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

Solid-State Lighting Research and Development

Multi-Year Program Plan

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Multi-Year Program Plan

SOLID-STATE LIGHTING RESEARCH AND DEVELOPMENT

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1 INTRODUCTION

In the United States, lighting consumed about 18 percent of the total site electricity use in 2010, according to a recent U.S. Department of Energy (DOE) report [1]. A second DOE report also finds that solid-state lighting (SSL) technology offers the potential to save 217 terawatt-hours (TWh), or about one-third of lighting site electricity consumption, by 2025 [2]. That savings in site consumption corresponds to about 2.5 quadrillion British thermal units (quads) of primary energy, which is approximately equal to the forecasted 2025 energy production from "other" renewable sources such as wind and solar, making SSL a significant contributor to energy supply issues by reducing the demand on energy resources [3].

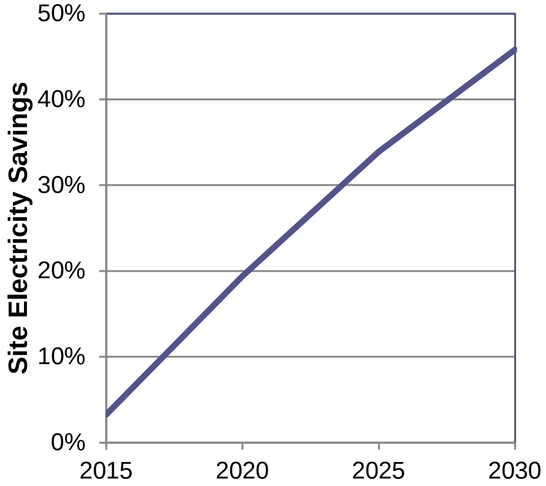

FIGURE 1.1 POTENTIAL SITE ELECTRICITY SAVINGS USING SOLID-STATE LIGHTING [2]

DOE has responded to this opportunity with the Solid-State Lighting Program, providing direction and coordination of many efforts intended to advance the technology and to promote adoption (see Appendix 5.1 for more information).

The energy savings projection in Figure 1.1 assumes significant progress in efficient SSL sources, as well as widespread market adoption. Specifically, by 2025, SSL sources would need to realize a luminaire efficacy of 200 lumens per watt (lm/W) and market penetration, in terms of lumen-hours, of about 60 percent. These are formidable goals, but significant progress on the efficiency portion has already been made, and market adoption is rapidly gaining momentum [4].

This SSL research and development (R&D) Multi-Year Program Plan (MYPP) is strongly directed at the efficiency goals, but also addresses other performance requirements such as product life, color fidelity and stability, and electronic control that may strongly influence market adoption. A companion SSL Market Development Support Plan addresses other initiatives to promote adoption, and DOE's SSL Manufacturing Roadmap concentrates on what is needed to assure that high-quality, cost-effective products will be available in quantity and on time to meet rapidly rising demand [5] [6].

Fundamentally, there are two complementary technology pathways within the SSL program: inorganic light-emitting diodes (LEDs) and organic light-emitting diodes (OLEDs). LED lighting has made significant progress over the last decade, to the point where numerous products are now being offered. While market penetration is just beginning, it is growing rapidly. Comparatively, OLEDs are several years behind in development at this time. Both technologies are considered in this document. In its recently published review of the DOE SSL program, the National Academy of Sciences confirmed the program direction, as well as the potential for solid-state lighting, stating, "The [review] committee finds value in supporting rapid developments in both [LED and OLED] technologies, as they both represent large possible markets, new applications, and tremendous energy savings" [7].

While there is still much work to do, during the past year SSL has shown some very significant advances:

- According to Strategies Unlimited, worldwide sales of LED lighting products, including replacement lamps and luminaires, totaled $14.4 billion, a 25 percent growth in 2012. Similar levels of growth are projected for the next several years.
- Efficacy continues to advance through a combination of fundamental advances along with innovative design approaches. Cree announced a commercially available LED package at 200 lm/W this year.
- The winner of the DOE L Prize,[1] Philips, has launched a variety of replacement lamps based on that technology, including several cost-effective, efficient, and attractive A-lamps, as well as an innovative color-changing lamp.
- The typical selling price of efficient, high-quality LED-based 60W replacements lamps has dropped from over $50 when they were first introduced to about $15 in 2012. Further price reductions are already being seen in 2013.
- In the OLED world, Panasonic and First-O-Lite have fabricated small devices with efficacies over 100 lm/W.
- While manufacturing costs remain an issue, commercial high-brightness OLED panels and luminaires are now available from LG Chem and Acuity Brands with efficacies over 50 lm/W and good lumen maintenance.

The remainder of this MYPP is organized into the following sections. Chapter 2 provides a view of the global market for SSL and discusses the barriers to adoption, particularly with regard to associated technology developments. The section on applications reviews where SSL is rapidly gaining traction and areas in which LEDs or OLEDs may have particular advantages. The greatest of the barriers is selling price, so the discussion of economic considerations gets special attention. Chapter 3 delves more deeply into the state of the art, including sections on source efficacy, luminaire performance, and reliability. It also includes a summary of worldwide R&D efforts.

Chapter 4 takes a deeper look at the key areas of R&D (referred to as “tasks”) that need attention by the community at this time. The tasks have been identified, with inputs from technology experts and participants at the annual DOE SSL R&D workshop, held this year from January 29 to 31 in Long Beach, California (Appendix 5.3 contains a full list of identified SSL R&D tasks). Each task, where possible, includes specific metrics, current status, and goals against which we can track progress. Additionally, projections of progress towards the program efficacy goals are discussed and compared to current performance.

The MYPP is updated annually, reflecting progress towards the goals and the shifting R&D priorities. For long-time readers of the document, we've tried to streamline it this year. Basic background material on LEDs and OLEDs is no longer included, and information on DOE programs and goals has been moved to an appendix, as has the definitions of component parts and metrics. Details of 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 [8] [9] [10] [11].

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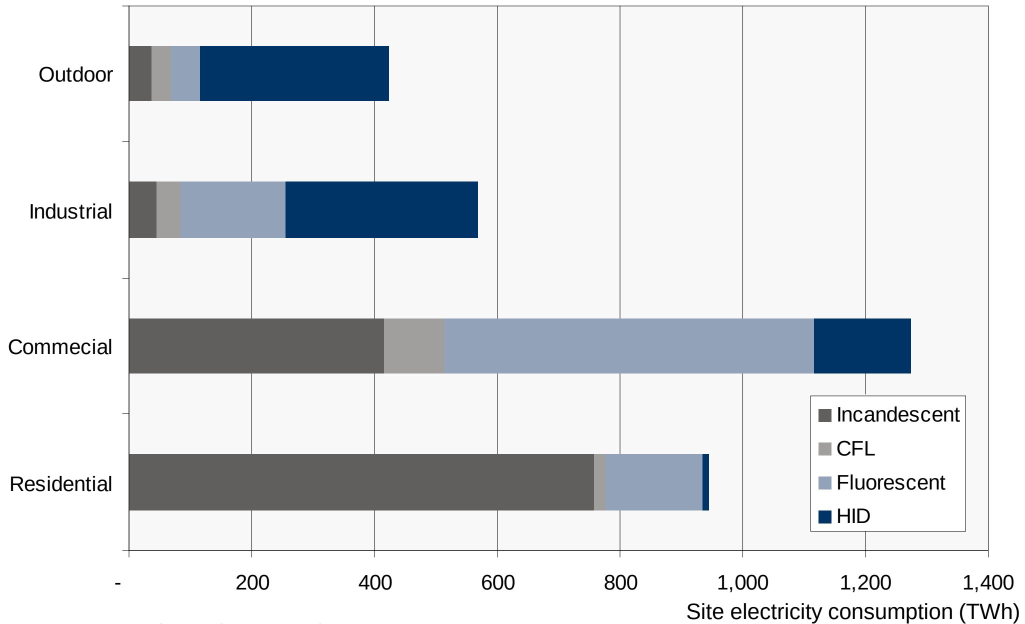
[1] For more information on DOE’s L Prize competition, see: www.lightingprize.org.

2 MARKET AND APPLICATIONS

Although still at a very early stage of adoption, SSL (almost all LEDs at this point) accounts for a small but increasing share of the total lighting market. DOE's 2012 study, “Energy Savings Potential of Solid-State Lighting in General Illumination Applications,” suggests that SSL could account for over half of all of the light produced in the United States by the year 2025. Other studies of the global market have reached similar conclusions. This chapter reviews the market for lighting and SSL, discusses some of the promising applications for SSL, and looks at price trends and barriers to the adoption of LED and OLED technology.

2.1 Global Lighting Market

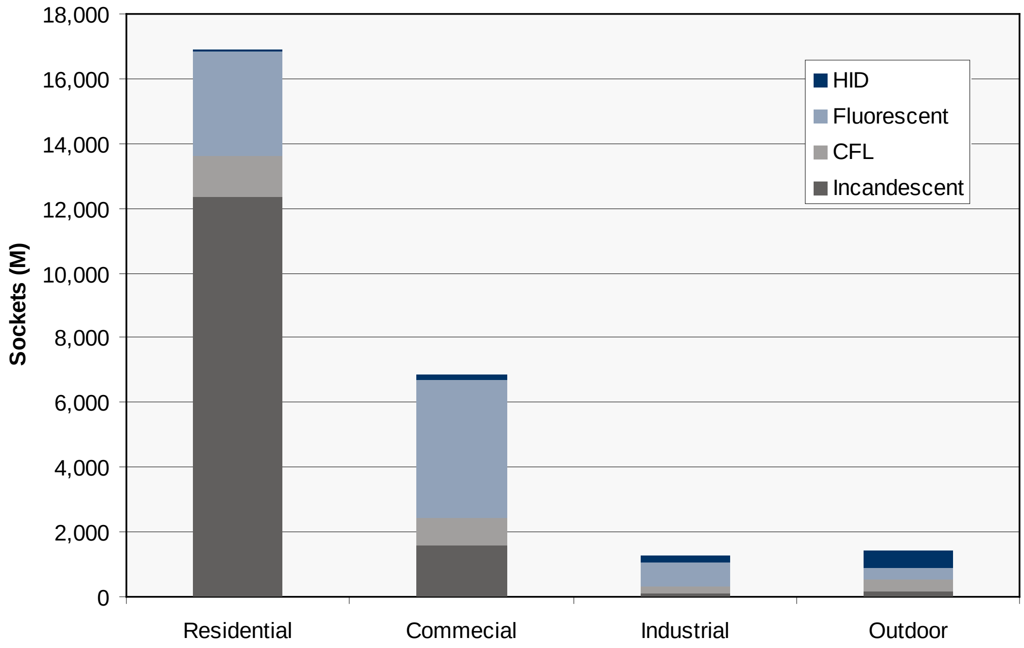
Lighting accounts for 17 percent of global electricity consumption, with the bulk being consumed by inefficient light sources such as the ubiquitous incandescent bulb, followed by linear fluorescent lamps. Figure 2.1 illustrates the distribution of lighting electricity consumption across the primary sectors and technology types, as estimated by Canaccord Genuity [12].



Source: Canaccord Genuity research

FIGURE 2.1 GLOBAL LIGHTING SITE ELECTRICITY CONSUMPTION, 2012 [12]

The incandescent lamps that dominate the residential sector convert only about 10 percent of the electrical power they consume into light. As a result, this sector generates merely 15 percent of global light (measured in lumen-hours), while consuming about one-third of lighting energy [12]. Fluorescent and high-intensity discharge (HID) lamps have higher efficiency and occupy fewer sockets than incandescents worldwide. Nevertheless, total energy use and light output are higher because of longer hours of use and higher light outputs per lamp. Figure 2.2 shows the estimated number of sockets by technology and market segment, as reported by Canaccord Genuity.



Source: Canaccord Genuity research

FIGURE 2.2 GLOBAL LAMP INSTALLATIONS BY SECTOR AND TECHNOLOGY, 2012 [12]

A somewhat similar pattern in socket penetration and energy use is evident in the United States, as illustrated in Figure 2.3. The same study from which these data came also reported that linear fluorescent lighting in the United States accounts for the plurality of electricity consumption, or approximately 42 percent, due to the popularity of these lamps in commercial and industrial buildings, and HID lighting consumes 26 percent due to its high output and long hours of use. Notably, however, incandescent lamps are not the primary energy consumers in the United States and are less prevalent than they are worldwide—domestically they occupy only 22 percent of lamp sockets—though they are still employed in 78 percent of residential sockets. Figure 2.3 also illustrates that 60 percent of light is produced in commercial buildings, demonstrating the potential for energy savings in that sector. While linear fluorescents are very efficient, SSL sources have demonstrated even higher efficacy, so penetration into the commercial sector is an important goal for overall energy efficiency.

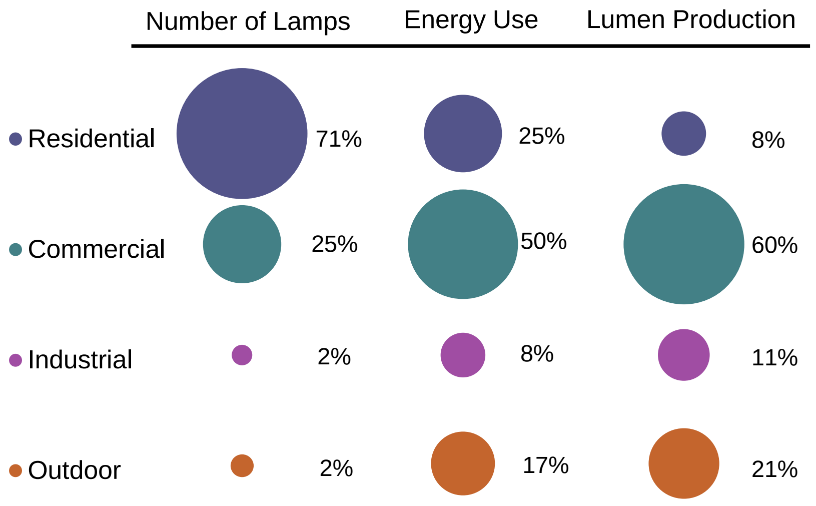


FIGURE 2.3 U.S. LIGHTING INVENTORY, ELECTRICITY CONSUMPTION, AND LUMEN PRODUCTION, 2010 [1]

Rising electricity prices and mounting concerns about climate change and energy independence are causing the global lighting market to shift toward energy-efficient light sources. In the United States, this trend is evident in a nine percent drop in annual lighting electricity consumption between 2001 and 2010 in spite of an 18 percent growth in number of installed lamps [1] [13]. It is occurring in all sectors and applications, but is most notable in the global migration away from incandescent lighting. Compact fluorescent lamps (CFLs) offer a relatively inexpensive alternative, but have encountered consumer resistance. As prices have fallen and consumer confidence has improved, LED sources have become increasingly attractive alternatives to incandescent lamps. In addition, a number of governments around the world have taken legislative and regulatory action in an effort to markedly reduce their energy footprint. The United States Congress passed maximum wattage standards for general service incandescent lamps as part of the Energy Security and Independence Act of 2007, which phase in between 2012 and 2014 and effectively require a 25 percent increase in the efficacy of general service incandescent lamps [9]. As in the United States, the European Union (EU), the United Kingdom, Japan, China, India, Russia, Brazil, Canada, Australia, Cuba, Taiwan, and Korea have all passed stringent regulations or phase-outs of incandescent bulbs, taking effect between 2008 and 2017. IHS forecasts that these regulations will reduce unit shipments[2] of incandescent lamps from 49 percent of shipments in 2011 to 12 percent in 2020 [14].

Similar shifts are apparent in commercial and industrial buildings, where efficient fluorescent T8 and T5 lamps are supplanting low-efficiency T12 lamps. Likewise, metal halide (MH) and high-pressure sodium (HPS) lamps have grown in popularity in outdoor applications at the expense of mercury vapor (MV) due to higher efficacies. The trend toward increasing energy efficiency in the United States demonstrates that lighting customers are willing to modify their purchasing behavior in the

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[2] A useful basis for reporting market share of lighting technologies is light production, measured in lumen-hours, generated by each lighting source. This metric reveals the demand for light and allows an estimate of the associated energy consumption. However, in the absence of lumen-hour breakouts, this report uses unit shipments-based market shares, rather than value- or revenue-based market shares, to approximate the energy-use profile of lighting.

face of compelling economics. This trend is illustrated by Figure 2.4 alongside DOE projections for LED penetration in these applications in 2030.

