	98%
Thermal stability – Relative optical flux at 100°C vs. 25°C	90% (Blue) 85% (Green) 50% (Red) 25% (Amber)[x]	98% (Blue, Green) 75% (Red, Amber)

[w] Optical power out divided by electrical power in for the LED package.
[x] 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	**2014 Status**	**2020 Targets**
Quantum yield (25°C) across the visible spectrum	95% (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.2.2 Novel Emitter Architectures		
Description: Devise novel emitter device architectures that show a clear pathway to lighting system efficiency improvement. Demonstrate a pathway to increased chip-level functionality offering luminaire or system efficiency improvements over existing approaches. Explore novel architectures for improved efficiency, color stability, and emission directionality. Examples include laser diodes for lighting, nanowire LEDs, superluminescent structures, and electroluminescent quantum dots.		
Metrics	**2014 Status**	**2020 Targets**
External Quantum Efficiency (EQE) at 35 A/cm^2, 25^{o}C	76%(Blue) 32% (Green) 54% (Red) 10% (Amber)	86% (Blue) 46% (Green) 65% (Red) 24% (Amber)
Current droop – Relative EQE at 100 A/cm^2 vs. 35 A/cm^2	77%	98%

7.4.2 LED Product Development Tasks

Product development tasks encompass a variety of aspects related to specific LED products and 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, but also addresses novel luminaire designs and smart controls and connected systems.

B.3.2 Encapsulation		
Description: Develop new encapsulant formulations that provide a higher 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, 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.		
Metrics	**2014 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.3.6 Package/Module Architecture Integration		
Description: Develop novel integrations schemes that focus combining the LED package and other luminaire subsystems or sensors into Level 2+ LED module products, which can be readily integrated into luminaires. Architectures should address the integration of driver, optics and package in a flexible integration platform to allow for easy manufacturing of customized performance specifications. Advanced features such as optical components that can shape the beam or mix the colored outputs from LED sources evenly across the beam pattern are encouraged, along with novel thermal handling and electrical integration while maintaining state of the art package efficiency. Integration of low cost sensors for added functionality of LED lighting systems is also encouraged.		
Metrics	**2014 Status**	**2020 Targets**
Luminaire efficacy	110 lm/W Depends on CCT, CRI, beam angle, luminance distribution, etc.	200 lm/W
Luminaire cost reduction	User defined cost (depends on application)	35% cost reduction
New functionality enabled by integration	User defined functionality	Proposed impact on performance and/or adoption case

B.6.4 Novel LED Luminaire Systems		
Description: Develop novel luminaire system architectures and form factors that take advantage of the unique properties of LEDs to save energy and represent a pathway toward greater market adoption. Novel form factors, luminaire system integration, and optical beam steering that diffuse and or shape the light output into a desirable beam pattern, or optical components that mix the colored outputs from LED sources evenly across the beam pattern should be considered to improve the efficiency of the light source and provide efficient utilization of light. Another important element of this task could be the integration of energy-saving controls and sensors to enable utilization of the unique LED properties and save additional energy.		
Metrics	**2014 Status**	**2020 Targets**
Luminaire efficacy (depends on application – user may define metrics for other use cases)	110 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

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

Resuming the improvements in efficacy of white OLED devices is, again, of high priority. This must be accomplished without compromises in lifetime or color quality. Since much of the past progress has been accomplished by using more complex structures with greater manufacturing costs, there is growing interest in the development of simpler structures that can be manufactured with higher yields and lower material costs. Projects with such goals are included in Task C.1.2, while task C.6.3 seeks efficacy improvements through novel light extraction techniques.

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 the 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	**2014 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	90	>90

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 waveguided 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	**2014 Status**	**2020 Target**
Extraction efficiency (EQE/IQE)	40%	70%

7.5.2 OLED Product Development Tasks

In previous years, product development tasks have been focused on the OLED panel. It is now appropriate to address some of the challenges that are faced by luminaire manufacturers. Although these manufacturers are highly motivated to develop features that distinguish their products from those of other companies, there are critical elements that could enable all producers to expand their markets, such as drivers and connectors. External optical systems that modify the distribution of emitted light could also be valuable. Task D.4.2 is designed to allow luminaire manufacturers a great degree of latitude in proposing innovative luminaires.