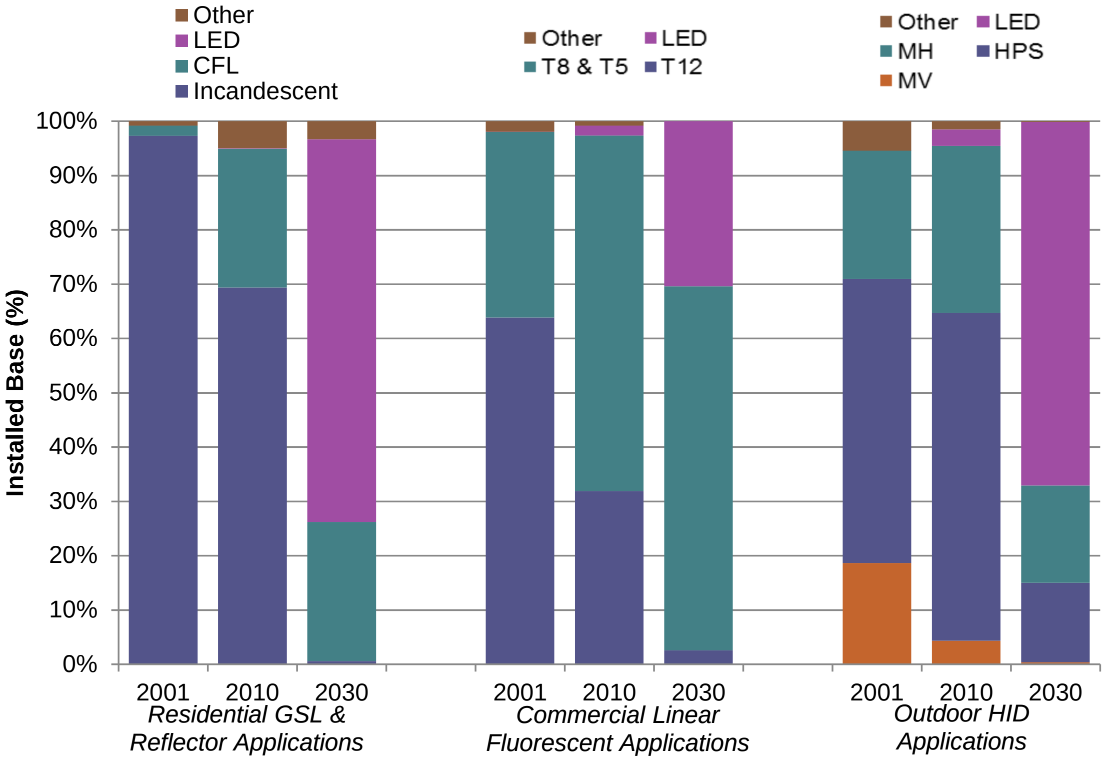

FIGURE 2.4 U.S. MIGRATION TOWARD ENERGY-EFFICIENT LIGHT [1, 2, 13]

Though still in its infancy, SSL is well positioned to capitalize on the prevailing demand for energy-efficient lighting solutions. Estimates of market penetration (measured in unit sales) in the range of 2-3 percent confirm that LED technology is already beginning to take a foothold in the lighting market [14] [15]. Long-term forecasts of market penetration range quite a bit, but there is broad consensus in the industry that if performance projections are met and costs continue to fall, LED lighting systems could see large gains in the market. McKinsey & Company estimates that LEDs will account for 52 percent of worldwide lamp and luminaire shipment volumes in 2020 [15]. Likewise, the market research firm IHS projects that 25 percent of lamps sold in 2020 will use LED technology [14]. Given the significant gains of SSL in certain applications to date (further discussed in Section 2.2) and expected continued advancement, DOE expects LED-based lighting to become a dominant market player in coming years. Specifically, DOE projects white-light LED sources to account for 74 percent of lumen-hour sales (roughly 71 percent of unit sales) in the United States and to save 297 TWh[3] by 2030. By 2020, DOE expects LED market share to hit 38 percent of U.S. lumen-hour sales (or 28 percent of unit sales). DOE also projects that 25 percent of lighting installations will incorporate an LED lamp or luminaire by 2020, climbing to 62 percent by 2030 [2].

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[3] Savings are estimated over a business-as-usual baseline forecast that represents the market composition in the absence of LED lighting.

Due to a number of geographical, political, and cultural factors, LEDs are likely to make even more remarkable progress in Asia. For example, the most rapid adoption of LEDs has been in Japan. Japan's energy-conscious culture, itself a product of limited natural energy-producing resources and high energy prices (approximately double that of the United States), has long favored fluorescent lighting, which constituted 65 percent of installed lamps in 2011 [16]. However, as the efficacy improves and the price gap narrows between LED and fluorescent technology, LED lighting has gained ground such that LED lamps constituted about nine percent of non-HID lamps sold in Japan in 2011 [14]. The Fukushima Daiichi nuclear disaster in March 2011 and the resulting seven-percent reduction of Japan's energy supply [17] is further catalyzing LED penetration, such that LED lamps are forecasted to account for 30 percent of non-HID lamps sold in Japan in 2020 [14].

Likewise, China is making a push for LED light sources to supplant other lighting technologies in an effort to stem rising demand for power generation. The Chinese government has set a target for LEDs to constitute 30 percent of domestic lighting market sales in 2015 [18]. In 2012, China experienced the fastest growth of any country in LED replacement lamps [4]. The China Solid State Lighting Alliance estimates that domestic shipments of LED lights in 2012 amounted to 130 million units, or 3.3 percent of all lighting products [19].

While LED lamps comprise the vast majority of LED units in today's market, a growing number of LED luminaires are being developed. As these become available, it is likely that the share of luminaires in the LED market will grow.

In contrast with LED lighting, white OLEDs are behind in their development as a general illumination solution. While OLED lighting technology continues to advance, issues such as high production cost and low life expectancy remain as barriers to the broader lighting market. The biggest OLED panel manufacturers are located in Korea and Japan and supply the majority of OLED panels in the United States. Recently, OLEDWorks, a company in New York State, installed the first U.S. manufacturing line for OLED lighting panels, and production should begin later this year.

2.2 Applications for Solid-State Lighting

The past decade has shown steady advancement of LED lamps and luminaires as a white-light solution, with today's LED installed base more than 40 times larger than in 2001 [1] [13]. DOE periodically profiles domestic lighting applications in which LEDs are competitive and those in which they are well positioned to gain ground against traditional light sources in the "Adoption of Light-Emitting Diodes in Common Lighting Applications" [20].[4] Table 2.1 below provides a summary from the most recent iterations of these reports. This section discusses some of the major domestic and global trends of LED-based lighting in these general lighting applications.

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[4] Previous editions of this report are available on the DOE SSL website under the title "Energy Savings Estimates of Light Emitting Diodes in Niche Lighting Applications."

TABLE 2.1 U.S. PREVALENCE OF LED SOURCES IN SELECT LIGHTING APPLICATIONS [20, 1]

Application	Estimated LED Penetration of Installed Stock (%)[1]	
	2010	2012
A-Type	–	<1
Directional	<1	5
MR16	3	10
Decorative	–	<1
Downlight	<1	<1
Troffer	–	–
High-Bay	–	<1
Parking[2]	<1	1
Streetlight[2]	1	2

Notes:
1. Values less than 0.1% are considered negligible.
2. These estimates have been updated using data from the 2010 U.S. Lighting Market Characterization report.

OLED technology has yet to enter the general lighting market as a viable alternative to other light sources, but the OLED community is making strides toward targeting certain applications. Most OLED prototypes developed thus far have yet to attain light output levels suitable for many general lighting applications. Therefore, these initial products have been largely decorative in nature. In addition to decorative lighting applications, some OLED products have been developed for task lighting applications, such as desk or table lamps.

2.2.1 LED Replacement Lamps

In 2012, replacement lamp applications comprised most of the LED lighting market, both domestically and globally [4], with omnidirectional A-type lamps, directional parabolic aluminized reflector (PAR) and multifaceted reflector (MR) lamps composing the majority of the replacement lamp market.

The 60W-equivalent A-type is the most commonly used lamp in the world. According to IHS, LED-based products are predicted to account for 44 percent of global A-type shipments by 2020 [14]. The impact on A-type shipments can be at least partially attributed to the various lighting efficiency standards and regional regulatory phase-outs of A-type incandescent lamps, as discussed in Section 2.1. Compared to general service lamps, which produce omnidirectional light, reflector lamps provide directional light and are commonly used in recessed can and track lighting fixtures. In retail and display applications, LED reflector replacement lamps are already installed on a significant scale, which is evident in the high penetration level and large installed LED lamp base observed in both these applications. Global LED reflector shipments are forecasted to surpass shipments of all other reflector lamp technologies by 2017 and climb to 58 percent by 2020 [14]. As their quality improves and prices continue to drop, LED lamps will penetrate the general lighting market at a faster pace. The increasing adoption of LED lamps, combined with their extended lifetimes, will have a significant effect on regional lighting markets, especially in the replacement lamp market.

2.2.2 LED Luminaires

LED luminaires are defined as a luminaire integrated with a non-replaceable LED light source. In general, LED luminaires offer better lighting performance than LED replacement lamps because electrical, thermal, and optical performance of the luminaire can be engineered together and there are fewer constraints on the form factor (e.g., fitting into a troffer volume rather than the volume of a linear fluorescent lamp). LED luminaires are a growing section of the LED lighting market and represent viable alternatives to traditional lighting fixtures for a range of commercial, industrial, and outdoor applications. LED luminaire products have proven themselves a good choice for recessed downlighting and track lighting used frequently in retail display. Other applications where LED luminaires fare well include recessed troffers, high-bay fixtures, outdoor roadway, and parking applications.

LEDs are attractive in track, accent, retail-display, and downlighting applications because they can offer good color quality, low cost of ownership, and better optical control than traditional light sources. In 2012, growth in the retail-display and commercial market segments was primarily fueled by the uptake of LEDs in commercial downlighting applications in Japan and, to a lesser extent, the United States, Europe, and the rest of the world [4].

Outdoor lighting is another rapidly growing sector for LED luminaires, especially in street and outdoor area lighting and parking lot applications. LEDs are competitive in these applications because they offer longer lifetimes and better lumen maintenance than incumbent HID technologies. This drastically reduces costly maintenance and repair and gives LED luminaires a competitive life-cycle cost. Pike Research, a part of Navigant’s Energy Practice, estimates that the average maintenance cost of LED luminaires in general outdoor lighting applications was less than half that of their HID counterparts. However, the installed inventory of LED luminaires in highway, road, and parking lot applications in the 2012 world market was only around 2.4 percent. Europe, which constitutes nearly 40 percent of the total global streetlight market with around 90 million installations, has less than one-half million LED fixtures installed in this application [21].

In 2010, DOE estimates that LED luminaires in outdoor area, parking, and roadway applications accounted for roughly three percent of all outdoor installations[5] in the United States [1]. Growth in LED outdoor area lighting has continued, with programs such as Los Angeles’ LED Street Lighting Energy Efficiency Program leading the charge. This effort is one of the largest LED street lighting retrofits undertaken to date, with 140,000 LED streetlights installed in the last three years [22]. In addition, the DOE SSL GATEWAY program has demonstrated installations of outdoor SSL systems in several areas across the country. More information on specific projects is available at: www.ssl.energy.gov/gatewaydemos_results.html.

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[5] Excludes traffic signal applications.

2.3 Economic Considerations

An evaluation of the economic benefit associated with the introduction of SSL sources must balance the longer term energy savings with the higher initial price. SSL will probably always be more expensive than conventional lighting on a first-cost basis, but higher operating efficiency and longer operating lifetimes (reduced maintenance/replacement costs) have enabled LED lighting to become competitive on a life-cycle basis in many applications. A life-cycle cost analysis gives the total cost of a lighting system, including all expenses incurred over the life of the system. The payback period is time it takes the consumer to recover the higher purchase cost of a more energy-efficient product as a result of lower operating costs. In a commercial setting with long hours of daily operation, this payback period might already be as short as one year.[6]

2.3.1 Cost of Lighting Sources

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 significantly higher than conventional lighting sources as shown in Table 2.2.

TABLE 2.2 COMPARISON OF TYPICAL MARKET PRICES FOR VARIOUS LIGHTING SOURCES

Lighting Source	Price ($/klm)
Halogen Lamp (A19 43W; 750 lumens)	$2.5
CFL (13W; 800 lumens)	$2
CFL (13W; 800 lumens dimmable)	$10
Fluorescent Lamp and Ballast System (F32T8)	$4
LED Lamp (A19 12W; 800 lumens dimmable)	$19
CFL 6” Downlight (13 W; T4; ~500 lumens)	$10
LED 6” Downlight (10.5 W; 575 lumens)	$50
OLED Panel	$800
OLED Luminaire	$2,400

On a normalized light output basis, LED lamps are currently around eight times the price of a halogen bulb and around twice the price of an equivalent dimmable CFL.

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[6] For examples, see: www.cree.com/news-and-events/cree-news/press-releases/2012/march/120329-expands-troffer-family or apps1.eere.energy.gov/buildings/publications/pdfs/ssl/gateway_intercontinental-hotel.pdf.

The first OLED products are only now becoming commercially available, and as the table above shows, these products are not yet cost competitive. However, these luminaires use prototype panels manufactured on R&D lines. Several lines designed for volume production will reach acceptable yields in 2013 and prices should fall rapidly over the next three years.

2.3.2 LED Package Prices

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. The selected data represents devices in the highest efficacy bins (taking the average value within that bin), which fall within specified ranges of correlated color temperature (CCT) and color rendering index (CRI). In all cases, the price is expressed in units of \$/klm and has been determined at a fixed current density of 35 amperes per square centimeter (A/cm^2) and a 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.

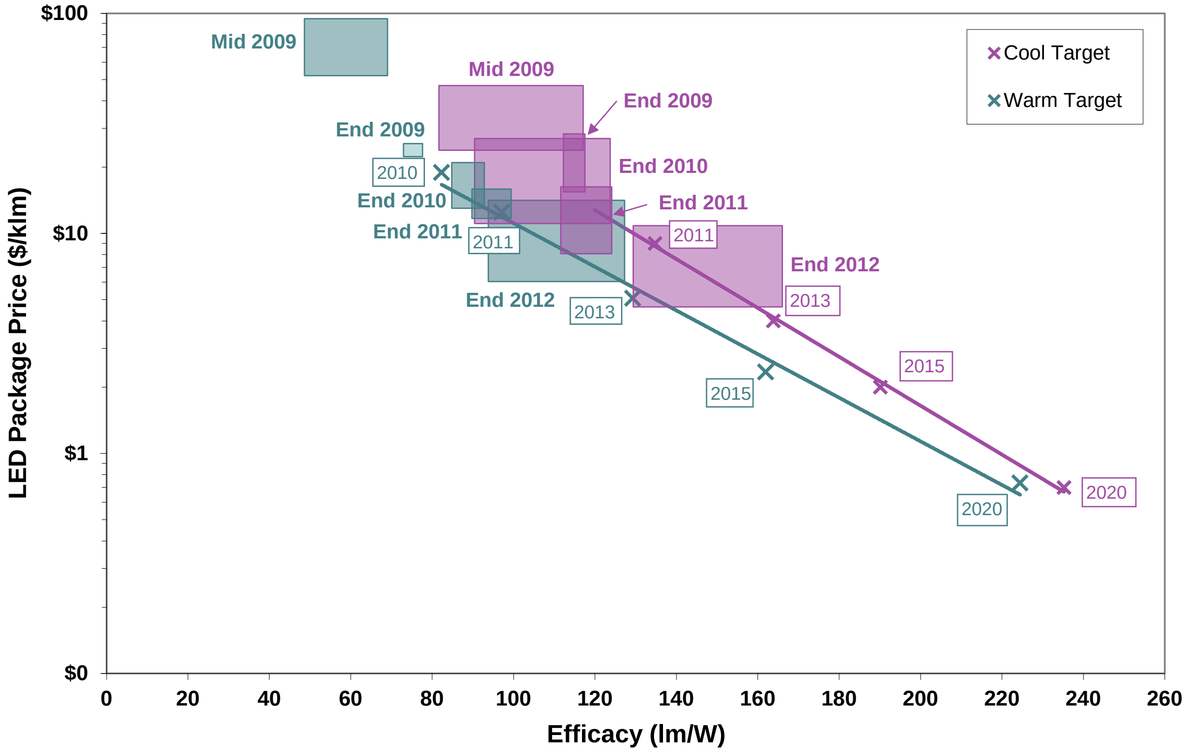

FIGURE 2.5 PRICE-EFFICACY TRADEOFF FOR LED PACKAGES AT 35 A/CM^2 AND 25 °C

Notes:

1. Cool-white packages assume CCT=4746-7040 K and CRI >70; warm-white packages assume CCT=2580-3710 K and CRI >80.
2. Rectangles represent region mapped by maximum efficacy and lowest price for each time period.
3. The MYPP projections have been included to demonstrate anticipated future trends.

Each period is characterized by the two sets of values associated with the highest efficacy and lowest price products, and this range is depicted graphically by a rectangle. The specific values used in Figure 2.5 for 2012 are listed in Table 2.3. As is to be expected, the higher efficacy product attracts the higher price. The price-efficacy projections are included in Figure 2.5 for comparison purposes and are summarized in Table 2.4. As can be seen in the table, there has been a significant improvement in both price and performance during the past year, and progress remains in good agreement with the projections.

TABLE 2.3 RANGE OF EFFICACY AND PRICE FOR WARM- AND COOL-WHITE LED PACKAGES IN 2012

Type	LED Package	Efficacy (lm/W)	Price ($/klm)
Warm-White	Cree XT-E	128	14
	Cree XM-L	94	6
Cool-White	Cree XT-E	166	11
	Philips Lumileds Luxeon M	130	5

TABLE 2.4 SUMMARY OF LED PACKAGE PRICE AND PERFORMANCE PROJECTIONS

Metric	2012	2013	2015	2020	Goal
Cool-White Efficacy (lm/W)	150	164	190	235	266
Cool-White Price ($/klm)	6	4	2	0.7	0.5
Warm-White Efficacy (lm/W)	113	129	162	224	266
Warm-White Price ($/klm)	7.9	5.1	2.3	0.7	0.5

Note: Projections for cool-white packages assume CCT=4746-7040 K and CRI >70, while projections for warm-white packages assume CCT=2580-3710 K and CRI >80. All efficacy projections assume that packages are measured at 25 °C with a drive current density of 35 A/cm^2.

2.3.3 LED Luminaire Prices

LED lamp and luminaire prices vary widely depending upon the application. 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 the most popular residential lamps, and consequently we have focused on the A19 60W-equivalent (800 lm) replacement lamp for our projections. Figure 2.6 shows how the retail price (neglecting subsidies) has dropped over the past five years and how it compares to a typical conventional 13W CFL. Also included in Figure 2.6 is the current MYPP projection. During 2012 we have continued to see a marked reduction in prices as manufacturing costs are reduced and competition intensifies. Typical retail prices have dropped to a low of around $15, corresponding to a normalized price of $19/klm, slightly ahead of the MYPP projection. Retail prices are projected to fall further during 2013 and approach the $10 range

($12.5/klm), which many believe may be a critical tipping point resulting in widespread deployment of such products in a residential setting. Early in 2013 we've already seen the retail price into the $16/klm range.

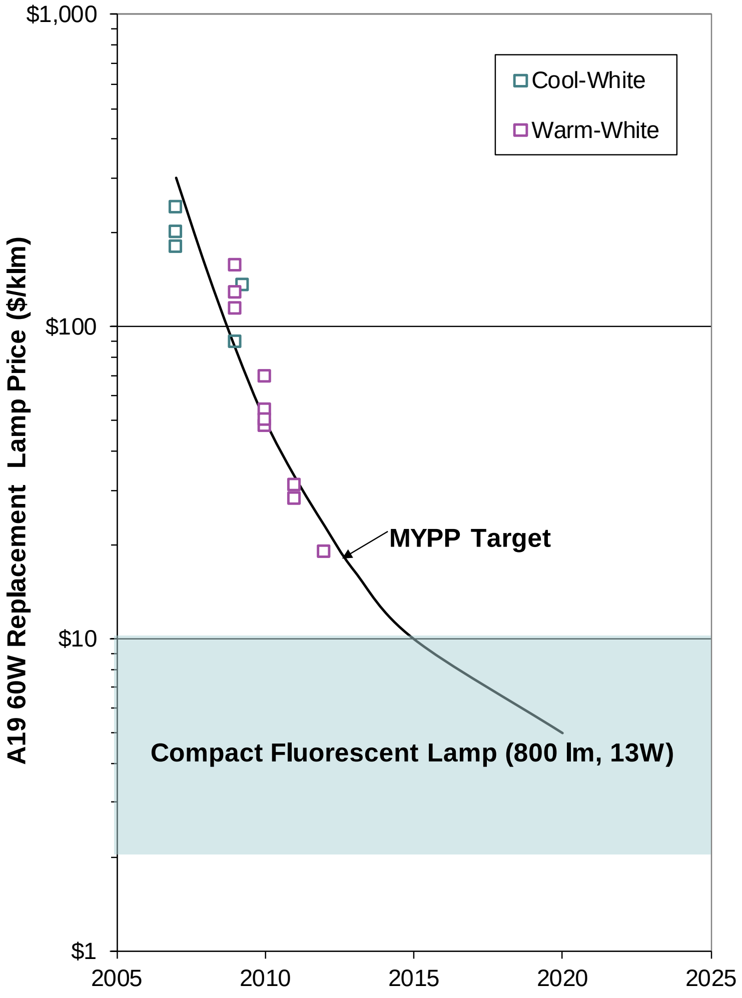

FIGURE 2.6 A19 REPLACEMENT LAMP PRICE PROJECTION (60W EQUIVALENT)
Note: The shaded region illustrates the price range for a typical equivalent performance CFL (13W self-ballasted CFL, non-dimmable at bottom, and dimmable at top).

Typical prices for LED replacement lamps over the past two years are summarized in Table 2.5. Price reductions have also continued for MR16-style reflector lamps while LED-based PAR38s and downlights appear to have roughly stabilized on price. Note that the energy usage is reduced by a factor of around three for LED-based MR16 and PAR38 lamps and around a factor of eight for downlights. Reducing energy consumption and/or reducing prices, combined with lifetimes ranging from 25,000 to 50,000 hours, continue to drive down the life-cycle costs and shorten the payback period.

TABLE 2.5 TYPICAL PRICES FOR LED-BASED REPLACEMENT LAMPS

LED Lamp Type	Light Output (Lumens)	Power Input (Watts)	Nominal Equivalent (Watts)	Prices ($/klm)	
				2011	2012
A19	850	13	60	30	19
PAR38	1300	24	75	34	34
MR16	500	10	35	60	44
Downlight	575	11	75	50	50

Note: The nominal equivalent (watts) column gives the approximate power consumption for an incandescent source providing an equivalent lumen output.

Outdoor lighting is another area where life-cycle costs are an important consideration. Over the past few years, the base price for LED outdoor fixtures providing around 8,000-10,000 lm (i.e., typical replacements for 150W HPS or 175W MH lamps) has dropped from around $150/klm to around $80/klm, and the efficacy has increased from around 50 lm/W to around 80 lm/W. In conjunction with the reduced maintenance overhead and lower power consumption, the simple payback period for many installations has reached around 8-10 years [23].

As a specific example, the City of Los Angeles began a streetlight replacement program in 2009, as mentioned in Section 2.2.2, and had replaced 115,000 of the planned 140,000 lights as of January 2013. From 2009 to 2012, the average price of each light has reduced from $432 to $245, while efficacy has improved from 42 lm/W to 81 lm/W. Purchasing in large quantities has reduced the average normalized price to around $50/klm. Average energy savings are 63.5 percent, providing a payback period of less than seven years [22].

2.3.4 OLED Panel and Luminaire Prices

While samples of OLED panels have been available since 2009, these have been produced on R&D lines and are very expensive on a $/klm basis. For example, a 10 cm x 10 cm panel from Lumiotec costing about $130 produces 55 lm (~$2,700/klm). An engineering kit from Philips at $520 contains three GL350 panels that produce 360 lm (~$1,500/klm). Fabrication lines designed specifically for higher volumes have been built by LG Chemical and First-O-Lite, and the main R&D lines operated by OSRAM and Philips have been upgraded to enable commercial production. Prices should come down substantially as these factories move into full production.

The retail prices of luminaires are even higher than for the panels. For example, the Hanger luminaire from Lumiotec provides 130 lm from a 210 cm^2 panel and was originally priced at $450, corresponding to $2,900/klm. The V-Lux from Blackbody contains two OLED panels with total area 200 cm^2 and produces 250 lumens. The introductory price was $700. As an example of a luminaire that extends the functionality of traditional lighting, the Philips LivingShapes interactive mirror contains 72 small OLED panels, giving a total of 400 lm at a price of $10,000/klm.

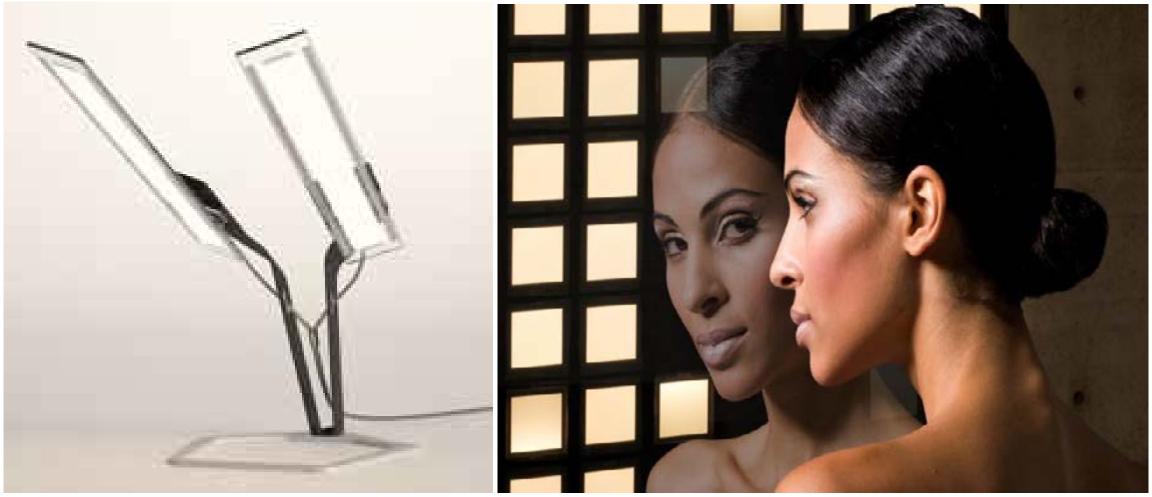

FIGURE 2.7 "V-LUX" OLED DESK LAMP AND "LIVINGSHAPES" INTERACTIVE OLED LIGHT AND MIRROR
Sources: Blackbody, Philips

2.4 Other Barriers to Adoption

The realization of energy savings from SSL will depend on both source efficacy and market adoption. While the relatively high price of SSL is the primary barrier to adoption, there are a number of additional considerations and uncertainties that prevent consumers from buying energy-saving lighting products. The barriers described below already apply to LED-based light sources and are anticipated to apply to OLED light sources as well. Removing these barriers is essential to the success of the SSL R&D Program and maximizing the energy savings that these products offer.

1. Lifetime: The full cost of lighting is a function of product price, energy consumption (efficiency), and lifetime (consumers will need to buy and replace fewer long-lived lights). For many applications, LED-based light sources can have a lower total cost of lighting, but this requires that SSL sources achieve their lifetime claims. However, these are new technologies with extreme lifetimes and new failure mechanisms, so the reliability of these products is not well understood. Lumen maintenance is somewhat understood for LED packages but does not fully describe the anticipated lifetime of the full luminaire and its full range of possible failure modes. Failure mechanisms such as color shifts, optics degradation, power supply failures, solder detachment, etc. can lead to the luminaire falling out of specified performance or catastrophic failure. The integration of the LED package into the luminaire can also have considerable impact on the lifetime of the system; namely, inadequate thermal handling can reduce the LED lifetime and the design of the power supply can also impact the lifetime of the LED and luminaire. A better understanding of the luminaire system lifetime and reliability is necessary to provide confidence that SSL products will meet stated lifetime claims and achieve a reduced cost of lighting. DOE has supported specific R&D and the creation of an industry consortium to foster understanding, but considerable additional work remains to establish a full reliability database of components and subsystems to aid luminaire design. Work to understand failure mechanisms intrinsic to the OLED device and panel will also be necessary as OLED lighting matures. OLEDs have fundamentally different failure mechanisms and environmental responses than those of the inorganic LEDs currently used in SSL. For example, even very small quantities of water vapor and oxygen can lead to rapid degradation of the organic materials and cathodes. A more thorough discussion of lifetime is provided in Section 3.3.

2. Color Quality: Many LED lighting products have demonstrated excellent color quality with CRI greater than 90, good R9 values, and a range of CCTs. However, the perception remains that LED lighting products have fundamentally worse color quality than conventional sources, in particular halogens. Some of the perception may be based on the recollection of the very first, low color-quality LED lighting products. And some of the perception may be due to using the wrong LED product in an application (cool-white product replacing a warm-white incandescent, for example). In addition, new color science, perception research, and anecdotal evidence are indicating that even with matching color metrics, different lighting technologies can be perceived differently. To address all of these concerns, a new and better understanding of color perception with new metrics may be necessary. OLEDs offer yet another light source technology with unique spectral power densities. The broad spectrum of OLED emission peaks allow for full coverage of the visible spectrum, but red emission in the infrared regime and the lack of efficient, long-life blue emitters limit options in terms of optimizing the tradeoff between color quality and efficacy. There have been only a handful of OLED products in the market so far, so it is not clear what the full range of color options will be. Improved understanding of color perception will allow for products to better meet the demands of the application and the consumer.
3. Lighting System Performance: For lighting products, and lamps (bulbs) in particular, consumers have come to expect full inter-changeability between various light source technologies. Replacement products are expected to be compatible with the legacy dimmer circuit and match the color quality, light distribution, form factor, and light output of the product they are replacing. Enabling full dimmer compatibility across the range of possible dimmer approaches adds considerable cost and complexity to the LED power supply and can reduce the efficiency of the system. In many cases, LED replacement products are not fully compatible with dimming circuits and there can be flickering, uneven dimming, or buzzing. As discussed in the previous section, there can be mismatches in color between old and new light source technologies, which can be a problem depending on the application. LED sources also often have different optical distributions that can impact the illuminance from a given light source and distort claims of equivalency between the sources. All of these factors can deter customer acceptance and be a barrier to adoption of the new light source technology.

3 TECHNOLOGY STATUS

In this chapter, we consider the factors affecting source efficacy for LED packages and OLED panels and identify likely practical limits. The incorporation of such components into luminaires involves additional losses and limits the ultimate efficacies achievable for SSL luminaires. These limits are analyzed, discussed, and compared with the state of the art for existing SSL lighting products. This chapter also considers issues relating to the determination of SSL reliability and lifetime and concludes with a brief consideration of global R&D efforts in SSL.

3.1 Source Efficacy

Total energy savings from SSL sources is a function of the source efficacy improvement and the level of adoption. The previous section discussed possible technical approaches to improve adoption, but there is also much that can be done to improve LED package, OLED panel, and luminaire efficacy. LED luminaires are already more efficient than incandescent sources and most CFL luminaires, although they still lag slightly behind linear fluorescent luminaires. Initial OLED luminaire products have similar efficacy to that of compact fluorescent sources but may offer significant benefits in terms of light utilization (i.e., using less light to accomplish the same lighting task). Increasing efficacy still remains a key goal and an important charter of the SSL Program. Continued innovation will lead to the development of SSL products with efficacies that can match or exceed those of linear fluorescent products and also retain excellent lighting performance and improve application efficiency. This section analyzes the technological elements impacting SSL system efficacy, identifies the state-of-the-art performance levels, and creates efficacy projections.