Developments in the OLED panel are still necessary, especially in regards 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 which can provide only up to about 1.6 times the extraction enhancement. Cost effective, scalable internal extraction techniques need to be developed to reach goals of greater than 3 times the extraction enhancement.

D.4.2 OLED Luminaire		
Description: Develop general illumination OLED luminaire systems and components that provide a pathway toward greater market adoption. Proposed luminaires should be primarily 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; improved electrical connections; etc. Proposals should provide quantitative targets for distinctive performance in addition to addressing the metrics below. Potential customer appeal as well as market size and penetration should be supported with a cost-benefit comparison and a competitive analysis that takes into consideration competitive products based on other lighting technologies.		
Metrics	**2014 Status**	**2020 Target**
Efficacy	51 lm/W	125 lm/W
Lumen Maintenance (L_{70})	15,000 hours	50,000 hours

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	**2014 Status**	**2020 Target**
Extraction efficiency (EQE/IQE)	40%	70%
Incremental cost		<$10/$m^2$
Angular variation in color (0-75°)	$\Delta u'v' \leq 0.004$	$\Delta u'v' \leq 0.002$

Although previous task lists have included work on new encapsulation techniques, particularly for devices using polymer substrates or covers, these were not prioritized for this year. This is partly because companies in Europe and Asia have claimed that acceptable thin-film encapsulation techniques are available [101]. Also 3M has demonstrated that laminating two sheets of films that are being produced for the display industry meets the requirements of OLED lighting panels [115]. Prioritization of this topic is therefore being suspended while the reliability and cost of these solutions are evaluated.

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. 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.

M.O.5 OLED Panel Manufacturing

Description: Support for the 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; TAC time; material utilization; equipment uptime; and process flow may be helpful to identify opportunities for improvements in terms of cost and performance.

Metrics	2014 Status	2020 Target
Panel Yield		≥80%
Reliability (Catastrophic Failure)	< 1/1000	< 1/10000
Panel to panel color control – $\Delta u'v'$	±0.004	±0.002
Panel Price		<\$100/klm

Although there are excellent facilities for the manufacturing of complete OLED panels by roll-to-roll techniques in Asia and Europe, such facilities are limited in the U.S. However, many believe that this approach offers the potential for greatest cost reduction. Task M.O.6 encompasses projects that are addressing the manufacture of critical components as well as complete OLEDs. This broad task area encompasses efforts on materials to enable roll-to-roll manufacture (substrates, solution processable electrodes and active layer materials, encapsulation films) as well as manufacturing process development and equipment. Due to the broad scope of this task, metrics are not outlined. In general, work under this category should strive to maintain or improve upon the state of the art performance while demonstrating compatibility with low-cost (e.g., high throughput, robust, minimally complex, and low-cost materials and equipment) roll-to-roll processing.

M.O.6 Roll-to-roll OLED Manufacture		
Description: Develop materials, processes, and equipment to support the advancement of roll-to-roll manufacture of OLED lighting devices. Roll-to-roll manufacture of OLED lighting devices may enable lower cost of manufacture and may be well suited to the manufacture of OLED devices on large area, flexible substrates. Thus, support for advancement of this approach is desired to eventually enable the introduction of low-cost, differentiated (large area, flexible/bendable lighting, thin) light sources. Materials that support high performance roll-to-roll manufactured devices, such as integrated flexible substrates, solution processed electrodes, active layer materials, and environmental barriers are needed. Processes and associated equipment for the patterning, printing, and coating of the various materials are also considered under this task.		
Metrics	**2014 Status**	**2020 Targets**
Manufacturing Cost Reduction		User Defined
Added Value		User Defined

7.6 Additional Priority R&D Topics

This year, through the course of the typical R&D prioritization discussions, several R&D topics arose, some of which are not suited for FOA R&D support. In general these tasks may require broader, longer term efforts with less concrete targets and outcomes. A brief discussion of the R&D topic and proposed support approach is provided below.

Power Supplies- In previous years this topic has been mentioned in the FOA; however, the current over-riding issues with this subsystem are more so related to reliability, selection of components suitable for lighting application (reliability and lighting performance), and characterization and communication of the performance attributes of the power supply to the luminaire manufacturer. Efforts are underway through IES and ANSI standards committees to more readily demonstrate power supply robustness and to more clearly communicate power supply performance parameters for their integration with LEDs in luminaires. In addition, Caliper-like tests are being developed for power supplies to further clarify and communicate performance parameters of power supplies.