3.1.1 LED Package Efficacy

This section explores the limits of LED package efficacy and provides some projections for improvement over time and eventual practical limits.

The performance of white-light LED packages depends on both the CCT of the package and on the CRI objective. In this report, the designation of cool and warm color temperature ranges (see Table 4.7) is based on the American National Standards Institute (ANSI) binning ranges outlined in ANSI C78.377-2008. As every case cannot be examined, efficacy projections and program targets have been grouped into two bands: one for cooler CCT (4746-7040 K) with CRI >70 and the other for warmer CCT (2580-3710 K) with CRI >80.

In order to analyze the potential efficacy of a white LED package, we start by identifying theoretical limits and then separately analyze the various sources of efficiency loss for two principal types of LED package: (i) the phosphor-converted LED (pc-LED) and (ii) the color-mixed LED (cm-LED).

MAXIMIZING LUMINOUS EFFICACY OF RADIATION

A starting point is the theoretical maximum efficacies of an SSL product given perfect conversion of electricity to light. This ideal performance is characterized by the luminous efficacy of radiation (LER), which is the amount of light, measured in lumens, obtained from a given spectrum per 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 [24] [25] [26]. If we call the theoretical best value LER_{max}, then LER/LER_{max} is the spectral efficiency of a given source. In this section, we have used NIST's model (v 7.5) to estimate efficacies for a number of CCT/CRI combinations, both for narrow-band monochromatic LEDs (color-mixed) and by simulating a phosphor using a combination of broadband LEDs and a narrow-band pump. Efficacies are optimized by varying the relative intensities and central wavelengths of the spectral components.

Table 3.1 shows LER_{max} of a cm-LED as computed with this model for a range of choices for CCT and CRI and the resulting package efficacy, assuming an overall package conversion efficiency of 67 percent, which is the estimated potential maximum conversion efficiency for this class of LED (see Table 3.3). The numbers in Table 3.1 assume a red, green, blue, amber (RGBA) configuration with each LED having a moderate full width at half maximum (FWHM) emission spectrum of approximately 20 nanometers (nm). Under these conditions, the analysis suggests that warm-white cm-LEDs could have higher efficacies than cooler ones. On the basis of this analysis, we can consider a practical example where we assume a CCT of 3000 K and a CRI of 85 for which LER_{max} is about 399 lm/W and the luminous efficacy for 67 percent conversion is about 266 lm/W. This value serves as an asymptote for what we consider to be reasonably achievable for practical devices in the future.

TABLE 3.1 ESTIMATED EFFICACIES AS A FUNCTION OF CCT AND CRI FOR A CM- LED

CCT (K)	Maximum LER (lm/W)			Efficacy for 67% Conversion (lm/W)		
	CRI 70	CRI 85	CRI 90	CRI 70	CRI 85	CRI 90
5000	380	365	356	255	245	239
3800	407	389	379	273	261	254
2700	428	407	394	287	273	264

In the case of pc-LEDs, broad phosphor spectra emit a considerable amount of the long-wavelength energy outside the visible spectrum, resulting in spectral inefficiency. Additionally, Stokes loss[7] constitutes an additional and unavoidable loss channel. In order to explore the potential benefit of a narrower red emission band and to estimate the effects of otherwise optimizing the phosphors, we simulated a pc-LED spectrum using the four-color LED NIST model,[8] this time assuming broader line widths (FWHM) as follows: blue, 15 nm; green, 110 nm; amber, 140 nm; and red, 30 nm. Current red phosphor line widths are typically around 100 nm by comparison, limiting efficacy.

In addition to these assumptions about spectral width, we also estimated Stokes efficiency at 82 percent by assuming that the mean phosphor emission is around 580 nm for all solutions. In fact, this is a rather imprecise assumption because the emission generally has a two-peak characteristic in which the red peak intensity is about 1.5 to 3 times that of the green, as shown in Figure 3.1. The 30 nm red phosphor emission decidedly reduces the spillover out of the visible spectrum and thus

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[7] Stokes loss arises from the difference in energy between the absorbed and emitted photons of the phosphor material.

[8] Although we used the 4-LED model for these simulations, in fact amber added little to the result; the broad green emission essentially covers that range.

would considerably improve package efficacy beyond what we typically see today, while still maintaining the simplicity of a phosphor solution.

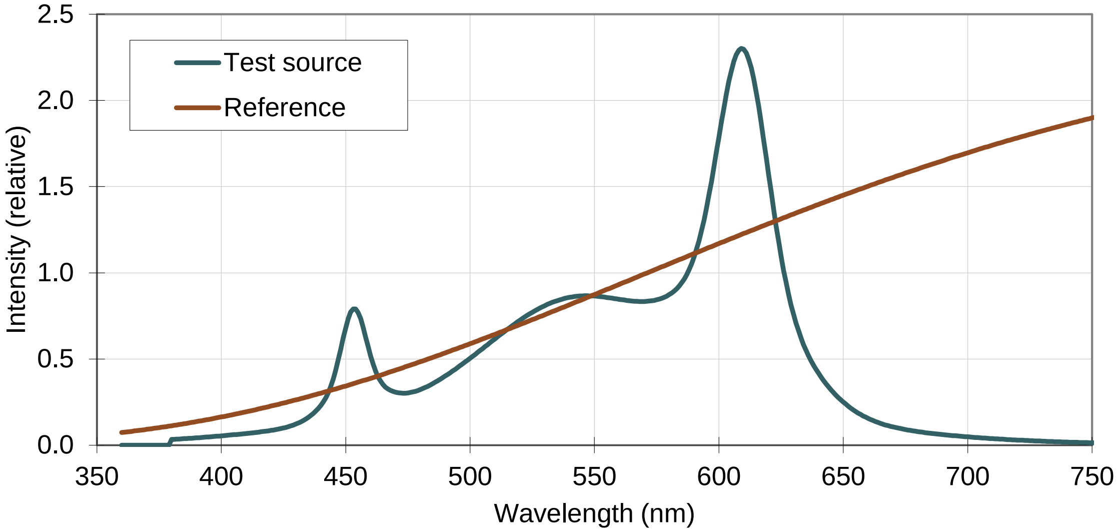

FIGURE 3.1 SIMULATED PC-LED SPECTRUM COMPARED TO BLACK-BODY CURVE (3000 K, 85 CRI)

Simulation results for several combinations of CCT and CRI are shown in Table 3.2. The electrical-to-optical conversion efficiency assumed for this table is a uniform 54 percent across all combinations, arrived at by multiplying the 67 percent conversion assumed for color-mixing by 82 percent, the estimated reduction due to Stokes loss (see Table 3.4). A detailed analysis would integrate the Stokes contribution under the entire spectrum and would thus vary depending on peak wavelengths and relative intensities. The overall effect would be to reduce efficacy somewhat for high CRI or low CCT while increasing it for low-CRI or high-CCT packages, generally reducing the spreads. Again using the assumption of 3000 K and 85 CRI as a typical central value for projections, we obtain a maximum LER of about 367 lm/W and arrive at an average asymptote for projections of about 199 lm/W for the phosphor conversion case.

TABLE 3.2 ESTIMATED EFFICACIES AS A FUNCTION OF CCT AND CRI FOR A PC-LED

CCT (K)	Maximum LER (lm/W)			Efficacy for 54% Conversion (lm/W)		
	CRI 70	CRI 85	CRI 90	CRI 70	CRI 85	CRI 90
5000	350	337	332	189	182	179
3800	369	352	350	199	190	189
2700	391	371	363	211	200	196

PHOSPHOR-CONVERTED LED

Figure 3.2 summarizes an analysis of the various sources of efficiency loss in a pc-LED package. For each loss channel, the chart shows an estimate of the present efficiency of that channel and an estimate of the potential headroom for improvement (i.e., the difference between today's efficiency and the MYPP program goal). Figure 3.2 shows the efficiencies (both status and target) as typically reported for packages (i.e., pulsed measurements taken at a 25 °C package temperature and at a nominal current density of 35 A/cm^2). Package loss channels include some that are intrinsic to the blue pump diode (electrical efficiency, internal quantum efficiency [IQE], extraction efficiency), and others that refer primarily to the phosphor (e.g., conversion efficiency, scattering/absorption efficiency).

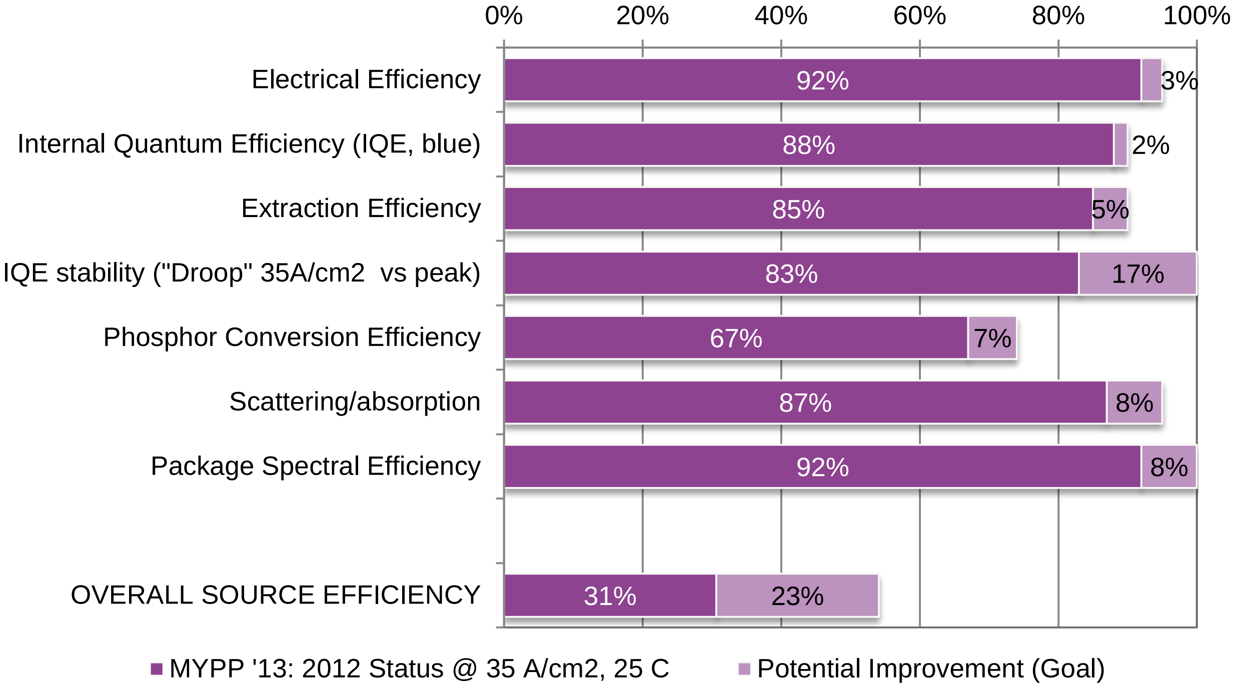

FIGURE 3.2 WARM-WHITE PC-LED PACKAGE LOSS CHANNELS AND EFFICIENCIES

Notes:

1. LED package efficiencies are reported at 25 °C and 35 A/cm^2.
2. The analysis assumes a CCT of 3000 K and CRI of 85. Different choices of CCT/CRI will lead to slightly different results.
3. The phosphor conversion efficiency is an estimate over the spectrum including the loss due to the Stokes shift (90 percent quantum yield times the ratio of the average pumped wavelength and the average wavelength emitted). The value here is typical of a blue LED pumping a yellow and red (for warm-white) phosphor system. Other phosphor formulations will give different results.
4. The current droop from the peak efficiency to that at the nominal current density is shown here as an opportunity for improvement, since there is still as much as a 15 percent gain in efficiency to be had by eliminating this loss at 35 A/cm^2, and much more if the diode is operated at higher currents.

Reducing the sensitivity of IQE to current density is a significant opportunity for improved efficacy and cost reduction, but there is room for improvement in other areas as well. Reducing thermal sensitivity of the LED package is another significant and related opportunity that would allow LEDs to be driven harder and thus emit more light.

The efficiencies and efficacy of a pc-LED are summarized in Table 3.3. Although it is uncertain whether all of the proposed improvements can actually be realized in a commercial, marketable product, these goals suggest that there is significant potential for an improvement over today's LED performance.

TABLE 3.3 SUMMARY OF WARM-WHITE PC-LED PACKAGE EFFICIENCIES AND EFFICACIES

Metric	2012 Status	Goal
Optical Power Conversion Efficiency (Blue)	50%	73%
Phosphor Conversion Efficiency	67%	74%
Spectral Efficiency	92%	100%
Source Efficiency	31%	54%
LED Package Nominal Efficacy (lm/W)	112	199

COLOR-MIXED LED

Figure 3.3 provides a similar analysis to the above for a color-mixed LED. The performance is characterized using four colors: red, green, blue, and amber. While this is a similar analysis to the pc-LED figure, the lack of commercial product of this type means that the current status is an estimate of what could be done today. As shown in Figure 3.3, the lack of efficient green and amber (direct-emitting) LEDs seriously limits the capability color-mixed LEDs today. In the bar chart, the "Weighted Power Conversion" represents an average conversion for the four colors, weighted by the relative intensity of each. The conversion for each color is listed in task A.1.2 in Section 4.4.1, and the relative intensities were calculated using the NIST simulator.

Because the color-mixed LED does not suffer from Stokes loss, it is theoretically capable of higher efficacies than the pc-LED, although the benefit may to an extent be offset by the need for color-mixing optics. There may also be stability issues of color-mixed luminaires that must be taken into account, such as additional driver complexity and cost. Other options exist for obtaining different color temperatures or CRI using a hybrid approach. For example, a warm-white color can be achieved by mixing white pc-LEDs with monochromatic red or amber LEDs. In fact, high-efficacy warm-white luminaires employing this hybrid approach have been on the market since 2009.

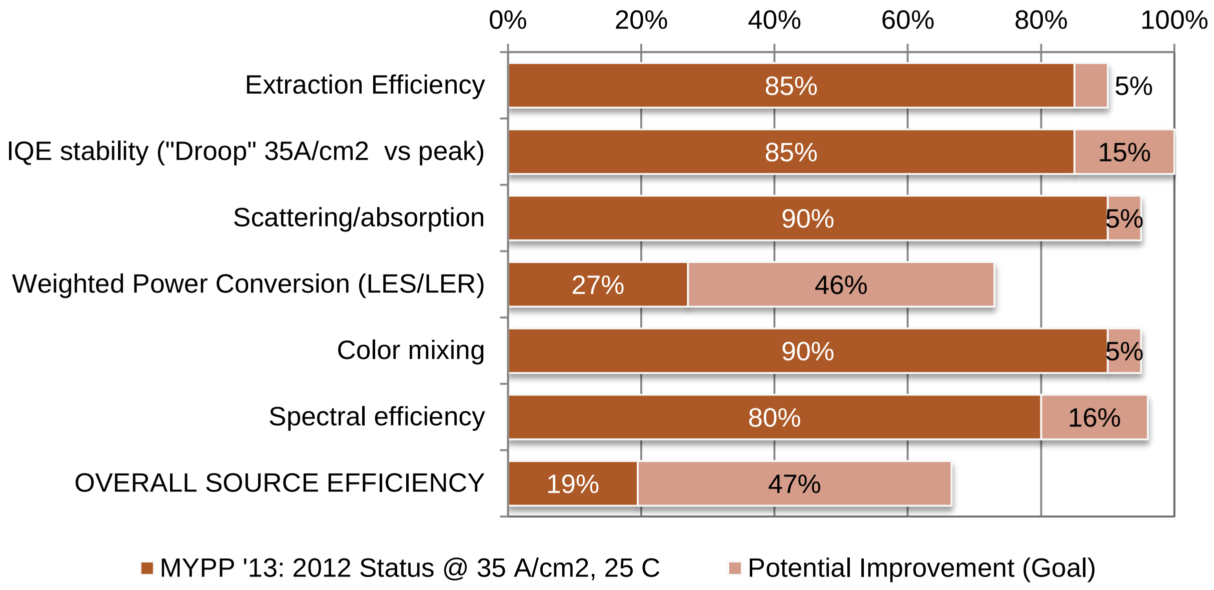

FIGURE 3.3 WARM-WHITE CM-LED PACKAGE LOSS CHANNELS AND EFFICIENCIES

Notes:

1. Efficiencies are as typically reported at 25 °C and 35 A/cm^2.
2. The analysis assumes a CCT of 3000 K and CRI of 85. Different choices of CCT/CRI will lead to slightly different results.
3. IQE statuses and targets assume wavelength ranges for each color as shown in Table 4.7, later in this document.

Achieving the efficiency targets identified in Figure 3.3 will require more efficient emitters, particularly green and amber LEDs. However, reaching this goal may not be possible with existing materials, systems, and designs. As a consequence, the need for work on innovative approaches remains an important priority. The ultimate goal is to raise the IQE to 90 percent across the visible spectrum, bringing the total package conversion efficiency to 67 percent.

Table 3.4 provides an overall summary of the efficiency and resulting efficacy for a color-mixed LED. Present performance is only estimated and is strongly affected by the low efficiency of green LEDs and by the lack of efficient LEDs at optimal wavelengths for maximum spectral efficiency. Nevertheless, the potential is quite a bit higher than for the pc-LED at 266 lm/W.

TABLE 3.4 SUMMARY OF WARM-WHITE COLOR-MIXED LED PACKAGE EFFICIENCIES AND EFFICACIES

Metric	2012 Status	Goal
Optical Power Conversion Efficiency	27%	73%
Color-Mixing Efficiency	90%	95%
Spectral Efficiency	80%	96%
LED Package Efficiency	19%	66%
LED Package Nominal Efficacy (lm/W)	78	266

3.1.2 OLED Panel Efficacy

As with LEDs, maximizing the efficacy of an OLED panel must be balanced against other important characteristics, such as lifetime, color quality, cost, and form factor. For example, in 2012 Panasonic demonstrated a white OLED with an efficacy of 142 lm/W at a luminance of 1,000 candelas per square meter (cd/m^2) and CRI of 85.[9] There were many useful technological advances that led to this achievement, but the area of the device was only 4 mm^2 and the technique used to enhance the extraction of light cannot be extended to large area at acceptable cost while maintaining the slim profile of the panel. In 2013, a similar approach was used by NEC Lighting to make a 156 lm/W 2 mm x 2 mm device with a luminance of 1,000 cd/m^2. Incorporating the same technology into a panel results in an efficacy of 75 lm/W.

Two companies have reported the fabrication of small devices using techniques that can be scaled to large area. By focusing on improvements in light extraction, First O-Lite has produced a 2 cm^2 OLED with an efficacy of 112 lm/W at 1319 cd/m^2 and a CRI of 88, while Panasonic reported a 1 cm^2 device giving 101 lm/W at 1,000 cd/m^2 with a CRI of 86.

This section focuses on the tradeoffs that must be made in the design of larger OLED panels, using recent research results to illustrate the magnitude of each one.

SPECTRAL EFFICIENCY

Although OLEDs are color-mixed devices, the spectral width of the light from the individual emitters is relatively high, typically over 50 nm. Figure 3.4 shows the spectra for each of the RGB components and the combined white light for the ORBEOS OLED panels from OSRAM. The major distinction from the spectrum of the pc-LED shown in Figure 3.1 is the extended tail into the infrared region. This leads to a reduction in the LER from the values of about 360 lm/W suggested in Table 3.2 (for warm-white spectra at CRI 90) to about 320 lm/W.

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[9] Most OLED reports give luminance on axis as a measure of brightness. The conversion to total luminous emittance depends upon the angular distribution of the emitted light. If this distribution is truly Lambertian, the luminance in cd/m^2 should be multiplied by 3.14 to obtain the total luminous emittance in lm/m^2. A more typical range is a factor of 2.6 to 3.0.

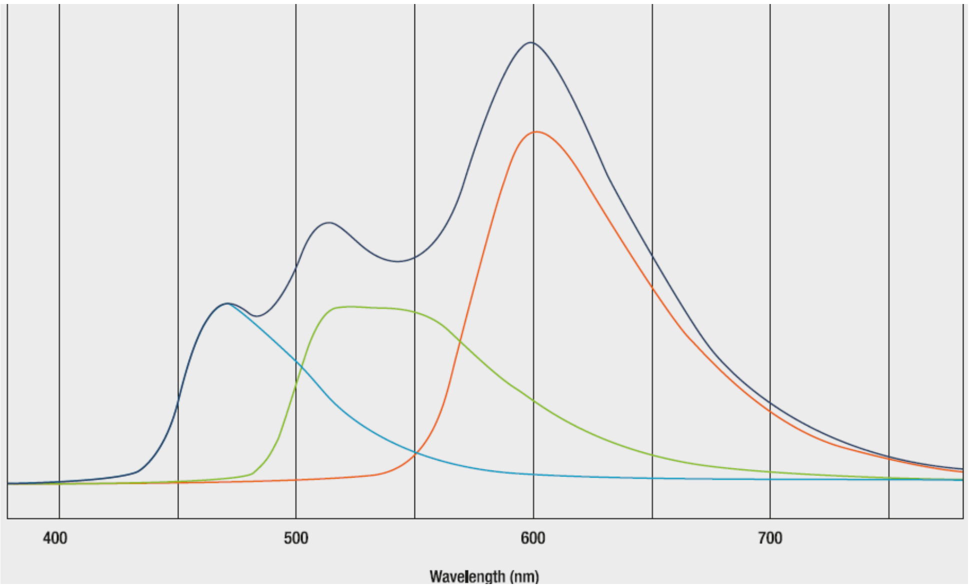

FIGURE 3.4 EMISSION SPECTRA FROM ORBEOS OLED PANEL [27]

ELECTRICAL EFFICIENCY

Electrical efficiency is the ratio of the average energy carried off by the emitted photons to the energy needed to inject a charged particle into the device from the edge. The factor contains several components:

- Ohmic losses as the charge is distributed over the panel area across the anode and cathode structures,
- Injection losses as the current flows from the electrodes into the recombination region where the photons are created, and
- The ratio of the average photon energy to the energy released in the recombination of an electron-hole pair.

The average photon energy varies slightly with the CCT and other details of the spectrum, but is around 2.25 electron volts, corresponding to warm-white light.

Under ideal conditions, the minimum drive voltage required to enable the spectrum to be extended to ~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. Toshiba has produced luminance of 1,000 cd/m^2 in their 70 mm x 80 mm panel with a driving voltage of 3.11 V. Raising the drive voltage to 3.5 V led to luminance of 3,000 cd/m^2. By comparing these results with those from a smaller device of area 2 mm^2, Toshiba has confirmed that ohmic losses in the anode structure can be reduced to <5 percent at 3,000 cd/m^2.

The electrical efficiency can be improved through the use of tandem structures because two or three times as many photons are produced for the same current density, albeit it at higher operating voltage. Novaled has shown that with a two-stack structure, luminance of 1,000 cd/m^2 can be achieved at 5.7 V and 3,000 cd/m^2 is obtained at 6.2 V, leading to an improvement in electrical efficiency of about 10 percent.

The major benefit of tandem devices is in the slower lumen depreciation, which also arises from the reduction in the current density required to produce the desired amount of light. This provides part of the explanation for the industry-leading value of L_{70}, at 15,000 hours from an initial luminance of 3,000 cd/m^2. However, these benefits come at the expense of added complexity, which will lead to lower yields and higher manufacturing cost.

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 it is usual to combine a dopant to produce the photons with a host that controls the charge transport.

Phosphorescent molecules have demonstrated near 100 percent 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, especially 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. Thus, most panel manufacturers use hybrid systems in which blue fluorescent emitters with lower IQE are combined with red and green phosphorescent molecules. Recent experiments have suggested that this leads to a reduction in IQE of about 25 percent.

EXTRACTION EFFICIENCY

The largest losses in OLED panels arise from the light being trapped inside the device. For OLEDs, the fraction of light emitted to air is typically in the range of 20-25 percent. This is due to the mismatch in the index of refraction between the organic materials, the substrate, 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 three ways to increase the amount of extracted light:

- Design the system so that the light is emitted preferentially in directions close to the normal to the plane of the panel. Large polymer molecules can be induced to lie down close to the plane of the panel and emit light non-uniformly. However, this effect has not been proven to be large enough to offset the relative inefficiency of polymer emitters. Controlling the orientation of small molecules is more difficult. For monochromatic emitters, micro-cavity effects can be used to enhance emission along the normal direction, but for white light these effects often lead to anomalies in the color of the light emitted at each angle. Precise cavity tuning is also difficult for light with a broad spectrum.
- Bend the light towards the normal. This can be accomplished though the inclusion of micro-lens arrays or patterned interfaces between layers of different refractive index. Such structures have been extremely successful in liquid crystal displays, for example in the brightness enhancement films pioneered by 3M. These light-bending structures can be applied at many levels with the panel. The simplest implementation is through lamination of a film on the outside of the substrate, but this typically leads to enhancements of 50 percent or

less. Attention is now focused upon the insertion of structures between the substrate and the transparent electrode. For example, Panasonic has reported an increase in the external quantum efficiency (EQE) from 22.2 to 46.8 percent through the insertion of an internal micro-lens array in which dry air is trapped between hemispheres of a resin with refractive index of approximately 1.8 formed on a thin plastic sheet with similar refractive index. When regular structures are used in this way, care must be taken to avoid angular variation in the color of the emitted light. This approach to increasing light extraction is illustrated by Figure 3.5.

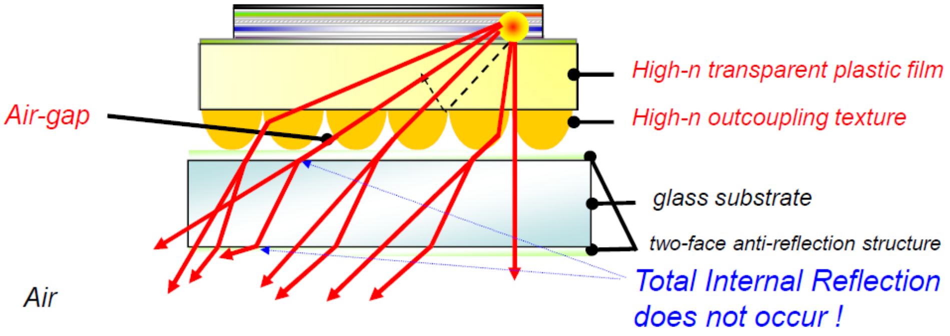

FIGURE 3.5 INTERNAL LIGHT MICRO-LENS ARRAY TO ENHANCE LIGHT EXTRACTION [28]

- Add scattering centers. If each of the interfaces in the panel is planar, much of the light that is reflected back into the panel will bounce back to the transparent substrate at the same angle. The return direction can be changed by the presence of rough or corrugated surfaces, or by the introduction of scattering particles. Several years ago, the Kodak group demonstrated that the emitted light can be enhanced by a factor of 2.3 by this approach. The Kodak IP was purchased by LG, and it is believed that this approach has been implemented in their commercial panels. Novaled has also obtained promising results by adding scattering particles to the transport layers within the organic stack.

  There are two main challenges in implementing this approach. One is to minimize absorption. In order to increase the enhancement factor to 3.0 or higher, it seems to be necessary to reduce the probability of photon absorption on each bounce to less than 10 percent. Increasing the density of scattering particles can also lead to unacceptable levels of absorption. Absorption in the metal electrodes can also be critical. For example, Panasonic has found that raising the reflectance of the cathode and optimizing the neighboring electron injection layer can improve the system efficacy by ~20 percent. Many analysts have concluded that the excitation of surface plasmon modes in metal electrodes can enhance the absorption losses, and many groups are searching of ways to mitigate this effect.

  The second challenge is to ensure that the insertion of the scattering layer does not hinder the deposition of the subsequent layers. The polymer binder should act as a smoothing layer as well as providing optical contrast for the scattering particles. In another approach used by Novaled, a conductive scattering layer inserted between the organic stack and the metal cathode is purposefully corrugated upon crystallization, which is thought to reduce the surface plasmon effects.

COST REDUCTION AND FORM FACTOR IMPROVEMENTS

Along with efficacy improvements, OLED developers have been working to enable the use of less expensive fabrication and to improve the form factor through the use of ultra-thin flexible substrates. Although these aspects are discussed at more length in DOE's SSL Manufacturing Roadmap, this section describes their effect on efficacy.

Though in the near-term competitive OLED lighting devices will likely be made using vacuum deposition or hybrid (combination of solution and evaporated layers) approaches, many of the proposed methods to reduce manufacturing costs involve the replacement of vacuum deposition methods by solution processing. This requires the development of new materials that initially exhibited much poorer performance in both efficacy and lifetime. Despite considerable effort in recent years by companies such as CDT, DuPont, and Merck, there is still a performance gap. The typical efficacy is lower by at least 50 percent as illustrated in Table 3.5 (the last two rows show solution processed results). The rate of lumen depreciation of red and green emitters has been reduced to acceptable levels, but that of phosphorescent blue emitters is still much too fast.

This shortfall is also holding up the introduction of OLEDs on flexible substrates and of roll-to-roll manufacturing methods. By far the most challenging problem in this respect is the development of reliable barriers to prevent ingress of water and oxygen through plastic substrates and covers.

SUMMARY OF OLED PROGRESS IN 2012

Table 3.5 summarizes some of the laboratory results reported during 2012.

TABLE 3.5 OLED LABORATORY PANELS REPORTED DURING 2012

Developer	Efficacy (lm/W)	Luminance (cd/m^2)	Area (cm^2)	CRI (Ra)	CCT (K)	L_{70} (1000 hrs)	Drive (V)
Toshiba[1]	91 78	1,000 3,000	56		3010 2960		3.1 3.5
Panasonic[1]	87	1,000	25	82	2700	>50[2]	6.1[3]
UDC[1]	70 57	1,000 3,000	~200	85 86	3030 2880	30 4	3.8 4.3
LG Chem[4]	60	3,000	76	>80	4000	15	5.8[3]
UDC/Acuity[5]	52	2,550	115	87	3000		
UDC[6]	43	3,000	225	84	3200		4.9
DuPont[7]	30	1,000	50				
CDT[8]	25	1,000	225	~70	3135		4.3

Notes:

1. All-phosphorescent systems
2. Scaled from data provided for L_{50}
3. Tandem device producing two photons per injected electron
4. Commercial hybrid device using fluorescent blue with phosphorescent red & green emitters
5. Color tunable
6. Flexible panel on a plastic substrate
7. Uses solution-processable materials to reduce fabrication costs
8. Uses polymer emitters

Figure 3.6 shows OLED loss channels, compares state-of-the-art performance to the program goal, and indicates how much improvement might be possible. For this chart, it is important to note that the efficiency levels shown have not been achieved simultaneously by an OLED panel. Accordingly, the overall nominal high-performance panel efficacy is somewhat overstated.