Lighting Controls- As described in the previous section, there is considerable interest in taking advantage of the fundamental controllability of LED sources to develop advanced control, intelligence, and communications systems that can further save energy and provide additional value for consumers. The increased implementation and adoption of controls is an enormous opportunity as lighting systems change from conventional technologies to LED based technologies. The primary barriers to implementation and adoption of advanced lighting controls technology are related to device interoperability, consumer acceptance, energy monitoring, and communication of the benefits of the controls approach. As with the early days of LED technology, implementation and acceptance of controls require the development of standardized characterization approaches. Standard characterization will enable easier comparison and communication of the performance will greatly increase consumer confidence and acceptance.

PNNL is currently organizing a program to address interoperability and energy measurement for LED lighting systems with controls.

The focus areas of this new program include:

- Collaborating with industry consortia efforts to contribute to standards development efforts on interoperability and energy measurement
- Assisting with and/or provide third party verification of device and system interoperability
- Evaluating the performance and implementation cost of various measurement approaches
- Designing and developing short-term mock-up test beds that allow for the evaluation of key challenges

Reliability – As mentioned above, the issue of developing a deep understanding of the reliability of LED lighting products is being partially addressed by the LSRC. The DOE SSL Program is also supporting an R&D project at RTI International to develop understanding and models for LED system reliability. Included in the larger topic of LED lighting system reliability are catastrophic failure, lumen depreciation, and color point stability. Each of these three failure modes needs improved understanding and the interplay of these failure modes needs improved understanding. The least understood failure mode is color point stability. Different LED packages color shift in different ways and changes in the optical materials in the luminaire can exacerbate the shift. All failure modes and their interplay require improved understanding, hence, this topic requires a combination of R&D efforts.

Human Factors – The R&D topic of human factors and productivity (self-labeled “Human Centric Lighting Systems”) was raised at the 2015 DOE SSL R&D Workshop during the R&D priorities discussion. The stated R&D challenges for this topic relate to the quantification of the physiological and productivity benefits of spectrally tuned lighting. R&D of this nature requires long-term, large scale studies to identify physiological and productivity impacts. The DOE SSL Program, through work at PNNL, has played a role in this topic through consolidating and communicating the findings of credible, corroborated research.[y] This is an important R&D topic for the long term success of energy efficient lighting. Future R&D on this topic could, perhaps, be supported through collaborative R&D between the DOE SSL Program, NIH, OSHA, and other interested agencies.

Light Quality – Accurately describing and characterizing light continues to be a challenge. Current metrics are based on decades old research and may not accurately describe the light quality from LED sources. In addition, current metrics implicitly assume light quality preferences (CRI equal to 100, white light on blackbody), but recent research shows that maximizing CRI may not account for preferences due to vividness or color gamut area which represent color saturation [116]. Recent research has also shown that there is not an inherent preference for white light that is on the blackbody curve [117]. The DOE SSL Program has supported and continues to support NIST for important research on color characterization and preference.

[y] For more information on this effort please see "True Colors" available at: http://www1.eere.energy.gov/buildings/ssl/pdfs/true-colors.pdf

8.0 Appendices

8.1 Definitions and Background

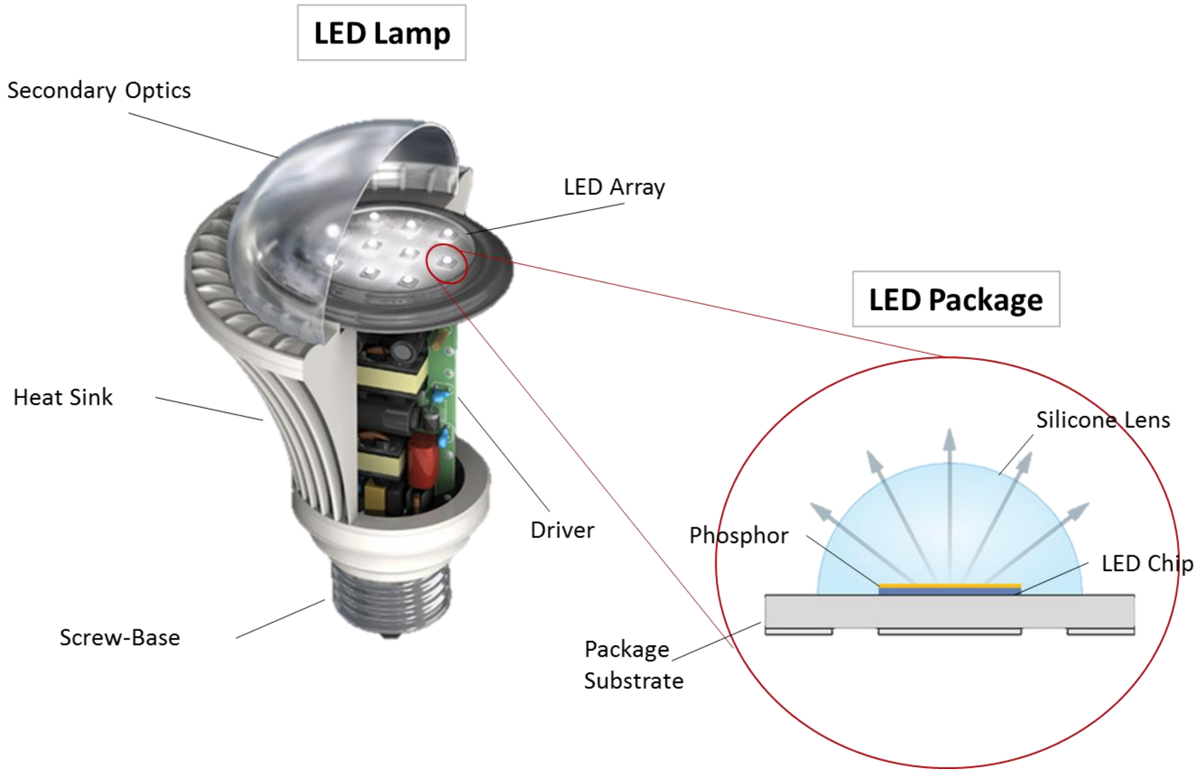

Figure 8.1 Components of an LED Lamp

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

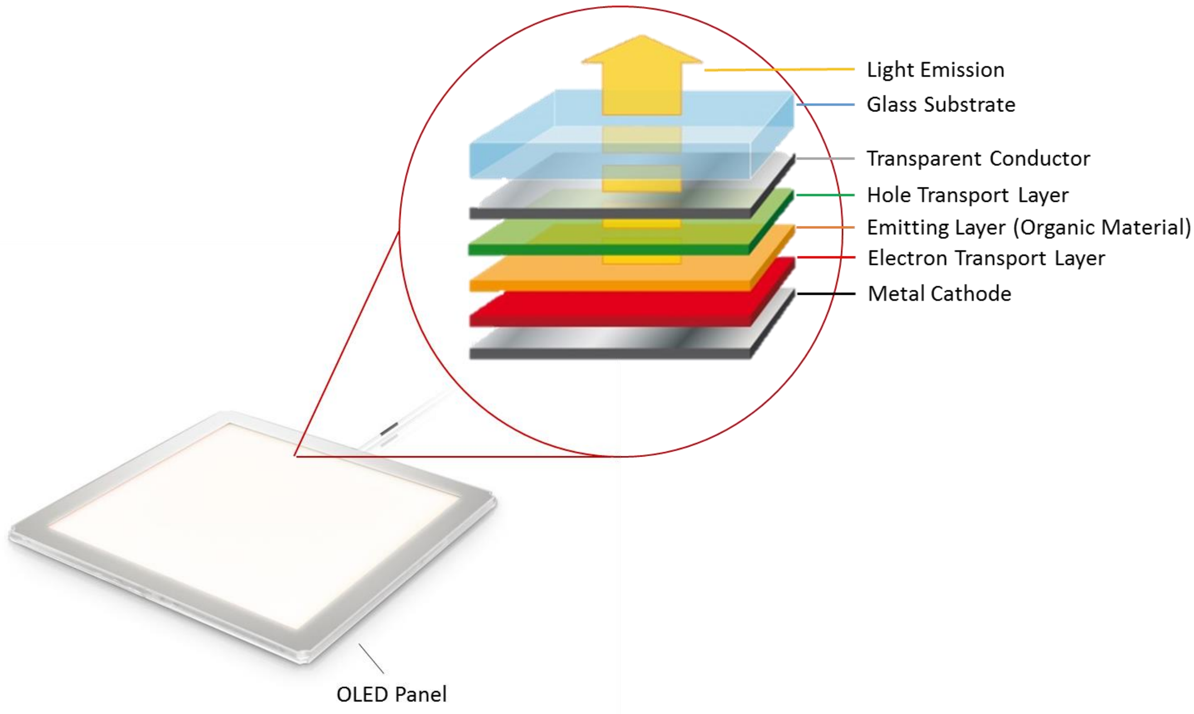

Figure 8.2 Components of an OLED Panel

Image Sources: a) Panel: http://www.lighting.philips.co.uk/lightcommunity/trends/led/oled/ 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 Streetlight/Roadway Examples
Streetlights/ 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
µm	micrometer
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.
°C	degrees celsius
CCT	correlated color temperature
cd/m^2	candelas per meter squared
CFL	Compact Flourescent
cm-LED	color mixed LED
COB	chip on board
CRI	Color Rendering Index
CSP	chip scale package
DALI	digitably addressable lighting interface
DC	direct current
DOE	Department of Energy
D_{uv}	distance from the blackbody locus in u-v colorspace
EMC	epoxy molding compound
ESD	electrostatic discharge
FOA	funding opportunity announcement
FWHM	full width half maximum
HID	high intensity discharge
IES	Illuminating engineering society
InGaN	Indium Gallium Nitride
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
QCM	quartz crystal micro-balance
R&D	Research and Development
R2R	roll-to-roll
RGBA	red, green, blue and amber
SMC	silicone molding compound
SSL	Solid-State Lighting
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 milimeter squared
WHTOL	wet high temperature operating life
$\Delta u'v'$	Magnitude of color shift in the CIE 1976 chromaticity diagram (u', v')
$\Omega/\square$	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**	• Applied Materials • Kurt Lesker • Trovato Mfg	• Aixtron • Beneq	• Canon Tokki • GJM • Hitachi Zosen • Jusung • SFA • SNU • Sunic • Ulvac
	Coaters and printers	• Dimatix • Kateeva • NovaCentrix • nTact • Xenon Corp.	• Coatema • Roth & Rau	• Dai Nippon Screen • Seiko Epson • Sung Am Machinery • Tazmo • Tokyo Electron • Unijet