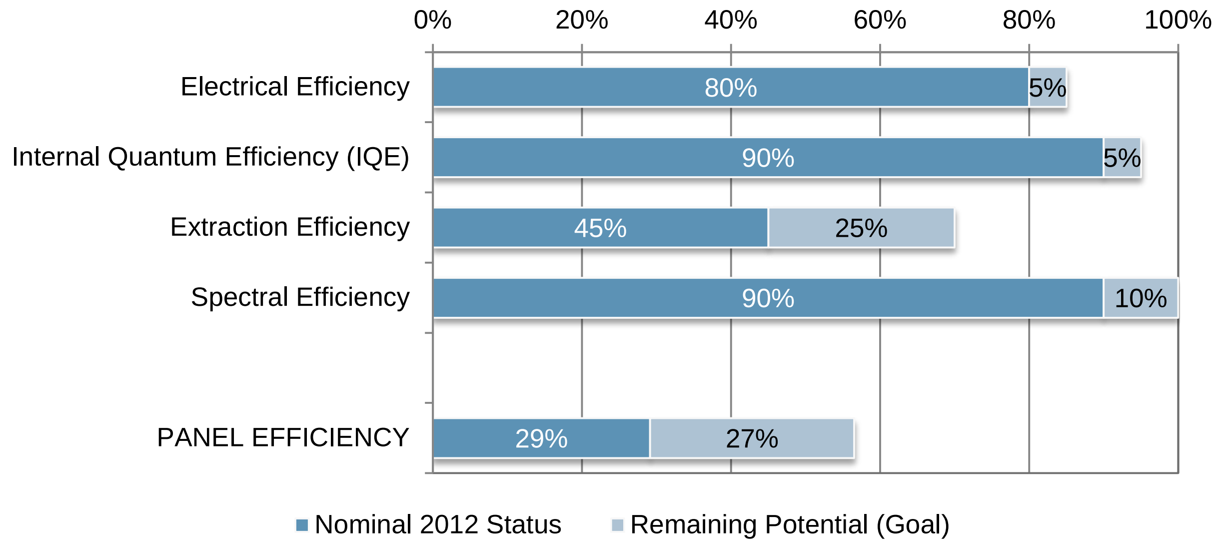

FIGURE 3.6 OLED PANEL LOSS CHANNELS AND EFFICIENCIES

For a more accurate representation of the status and an indication of the variation, Table 3.6 summarizes the ranges of the efficiencies of the various loss channels of the panels listed in the first four rows of Table 3.5 at a luminance of 3,000 cd/m^2.

TABLE 3.6 COMPONENTS OF OLED PANEL EFFICACY

Metric	2012 Status	Goal
Electrical Efficiency	55-80%	85%
Internal Quantum Efficiency	60-90%	95%
Extraction Efficiency	35-45%	70%
Spectral Efficiency	80-90%	100%
Panel Efficiency	16-22%	56%
Panel Efficacy (lm/W)	57-75	190

3.2 Luminaire Performance

The performance of LED and OLED luminaires begins with the performance of the LED package and OLED panel, as described in the previous section. Integrating the LED package or OLED panel into a luminaire will result in some efficiency losses because power supply efficiency, optical efficiency, and thermal losses are included in the full luminaire performance characterization.

Figure 3.7 shows projected efficacies for LED light sources compared to high-efficiency HID and linear fluorescent (LFL) light sources. As shown in the figure, LED products are expected to surpass the efficacy of the most efficient conventional light sources within a few years and are projected to reach efficacy levels of greater than 200 lumens per watt within a decade. Table 3.7 compares the current performance of some SSL luminaire product with conventional lighting technologies. Projections for the efficiency breakdown of LED and OLED luminaires are provided in Table 3.8 and Table 3.9. The figure and the tables should be considered as the most generic case for SSL performance. SSL luminaires have a wide range of form factors, efficacy, color quality, lifetime, and color temperature based on the intended application, product quality, and technical approach embedded in the luminaire. LED luminaire and lamp efficacy can range from 10 lm/W to greater than 100 lm/W with CCT from 2700 K to 6500 K and CRI from 60 to greater than 90. These variations add a significant level of complexity in comparing products and in specifying and selecting products.

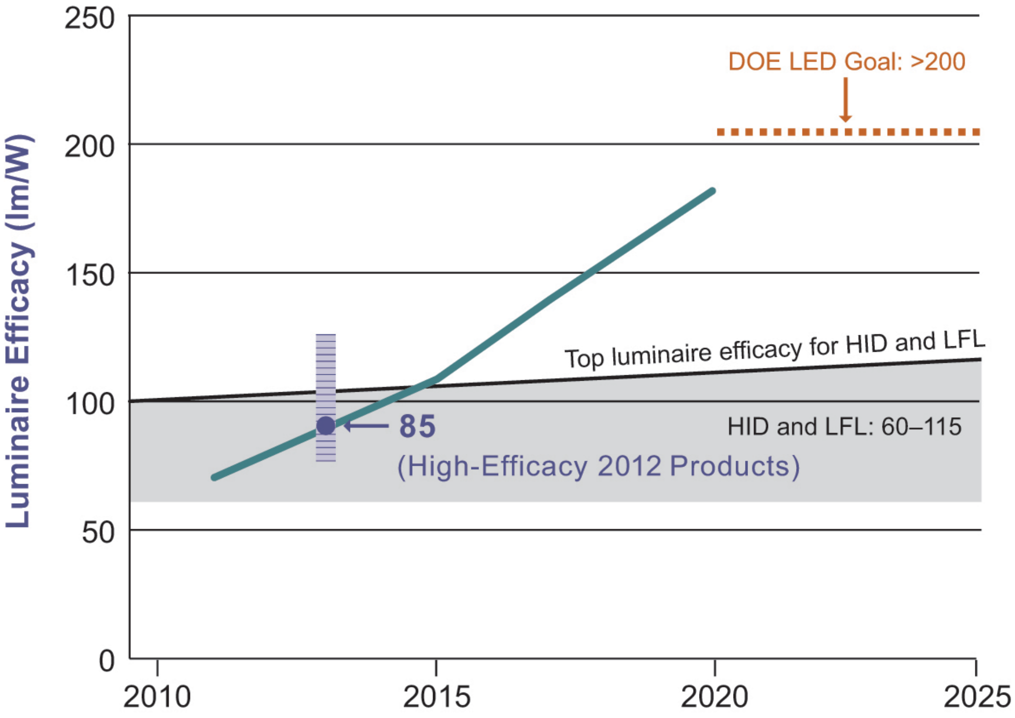

FIGURE 3.7 COMPARISON OF SSL AND INCUMBENT LIGHT SOURCE EFFICACIES

Source: LED Lighting Facts product database

TABLE 3.7 SSL PERFORMANCE COMPARED TO OTHER LIGHTING TECHNOLOGIES

Product Type	Luminous Efficacy (lm/W)	CCT (K)	L_{70} (hours)
LED A19 Lamp (Warm-White)[1]	94	2700	30,000
LED PAR38 Lamp (Warm-White)[2]	78	3000	50,000
LED Troffer 1' x 4' (Warm-White)[3]	118	3500	75,000
LED High/Low-Bay Fixture (Warm-White)[4]	119	3500	75,000
OLED Luminaire[5]	52	3500	15,000
HID (High Watt) System[6]	115	3100	15,000
Linear Fluorescent System[6]	108	4100	25,000
HID (Low Watt) System[6]	104	3000	15,000
CFL	73	2700	12,000
Halogen	20	2750	8,400
Incandescent	15	2760	1,000

Notes:

1. Based on Philips' L Prize winning A19 lamp.
2. Based on Lighting Facts data label for Cree LRP38-10L-30K lamp.
3. Based on Lighting Facts data label for Cree CS14-40LHE-35K luminaire.
4. Based on Lighting Facts data label for Cree CS18-80LHE-35K luminaire.
5. Based on Acuity Brands luminaires.
6. Includes ballast losses.

The efficacy of the LED package or OLED panel at a given operating current represents the upper limit for SSL luminaire efficacy. Within a luminaire, this efficacy is then further degraded by the luminaire optical efficiency, driver electrical efficiency, and thermal losses resulting in the luminaire efficacy as shown in Figure 3.8 and Table 3.8. The overall system can be particularly sensitive to thermal management. Since SSL sources do not radiate heat, it must be dissipated through the luminaire itself, in contrast to the conventional lamp and fixture combination. Optical efficiency depends on the optical system in the luminaire. Lenses, optical mixing chambers, remote phosphors, diffusers can all be employed depending on the lighting application, desired optical distribution, and form factor of the lighting product. Well-designed luminaires in certain applications can experience less than 10 percent optical losses, and new approaches may reduce that 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.

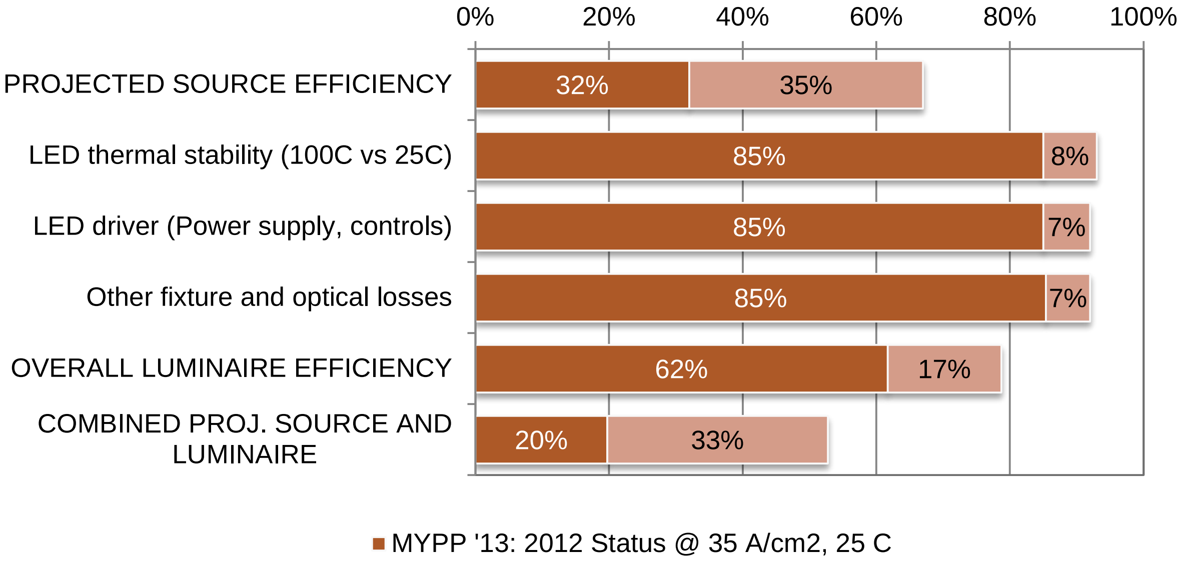

FIGURE 3.8 LED LUMINAIRE EFFICACY FACTORS

TABLE 3.8 BREAKDOWN OF LED LUMINAIRE EFFICIENCY

Metric	2013	2015	2020	Goal
Package Efficacy (lm/W)	129	162	224	266
Thermal Efficiency	85%	88%	90%	93%
Efficiency of Driver	85%	87%	90%	92%
Efficiency of Fixture	85%	89%	92%	92%
Resultant Luminaire Efficiency	62%	68%	74%	79%
Luminaire Efficacy (lm/W)	80	110	166	210

Notes:

1. Package efficacy projections are for the color-mixed case, per Figure 4.1
2. Warm-white packages and luminaires have CCT=2580-3710 K and CRI ≥80
3. All projections assume a drive current density of 35 A/cm^2, reasonable package life, and steady-state operating temperature
4. Luminaire efficacies are obtained by multiplying the resultant luminaire efficiency by the package efficacy values

The electrical efficiency of a pc-LED luminaire describes the efficiency of the power supply in converting alternating current (AC) line power to an electrical input suitable for running the LED package or packages. 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 may not be consistent 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 and overcome some driver efficiency losses that may be associated with high drive current. Luminaire designers can take advantage of these products to reduce the cost and improve the efficiency of the power supply within the luminaire.

Thermal efficiency represents the drop in efficiency of the LED as it is operated at an elevated temperature. 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 and its thermal efficiency. Improved thermal handling and/or reduced operating current will result in a lower operating temperature of the LED and 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.

A similar breakdown of OLED luminaire losses is shown in Figure 3.9 and Table 3.9. As noted in the discussion of panel losses in Section 3.1.2, the nominal panel efficiency has not, to date, been realized. For optical efficiency, OLED luminaires will most likely require additional light distribution optical elements that will incur some level of loss. These optical elements may be embedded into the substrate, could be in the form of a secondary optic, or use some other novel approach. At this point in the commercial cycle for OLED luminaires, it is not clear how the optical distribution will be engineered and what the most beneficial lighting distribution will be for OLED sources. OLED luminaires are expected to have similar power supply efficiency (and integration issues) as LED luminaires.

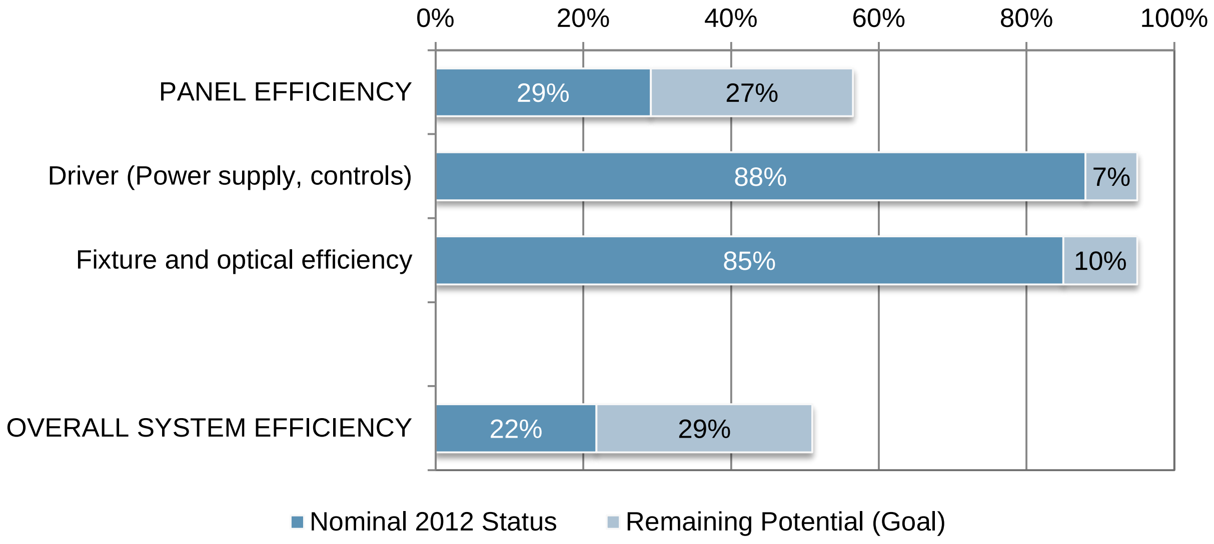

FIGURE 3.9 OLED PANEL AND LUMINAIRE LOSS CHANNELS AND EFFICIENCIES

TABLE 3.9 BREAKDOWN OF OLED LUMINAIRE EFFICIENCY

Metric	2013	2015	2020	Goal
Panel Efficacy[1] (lm/W)	80	100	140	190
Optical Efficiency of Luminaire	85%	88%	92%	95%
Efficiency of Driver[2]	88%	91%	93%	95%
Total Efficiency from Device to Luminaire	75%	81%	86%	90%
Resulting Luminaire Efficacy[1] (lm/W)	60	81	120	171

Notes:

1. Efficacy projections assume CRI >80, CCT 2580-3710 K
2. Drive efficiency for OLED luminaires is not well characterized, given the small number of products available

The effective efficiency of a luminaire is also affected by light utilization, which represents how well the spatial distribution of light from the luminaire suits the target application. For example, new LED streetlights have demonstrated the ability to provide suitable illuminance levels using significantly lower total light output than the conventional lighting products they have replaced. This is accomplished through improved light distribution that reduces overlighting and improves illuminance uniformity. For any lighting application, using less light to achieve suitable illuminance levels represents an improvement in light utilization. LED and OLED sources enable entirely new lighting form factors and light distributions that could significantly improve application efficiency. For example, the low brightness of OLED sources could enable them to be used very close to the task surface without glare, enabling less light from the source to illuminate the task. For LED and OLED sources to maximize light utilization, they will need to move beyond legacy form factors such as the light bulb and find form factors that maximize application efficiency as well as optical, electrical, and thermal efficiency. Examples of prototype OLED luminaires are shown in Figure 3.10.

FIGURE 3.10 OLED LUMINAIRES FROM ACUITY, SELUX, AND TAKAHATA ELECTRONICS

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—that is, dimmable and instant on/off—which makes them compatible with the full range of lighting controls. Dimming or turning off lights when not necessary for the task is another mechanism for using less light without impacting the task.