	Encapsulation	• Coherent • Veeco	• MBraun • Oxford Lasers	• Avaco • Wonik IPS • YAS • Canon Tokki • Ulvac
	Test and inspection	• Colnatec • Radiant Zemax	• Laytec	
Materials Suppliers	**Substrates**	• Alcoa • DuPont-Teijin • Pilkington • Corning • PPG	• ArcelorMittal • St. Gobain • Schott Glass	• Asahi Glass • LG Chem • Nippon Electric Glass • Samsung-Corning
	Extraction Materials	• 3M • Pixelligent	• Novaled	
	Active organic materials	• DuPont • PPG • UDC	• BASF • Cynora • Merck • Novaled • Solvay	• Aglaia • Samsung SDI • Daejoo • Doosan • Dow Electro-Materials • Duksan Hi-Metal • Hodogaya • Idemitsu Kosan • Jilin Optical • JNC/Chisso • LG Chem • Lumtech • Mitsubishi Chemical • Mitsui Chemical • Nippon Steel Sumikin • Nissan Chemical • RuiYuan • Sumitomo Chemical • eRay Opto
	Conductors	• Cambrios • DuPont • ElectronInks • Intrinsiq Materials • NovaCentrix	• Agfa • Heraeus • St. Gobain	
	Encapsulation	• DuPont • 3M • Vitriflex	• Delo • Henkel • SAES Getters • Sud-Chemie	• Samsung SDI • Dynic Tera-Barrier Films

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

Supply Chain	North America	Europe	Asia		
Panels	• OLEDWorks • OTI Lumionics	• Astron-Fiamm • Osram Opto • Philips • Fraunhofer COMEDD	• First O-Lite • Kaneka • Konica Minolta • Lumiotec • Mitsubishi Chemical	• NewView • Nippon Seiki •Pioneer • Showa Denko	• Sumitomo Chemical • Toshiba • Visionox • LG Chem • Mitsubishi Pioneer (MPOL)
Luminaires	• Acuity • WAC Lighting • Blackjack Lighting • Alkilu • Aerelight	• Blackbody • Liternity • Osram Opto • Philips • Tridonic	• Hanyoung • KwangMyung Lighting • Mitsubishi-Pioneer • NEC Lighting	• Verbatim • Visionox • Synqroa • Intelas	

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 $25.8 million from Congress for SSL R&D in the 2015 fiscal year (FY 2015, which began in October 2014). These levels are consistent with congressional appropriations from previous years, which have hovered around $25 million each year. 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.