The SSL source form factor, light distribution, color quality, placement, and controls make up the lighting system. Beyond energy savings, SSL offers new light source form factors, light distribution possibilities, color options, placement options, and control options. Reverting to legacy lighting form factors for SSL takes away some of the new design freedom offered by the technology and limits the potential of the technology. A major theme that has emerged with regard to SSL performance is that SSL can not only improve efficacy and match the lighting performance of existing lighting technologies, but can also add significant value. SSL luminaires can add value in terms of color quality and color control, controllability and integration with lighting controls, and form factors for enhanced lighting application and building design. Adding some of this value to LED and OLED luminaires will enable consumers to look past the high price of SSL sources and embrace the full value (including energy savings) of these sources.

3.3 SSL Reliability and Lifetime

At this stage of development of SSL technology, we do not know exactly how long the products will last. In some cases, very well-designed products operated well below design limits, seem to show no signs of degradation even after long periods of operation at moderately elevated temperatures [29]. At the same time, there are many other examples of products lacking proper thermal management that have failed in less than 1,000 hours of operation, the typical life of an incandescent lamp.

The LED package useful life has been often cited as the point at which the lumen output has declined by 30 percent, referred to as "70 percent lumen maintenance" or "L_{70}." Performance in this regard has increased steadily since the program began, and several manufacturers claim that L_{70} is currently above its former target of 50,000 hours with some claiming 100,000 hours of operation or more. Lumen depreciation, in earlier years thought to be the dominant determinant of useful life of an LED package, may not, in fact, be so important. Indeed, it is likely that other modes of failure would come into play long before 100,000 of operation has elapsed (perhaps as much as a century for some applications). Especially when driven at lower drive currents or operated at lower temperatures, lumen depreciation can be so low as to be difficult to project to the eventual 30 percent point. 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 the Illuminating Engineering Society (IES) has documented a forecasting procedure as IES TM-21 [30]. This technical memorandum stipulates that the projections may not exceed a multiple of the actual hours of data taken, which helps avoid at least some of the more questionable claims.

Using LED package lumen maintenance as a proxy for luminaire lifetime is not acceptable as it does not sufficiently consider other failure mechanisms.

Often, we see examples where the useful life of a luminaire (or lamp) is stated to be the same as the L_{70} lumen maintenance figure as determined by the manufacturer of the diodes used in the product. In fact, the luminaire lifetime may be much shorter than the LED package 70 percent lumen maintenance metric. There are many other potential failure mechanisms. Additional components and subsystems such as the drivers, optical lenses, or reflectors can fail independently of the LED. Apart from possible assembly defects, which will always lead to a small probability of random failure, attachments, optical, or other materials, or anything else in the system may eventually fail under normal operation before the light source. Moisture incursion can be an important determinant of life for an outdoor luminaire. Beyond such wear-out mechanisms, poor luminaire design can shorten the life of an LED package dramatically through overheating. Inappropriate or poorly executed drivers may also limit the lifetime of an LED package, hastening lumen depreciation parametrically by overstressing the LED. In the case of traditional commercial lighting products, an early failure rate due to defects in manufacture or installation of perhaps ten percent of product is probably the maximum acceptable value. However, with the higher prices of LED products, customers seem to expect a much lower early failure rate, not to mention a long useful life.

Many such questions have been explored by a luminaire reliability study group sponsored by DOE. The most recent publication of that group, "LED LUMINAIRE LIFETIME: Recommendations for Testing and Reporting (second edition)," [31] identified what testing might be necessary to provide a useful estimate of life taking all failure mechanisms into consideration and provided a working definition of luminaire lifetime. However, the group also concluded that measuring full luminaires (required in principle) is prohibitively expensive and strongly recommended that the industry cooperate to develop accelerated tests, perhaps at the materials, component, or subsystem level, along with suitable means to simulate full system failure rates. This is an important area of work, and there is an identified task for it (research task B.6.3) described in Section 4.4.2. The DOE SSL program is already funding a core task to begin looking at software approaches to simulating failure rates. In parallel, a consortium of manufacturers in the industry, facilitated by DOE, has begun to explore means of gathering the necessary component and subsystem reliability data needed to drive the simulation effort.

If little is known about LED luminaire lifetime at this point, even less is known about OLEDs. Certainly, the absence of an accepted common design and fabrication method for OLED lighting limits our ability to explore reliability issues in this technology. There are also few products on the market, so there is no real base of field experience, although the large population of portable electronic devices using small OLED panels may eventually provide relevant data. OLEDs have a few known or suspected degradation mechanisms (for example, material degradation due to moisture) that do not apply to or are less severe in LEDs. Efforts to get more light out of the OLED by driving it harder also tend to shorten its life. Not much can be usefully done on the matter of OLED luminaire life at this point in the technology development. Some of what is being learned about LEDs may apply to OLEDs, but it is also quite likely that some different design approaches and testing methods will need to be developed to ensure an acceptable level of product reliability.

3.4 Global R&D Efforts in SSL

SSL is a global industry with significant R&D activities underway in many regions of the developed world. This R&D is primarily funded by industry, but governments also play a role in supporting the development of energy-efficient lighting technologies such as SSL. Worldwide government support for LED- and OLED-based SSL R&D is discussed in the following sections.

3.4.1 LED-Based SSL Technology

This section provides a brief overview of government support for LED-based SSL technology R&D in other regions of the world. Table 3.10 provides a summary of forecasted total R&D spending for the major geographical regions involved in SSL technology, along with estimates of the total government spending on R&D and of government spending on SSL R&D. These are rough estimates based on available data and will depend on how each geographical region defines R&D spending, which may in some regions include support for capital equipment and near-market activities.

TABLE 3.10 ESTIMATED WORLDWIDE LED-BASED SSL R&D SPENDING IN 2012 [32] [33]

Country	Total R&D Spend ($ million)	Government R&D Spend ($ million)	Government SSL R&D Spend ($ million)
USA	436,000	125,700	21
Europe	338,100	118,000	40
China	198,900	50,000	1,000
Taiwan	22,300	6,700	250
South Korea	56,400	15,000	N/A
Japan	157,600	25,000	N/A

The primary source of R&D funding in Europe is business enterprise with the government contributing around 35 percent. Europe spends less overall on R&D than the United States, but the larger government contribution means that government R&D spending is quite similar. SSL R&D

activity in Europe is generally coordinated through industry consortia such as the European Photonics Industry Consortium[10] and voluntary cross-border associations such as Photonics21.[11] Much of the government funding in SSL is channeled through European Union collaborative R&D projects; however, national governments provide additional R&D support. At the end of 2011, the European Commission published a Green Paper on Solid State Lighting (SSL), "Lighting the Future: Accelerating the deployment of innovative lighting technologies," to explore the barriers for the widespread deployment of SSL technology and to launch a public consultation on the future of LED-based lighting [34]. They will use the inputs they received to develop a European strategy on SSL. Active EU collaborative R&D projects in the field of LED-based SSL during 2012 include NWS4LIGHT (nanowire LEDs), CYCLED (life-cycle analysis), HERCULES (light quality), NPLC-LED (thermal management), SSL4EU (multi-chip LED light sources), SMASH (nano-structure LEDs), DERPHOSA (remote phosphors), NANOLEDS (nano-structure LEDs), ALIGHT (amber aluminum gallium indium nitride LEDs on semi-polar templates), NEWLED (phosphor-free white LEDs), and GECCO (3D gallium nitride LEDs). These projects have a combined total project value of approximately $59 million, with funding of $41 million provided by the European Union. Projects are typically of two or three years in duration.

EU funding for SSL Pilots under the Competitiveness and Innovation Framework Programme was also launched in 2011 with a specific objective to develop "[i]nnovative lighting systems based on Solid State Lighting." This program funds large-scale pilot actions to demonstrate the best use of innovative lighting systems based on SSL for better light quality and control with a substantial reduction in energy consumption. Projects are currently under negotiation in the areas of exterior lighting (streets, restaurant areas, and public buildings) as well as interior lighting (museums and other visitor centers), and were expected to start early in 2012, although nothing formal has yet been announced through CORDIS [35]. It is anticipated that two to three projects will be supported with a total EU funding of up to $13 million (50 percent cost share).

According to the Next Generation Lighting Industry Alliance (NGLIA), the Chinese central government spends around $1 billion annually on SSL R&D alone, with the provinces providing additional incentives [36]. This is around 0.5 percent of the country's total R&D spend, which was around $199 billion in 2012 according to Battelle [32]. Overall, government funding for R&D composes around 25 percent of the total.

China's 12th Five Year Plan has identified LED manufacturing as an important strategic market and has provided significant financial incentives for companies to locate there, including tax incentives, equipment subsidies, and funding for R&D. In previous years, the government had provided approximately $1.6 billion in subsidies for the purchase of metal organic chemical vapor deposition (MOCVD) equipment (up to $1.8 million per machine). Consequently, China's installed base of such equipment has risen from around 135 in 2009 to around 800 in 2012, only being slowed by the overcapacity that developed in the LED die manufacturing industry during the second half of 2011 [37]. A total of 13 industrial science parks have been established throughout the country for SSL R&D and manufacturing.

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[10] For more information, see: www.epic-assoc.com.

[11] For more information, see: www.photonics21.org. Note that their Strategic Research Agenda (SRA) "Lighting the way ahead" was published in January 2010.

In Taiwan, the primary source of R&D funding is the business sector, at around 70 percent, followed by the government, at around 30 percent. Total R&D spending in the LED industry was thought to top $600 million in 2010 [38].

The private sector is similarly a key player in South Korean R&D activities, contributing around 75 percent of R&D funding in 2011 [39]. The major contributors to South Korea's R&D activity are South Korean global companies in high technology industries, such as Samsung electronics, LG electronics, Hynix, and Hyundai Automobile. Until recently, the white LED activity has been driven by the needs of the backlighting industry through major display and television manufacturers such as Samsung and LG Innotek. LED manufacturing and R&D capabilities at these and other companies such as Seoul Semiconductor are increasingly being directed toward the production of lighting class LEDs to meet South Korea's target of achieving a 30 percent share for LED lighting by 2015. One vehicle for government support has been through the research institutes, which are closely linked to industry. For example, Samsung LED and the Korea Photonics Technology Institute signed a technology collaboration agreement on June 30, 2011 to accelerate the development of LED lighting-related technology and the cultivation of highly skilled R&D manpower.

Historically, Japanese industry has provided a more significant percentage of R&D funding than the government in comparison with other developed countries. In 2010, the industry provided as much as 84 percent of the funding for R&D. In 2012, the country's total R&D spend was around $158 billion, with around $25 billion consequently provided by government [33]. However, the amount spent specifically on SSL R&D is not known.

3.4.2 OLED-Based SSL Technology

Governmental support of OLED lighting research is strong in Europe, with approximately 20 active projects, each involving multiple partners. The European Union has supported many projects involving international collaborations. One of the most recent projects of this type is IMOLA (Intelligent light management for OLED on foil applications).[12] This four-year $6.6 million program aims to realize large-area OLED lighting modules with light intensity that can be adjusted uniformly or locally according to the time of day or a person's position. The envisaged applications include wall, ceiling, and in-vehicle (dome) lighting.

The EU efforts have been supplemented by national R&D programs. For example, the German Ministry of Education and Research has provided about $130 million over a five-year period, with the goal of encouraging corporate investment of about $520 million. Three major programs were completed in 2012. In the $39 million NEMO project, Merck led a team of 11 partners to develop "New Materials for OLEDs from Solutions," searching for new electrode structures as well as organic emitters and transport layers [40]. The $20 million So-Light project was designed to address the complete value chain, from primary OLED materials to OLED lighting applications, exploiting the vacuum-processing techniques through new equipment designed by Aixtron.

Cost reduction was the focus of the LILi (Light In Line) project, which was carried out at the Alzenau facility of the U.S. company, Applied Materials, with materials from Merck and OLED design support from the Braunschweig Technical University. This project successfully demonstrated the viability of the in-line fabrication concept that has now been adopted by leading Asian manufacturers [41].

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[12] For more information on the IMOLA project, see: www.oled-info.com/imola.

European researchers have been very active in the development of flexible OLEDs, primarily through two cooperative programs at the Holst Centre in Eindhoven and the Fraunhofer IPMS in Dresden. This thrust received a boost from the award of $15 million as part of the EU's 7th Framework Programme. The Flex-o-Fab project will create a pilot-scale manufacturing chain for flexible OLEDs and use it to develop reliable fabrication processes [42]. The project involves 12 partners from eight countries and aims to have a pilot line operational by September 2015, with the goal of bringing flexible OLED lighting panels to market within six years.

The greatest investments in OLED technology have been made in Korea. Samsung's OLED investments have averaged about five billion dollars per year recently [43]. Although it is unclear how much of this is aimed at lighting applications, the manufacturing experience that they are gaining for displays will be of great value in reducing the cost of OLED lighting. Although LG has lagged behind Samsung in sales of OLED displays, the conglomerate is aggressively competing for the lighting markets, mainly through their materials subsidiary, LG Chemical.

Although the Korean government has provided some funding for companies, for example, to encourage the development of the OLED supply chain, its principle contribution has been through support of universities and research institutes. Despite the small size of the country, Korea has by far the most extensive network of academic R&D in OLED technology.

Academic research groups in Japan have been responsible for many of the fundamental developments in OLED lighting, for example at Kyushu and Yamagata Universities and the Japan Advanced Institute of Science and Technology. This has led to the availability of experienced young researchers in corporate R&D efforts. Japanese companies are now vigorously pursuing the OLED lighting market, having lost control of OLED display manufacturing.

Government support of OLED research in Taiwan has also been focused upon universities and research laboratories, such as ITRI, although Taiwanese companies have as yet been hesitant to exploit this research. In mainland China, there are few universities carrying out research, and Chinese companies have been hiring experienced OLED researchers from overseas to staff the growing corporate activities in R&D and manufacturing.

4 RESEARCH AND DEVELOPMENT PLAN

This chapter discusses the LED and OLED performance projections, overarching DOE SSL Program milestones, and specific, critical R&D tasks and targets that will contribute to the achievement of the projections and milestones. The R&D tasks described in this chapter will be considered by the DOE SSL Program for the next round of R&D funding.

4.1 Goals and Projections

High-level goals for the DOE SSL program were described in Chapter 3. This section describes some expectations for progress towards DOE's 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. However, it is important to note that while the projections are based on best-in-class performance, normalized to particular operating conditions in order to track progress, the program’s 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 chapter, are a number of metrics specific to that task and individual goals that together will enable us to achieve the goals of the program.

4.1.1 Efficacy Projections for LEDs

Figure 4.1 shows anticipated package efficacy improvement over time for warm-white and cool-white pc-LEDs and color-mixed LED packages based on experience to date. To show anticipated progress over time, we use a logistic fit to the data points with an assumed upper asymptote derived as explained in Section 3.1.1. All of the data points are for pc-LED solutions. The curves have been fit using the best-in-class qualified data points. In order to track progress over time, available data have been divided into "qualified" or "non-qualified" categories. The qualified data points can be compared with similar historical results. Qualified data points are either reported to be in accord with the reference values of parameters defined for the various curves (see notes with graphs), or have been normalized to those values. Non-qualified points have one or more parameters that are unknown or do not correspond to the reference values.

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 the standard current density and temperature and reporting within limited ranges of CCT and CRI shows how more basic improvements such as light extraction, phosphor development, and reduction of current droop are proceeding. Recognizing these innovative ways to increase efficiency, however, we've included some other illustrations to show how designing the luminaire for lower drive current will affect performance.