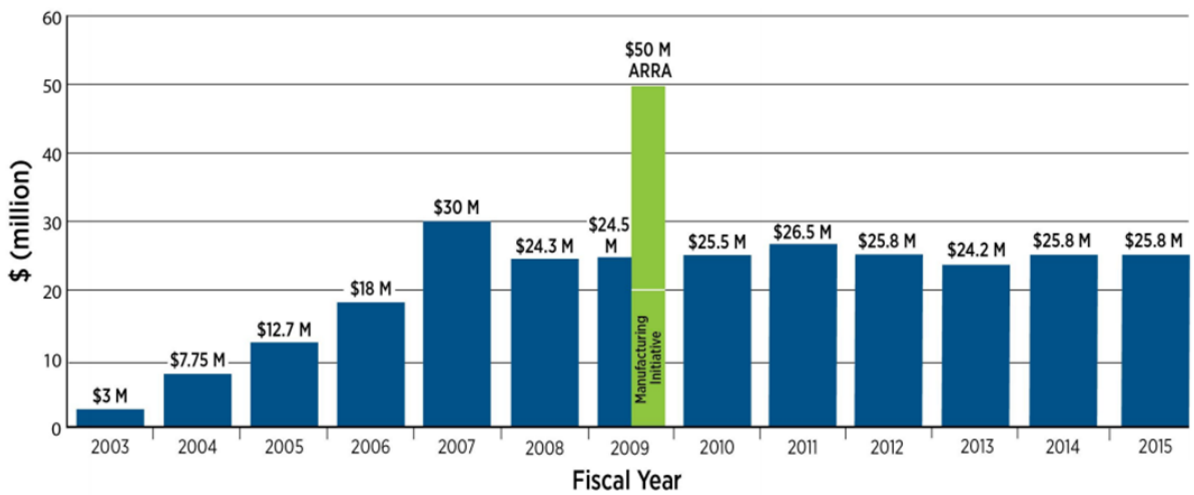

Figure 8.3 Funding Allocations for SSL, FY 2003 to 2015

Source: James Brodrick, DOE SSL R&D Workshop, San Francisco, CA, January 2015 [114]

8.4.2 Current SSL Portfolio

The active DOE SSL R&D Portfolio[z] as of March 2015, shown in Figure 8.4, includes 27 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 and university participation. The portfolio totals, approximately, $50.9 million in government and industry investment.

[z] For the full list of all current and previous DOE SSL funded projects see: http://energy.gov/sites/prod/files/2015/01/f19/2015_ssl-project-portfolio.pdf.

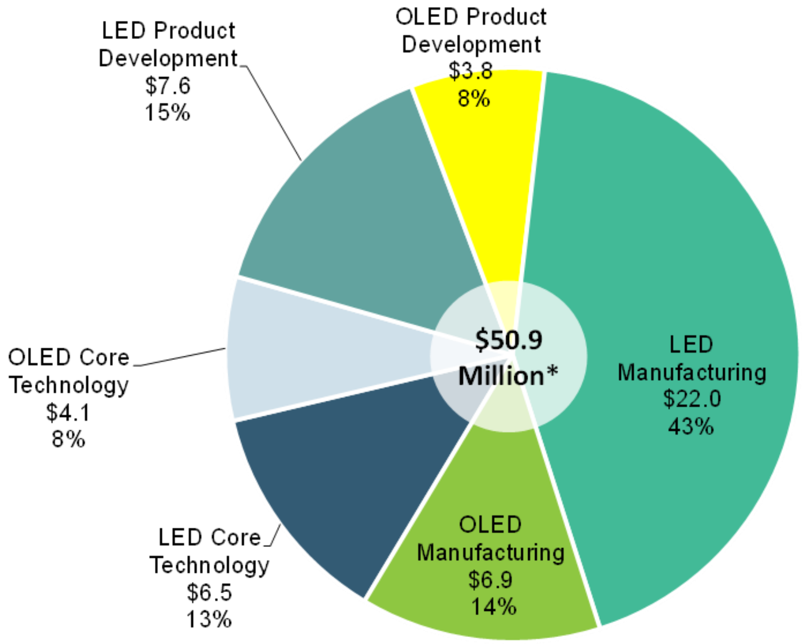

Figure 8.4 DOE SSL Total Portfolio Summary, March 2015

Figure 8.5 provides a graphical breakdown of the funding for the current SSL project portfolio as of March 2015. DOE is currently providing $31.8 million in funding for the projects, and the remaining $19.1 million is cost-shared by project awardees. Of the 27 active projects in the SSL R&D portfolio, 17 focus on LED and 10 focus on OLED technology.

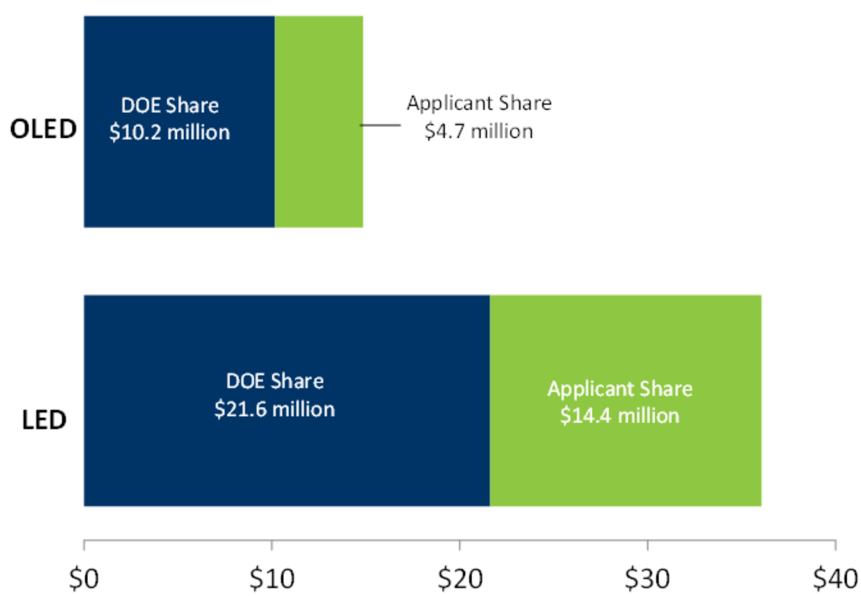

Figure 8.5 Funding of SSL R&D Project Portfolio by Funder, March 2015

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

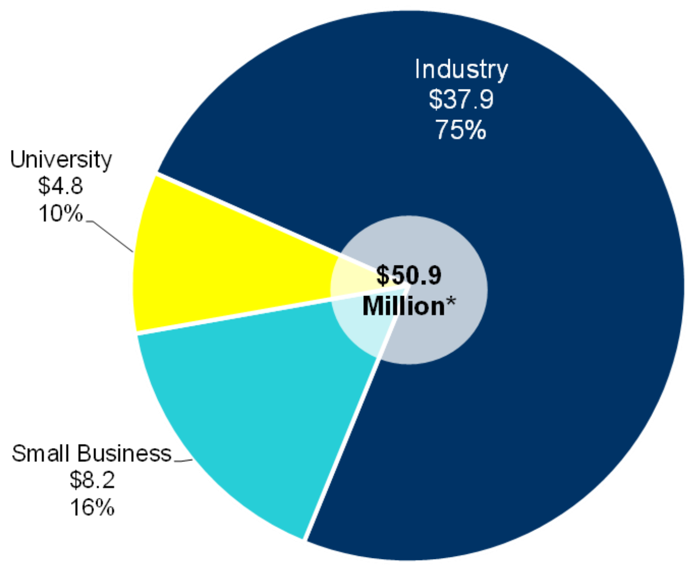

Figure 8.6 DOE SSL Total Portfolio Summary by Recipient Group, March 2015

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. Both 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 2015

Task	Number of Projects	Funding ($ million)
Light-Emitting Diodes	**3**	**$6.5**
Emitter Materials	1	$1.0
Optimizing System Reliability	1	$3.6
Down Converters	1	$1.9
Organic Light-Emitting Diodes	**4**	**$4.1**
Novel Light Extraction Approaches	3	$3.3
Novel Materials	1	$0.8
Total	**7**	**$10.6**

Table 8.8 SSL R&D Portfolio: Product Development Projects, March 2015

Task	Number of Projects	Funding ($ million)
Light-Emitting Diodes	**10**	**$7.6**
LED Package Optics	1	$0.1
LED Package Architecture	5	$6.3
Novel Luminaire System	1	$0.7
Lighting Systems and Controls	3	$0.5
Organic Light-Emitting Diodes	**3**	**$3.8**
Light Extraction	1	$1.0
Low Cost Electrode Structures	1	$1.8
Substrate	1	$1.0
Total	**13**	**$11.4**

Table 8.9 SSL R&D Portfolio: Manufacturing Projects, March 2015

Task	Number of Projects	Funding ($ million)
Light-Emitting Diodes	**4**	**$22.0**
Package Manufacturing	1	$3.8
Luminaire Manufacturing	2	$9.6
Test and Inspection	1	$8.6
Organic Light-Emitting Diodes	**3**	**$6.9**
OLED Deposition	1	$2.1
Integrated Substrate Manufacturing	1	$4.7
Panel Manufacturing	1	$0.1
Total	**7**	**$28.9**

Table 8.10 SSL R&D Portfolio: Current Research Projects, March 2015

	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, Inc.	Scalable Light Module for Low-Cost, High-Efficiency LED Luminaires
	Cree, Inc.	Low-Cost LED Luminaire for General Illumination
	Eaton Corporation	Print-Based Manufacturing of Integrated, Low-Cost, High- Performance SSL Luminaires
	Innotec, Corp*	Integrating Energy efficient SSL with Advanced Sensors, Controls and Connectivity
	KLA-Tencor Corporation	High-Throughput, High-Precision Hot Testing Tool for HBLED Testing
	Lumisyn*	Nanocrystal-based phosphors with enhanced lifetime stability
	MoJo Labs Inc	Task-to-Wall Solid State Lighting Sensing and Control
	Momentive Performance Materials Quartz, Inc.	Next-Generation LED Package Architectures Enabled by Thermally Conductive Transparent Encapsulants
	Philips Lumileds	Development and Industrialization of InGaN/GaN LEDs on Patterned Sapphire Substrates for Low-Cost Emitter Architecture
	Philips Lumileds Lighting, LLC	High-Voltage LED Light Engine with Integrated Driver
	Philips Research North America	Innovative Patient Room Lighting System with Integrated Spectrally Adaptive Control
	PhosphorTech Corporation*	Plasmonic-enhanced High Light Extraction Phosphor Sheets for Solid State Lighting
	Research Triangle Institute	System Reliability Model for SSL Luminaires
	Soraa	Light-Emitting Diodes on Semipolar Bulk GaN Substrate with IQE >80% at 150 A/cm^2 and 100°C
	Triton Systems*	Improved Light Extraction from GaN LEDs
	VoltServer, Inc*	Low-Cost, High Efficiency Integration of SSL and Building Controls using a PET Power Distribution System
OLED	Arizona State University	High-Efficiency and Stable White OLED Using a Single Emitter
	MicroContinuum, Inc.*	Roll-to-Roll Production of Low-Cost Integrated OLED Substrate with Improved Transparent Conductor & Enhanced Light Outcoupling
	OLEDWorks, LLC	OLED Lighting Panel with Directional Light Output and High Efficiency
	OLEDWorks, LLC	High-Performance OLED Panel and Luminaire
	OLEDWorks, LLC	Innovative, High-Performance Deposition Technology for Low-Cost Manufacturing of OLED Lighting
	Pixelligent Technologies LLC*	Advanced Light Extraction Material 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
	University of California-Los Angeles	The Approach to Low-Cost High-Efficiency OLED Lighting

*Small Business Innovation Research projects.

8.4.3 Patents

As of January 2015, 96 SSL patents have been awarded to research projects funded by the U.S. DOE. Since December 2000, when DOE began funding SSL research projects, a total of 247 patent applications have been submitted, ranging from large businesses (79) and small businesses (90) to universities (66) and national laboratories (12). These patents are listed on the DOE website at: http://energy.gov/sites/prod/files/2015/01/f19/patents_factsheet_jan2015.pdf.

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