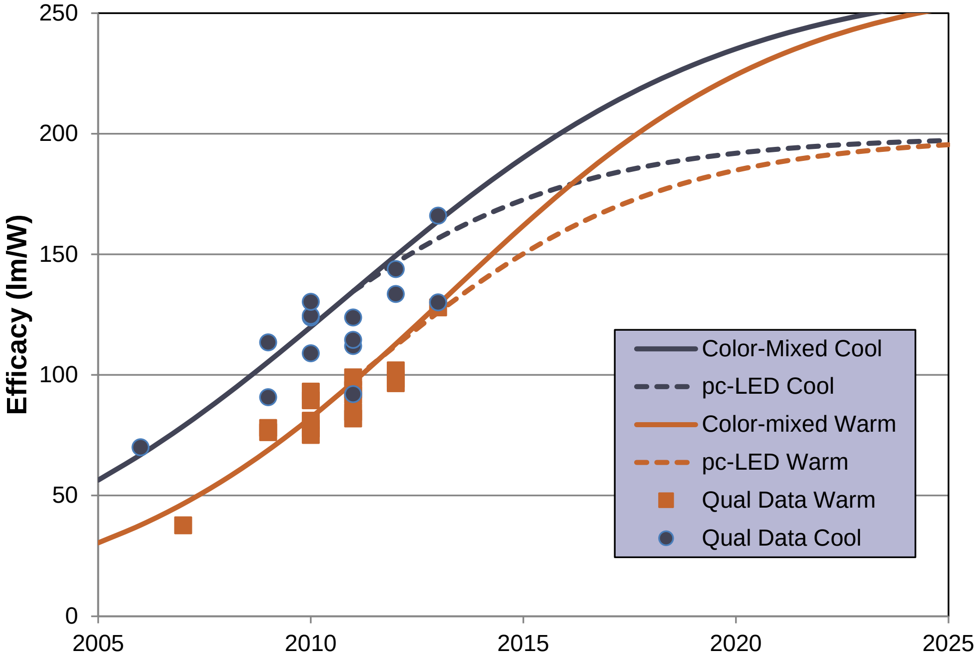

FIGURE 4.1 WHITE-LIGHT LED PACKAGE EFFICACY PROJECTIONS FOR COMMERCIAL PRODUCT

As noted in the discussions above, the ultimate pc-LED efficacy appears to be about 199 lm/W as compared to the color-mixed limit of about 266 lm/W, although up to now the fitted curves are very nearly identical. It is becoming apparent, though, that progress for best in class has been slowing for the past couple of years. At the same time, there has been an increase in the number of offerings approaching the best in class, perhaps pointing toward energy savings resulting from the widespread availability of high-performing products. Table 4.1 provides projections for selected years.

TABLE 4.1 PROGRESS PROJECTIONS FOR LED PACKAGE EFFICACY (LM/W)

Package Type	2012	2013	2015	2020	Goal
Cool-White (Color-mixed)	150	164	190	235	266
Cool-White (Phosphor)	147	157	173	192	199
Warm-White (Color-mixed)	113	129	162	224	266
Warm-White (Phosphor)	112	126	150	185	199

Notes:

1. Projections for cool-white packages assume CCT=4746-7040 K and CRI >70, while projections for warm- white packages assume CCT=2580-3710 K and CR I>80. All efficacy projections assume that packages are measured at 25 °C with a drive current density of 35 A/cm^2.
2. The asymptote for a color-mixed solution is 266 lm/W, and for phosphor-converted is 199 lm/W; hybrids will lie somewhere in between.

4.1.2 Efficacy Projections for OLEDs

As described in Section 3.1.2, 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. The most aggressive corporate roadmap is that of LG Chemical as shown in Table 4.2 below.

TABLE 4.2 LG CHEM PERFORMANCE ROADMAP [44]

Metric	2012	2013	2014	2015
Efficacy (lm/W)	60	80	100	135
Luminance (cd/m^2)	3,000	3,000	–	4,000
L_{70} Lumen Maintenance (1,000 hours)	15	20	30	40
Area (mm)	100 x 100	150 x 150	300 x 300	300 x 300

The company has announced that the technology is already available to meet the 2013 target and that such panels will be available in July 2013. However, reaching the targets for 2015 will require the use of all-phosphorescent systems and substantial improvements in light extraction. Other companies, such as Panasonic and Philips, do not anticipate reaching 130 lm/W until 2018 or 2019.

Figure 4.2 shows a projection of future progress on the efficacy of OLED panels based on past performance panel data and the goals set out in Table 4.3. The data on panels is rather sparse, limited to a few recent years, and shows a lot of variation, so there is considerable uncertainty in the 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, CRI ≥ 85, luminous emittance ≥3,000 lm/m^2, and lumen maintenance L_{70} ≥10,000 hours. Where these parameters are known or where the data can be normalized to comply, the data point is called qualified.

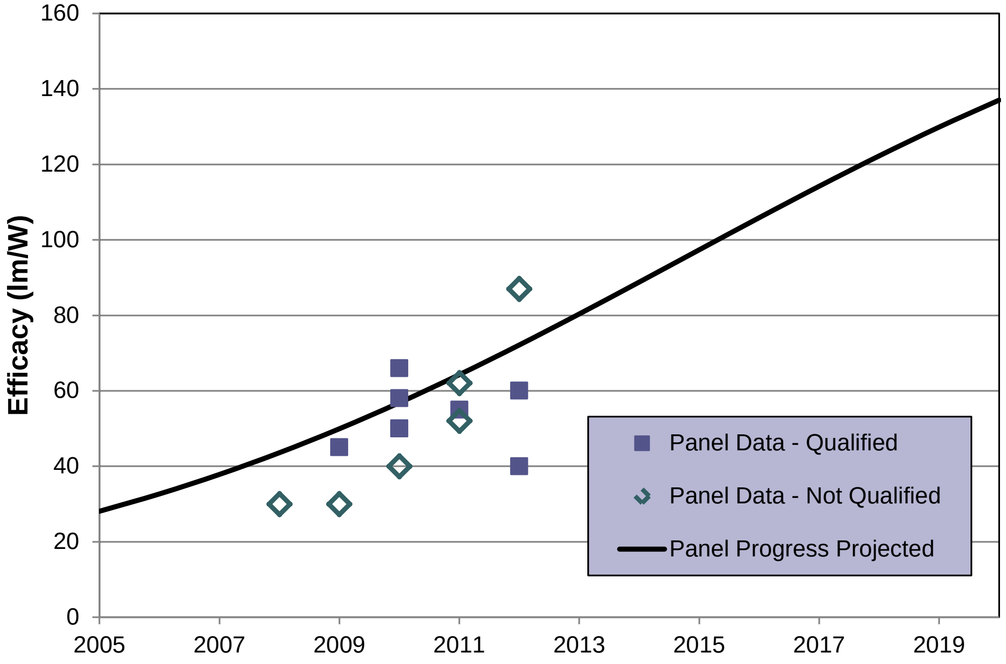

FIGURE 4.2 WHITE-LIGHT OLED PANEL EFFICACY PROJECTIONS

Table 4.3 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 the same goals.

TABLE 4.3 SUMMARY OF OLED PANEL PERFORMANCE TARGETS

Metric	2013	2015	2018	Goal
LER (lm/W)	320	330	350	360
Internal Quantum Efficiency	85%	90%	90%	90%
Electrical Efficiency	75%	80%	85%	85%
Extraction Efficiency	40%	50%	60%	70%
Panel Efficacy (lm/W)	80	100	120	190
L_{70} Lumen Maintenance (1,000 hours)	15	20	25	30

Note: Projections assume CRI > 85, 2580-3710K; 10,000 lm/m^2 emittance.

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 necessitates extensive encapsulation of the OLED panel, particularly on flexible substrates. In addition, oxygen, moisture, and other contaminants can get embedded into the OLED in the fabrication process, reducing the panel lifetime.

4.2 Milestones and Interim Goals

To provide some concrete measures of progress for the overall program, several targets and milestones have been identified through the roundtable and workshop discussions that will mark progress over the next ten years. These milestones are updated annually, but are not exclusive of the progress graphs shown earlier. Rather, they are highlighted targets that reflect significant gains in performance. Where only one metric is explicitly targeted in the milestone description, it is assumed that progress on the others is proceeding, but the task priorities are chosen to emphasize the identified milestone.

The LED package and luminaire milestones in Table 4.4 were revised in 2010 to reflect recent progress. FY2010 and FY2015 milestones reflect efficacy and/or price targets for LED packages with lumen maintenance values of 50,000 hours. The FY2012 milestone focused on the development of higher-efficiency luminaires. The SSL community successfully demonstrated the FY2012 LED goal of a high-efficiency luminaire with an output of 1,000 lumens, 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.

By FY2015, it is expected that costs for LED packages will fall to around \$2/klm while retaining the high efficacy of >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/luminaire systems.

The LED package and luminaire milestones represent well defined phases in the development of low-cost, high-performance SSL luminaries. The first phase was to develop a reasonably efficient white LED package that is sufficient for the lighting market. This phase was completed a couple of years ago. The second phase, which is ongoing, is to further 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 begun to shift the focus toward the development of efficient luminaries. This then becomes the thrust of the third phase. Finally, the fourth phase is to significantly reduce the cost of LED lighting to the point where it is competitive across the board. This phase, currently underway, is further supported through the R&D manufacturing initiative.

TABLE 4.4 LED PACKAGE AND LUMINAIRE MILESTONES

Year	Target
FY10	Package: >140 lm/W (cool-white); >90 lm/W (warm-white); <$13/klm (cool-white)
FY12	Luminaire: 100 lm/W; ~1,000 lumens; 3500 K; 80 CRI; 50,000 hours
FY15	Package: ~$2/klm (cool-white); ~$2.2/klm (warm-white)
FY17	Luminaire: >3500 lumens (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 35 A/cm^2.

The overarching DOE milestones for OLED-based SSL are shown in Table 4.5. DOE milestones for OLEDs have transitioned from OLED pixel results to OLED panel and luminaire results and have been revised to reflect current developments in the state of the art.

As shown in Table 3.5, the OLED luminaire efficacy is expected to be just 10–20 percent less than panel efficacy due to losses in the power supply and possible optical losses that must be accounted for in luminaires. Color specifications and lumen maintenance should be similar for the panel and luminaire. Luminaires will incur additional costs in the power supply, mechanical structure, and any added secondary optics or thermal management. However, these costs currently are far outweighed by the cost of the panel. When high-performance OLED panels are available at affordable prices, the next phase of development is the commercialization of luminaires. The thrust of this phase of development is to achieve high-efficacy luminaires with dramatic reductions in overall system cost. Though not highlighted as a milestone, the approach to luminaire development will affect the adoption of this lighting technology. It is recognized that differentiation of the technology—whether in thinness, flexibility, transparency, light distribution, color quality, or other means—is essential.

The FY2010 OLED milestone was the demonstration of OLED panels with 60 lm/W efficacy. Universal Display Corporation (UDC) came very close to meeting this goal with panels that reached 58 lm/W with CRI of 84, CCT of 3320 K and lumen maintenance (L_{70}) of 10,000 hours. UDC also produced a laboratory panel with efficacy of 66 lm/W, but with CRI relaxed to 79. These panels were measured at luminous emittance levels of around 3,000 lm/m^2 and, as lab-scale devices, the costs were uncertain. At this point commercial panels were also becoming available, offered by foreign suppliers producing in small volume on laboratory lines leading to very high prices.

The FY2012 milestone was a laboratory panel with an efficacy of >70 lm/W, CRI >85, and lumen maintenance (L_{70}) of >10,000 hours. This goal assumes a panel of large enough area and luminous emittance to obtain 200 lm output. Much progress was made towards this goal. Panasonic demonstrated a small lab device (25 cm^2) with an efficacy of 87 lm/W at 1,000 cd/m^2. Furthermore, commercial panels from LG Chem became available. These panels deliver 72 lumens at an efficacy of 60 lm/W at 3,000cd/m^2, CRI >85, CCT of 3500 K, and lumen maintenance (L_{70}) of 15,000 hours. These are the same panels found in the Acuity Brand Kindred, Revel, and Trilia luminaires. LG Chem has announced the development of panels with even higher efficacy that they plan to mass produce in mid-2013. These 10 cm x 10 cm panels are claimed to deliver 80 lm/W at 3,000 cd/m^2 with a CRI of 85, CCT of 3000 K, and L_{70} >20,000 hours.

The FY2015 milestone focuses on cost reduction. The goal is a commercial panel priced at $50/klm with an efficacy of 100 lm/W and L_{70} of 20,000 hours. LG Chem, Philips, and Panasonic are targeting efficacies of 135 lm/W, 90 lm/W, 100 lm/W, respectively, for their 2015 products, and they expect to achieve these efficacies at very high luminous emittance of at least 10,000 lm/m^2 [44] [45] [46]. However, the pricing is still highly uncertain. It seems doubtful that this cost target can be met with the equipment used in current production. However, U.S. OLED developers have argued that a new approach to manufacturing will enable limited productions priced close to this level.

OLED developers are close to reaching the desired targets for lumen maintenance and color quality. However, further attention needs to be paid to other factors that limit the lifetime of the device. The rapid improvements in the performance and style of diffuse LED luminaires mean that OLED developers must retain aggressive goals with respect to efficacy and cost. Meeting the target panel price of $50/klm by 2015 or soon thereafter seems necessary in order to create a large enough demand to justify further investments in R&D and manufacturing capability. The target luminaire price of $50/klm is appropriate for 2020 if OLEDs are to gain sufficient market penetration to contribute significantly to global energy savings.

TABLE 4.5 OLED PANEL AND LUMINAIRE MILESTONES

Year	Target
FY10	Panel: >60 lm/W
FY12	Laboratory panel: 200 lm/panel; >70 lm/W; >10,000 hours
FY15	Commercial panel: <$50/klm (price); >100 lm/W; 20,000 hours
FY18	Luminaire: 100 lm/W
FY20	Luminaire: price <$50/klm

Note: CRI > 85, CCT < 2580-3710 K

4.3 Critical Priorities and Tasks

R&D roundtables of invited experts were held in November of 2012 in advance of the January 2013 R&D workshop.[13] This year the roundtables recommended 16 tasks as potential priorities for SSL technology development. Following discussions at the workshop, several of the tasks were somewhat modified: four were combined and two dropped, leaving 12 tasks prioritized for attention during the next year or so, as listed in Table 4.6. DOE SSL program funding solicitations are 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, but 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. Of the 12 prioritized tasks, two (A.8.1 Light Quality Research and B.6.3 System Reliability) were thought not particularly suited to the Funding Opportunity Announcement (FOA) process but might better be handled through consortia or contracted efforts with DOE assistance to the extent possible.

TABLE 4.6 PRIORITY R&D TASKS

	Core Technology Research	Product Development
LED	A.1.2 Emitter Materials Research A.1.3 Down Converters A.8.1 Light Quality Research	B.1.1 Substrate Development B.3.6 Package Architecture B.6.3 System Reliability and Lifetime B.6.4 Novel LED Luminaire Systems
OLED	C.1.2 Stable White Devices C.3.1 Fabrication Technology Research C.6.3 Novel Light Extraction Approaches	D.2.2 Low-Cost Electrode Structures D.6.3 Panel Light Extraction and Utilization

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[13] For a summary report of the roundtable meetings, see “Roundtable Discussions on Recommended R&D Tasks for Solid-State Lighting,” available at: apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl-rd-roundtable-report_dec12.pdf.

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 4.7 below.

TABLE 4.7 ASSUMPTIONS FOR WAVELENGTH AND COLOR AS USED IN THE TASK DESCRIPTIONS

Color		Peak Wavelength or CCT Range	CRI
Blue		440-460 nm	-
Green		520-540 nm	-
Amber		580-595 nm	-
Red		610-620 nm	-
White	Warm	2580-3710 K (ANSI 2700, 3000, 3500 K)	>80
	Neutral	3711-4745 K (ANSI 4000, 4500 K)	>70
	Cool	4746-7040 K (ANSI 5000, 5700, 6500 K)	>70

4.4 LED Priority R&D Tasks

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. The roundtables prior to the R&D workshop began the process of task selection by providing an initial recommendation regarding the most important areas of work. This initial subset of tasks was presented for consideration and discussion at the workshop. After the workshop, the list was shortened to a handful of priority tasks that will be described in the following sections.

4.4.1 LED Core Technology Research Tasks

Core technology research remains central to the DOE SSL effort, and several projects on LED emitter and down-conversion materials continue to advance the technology year by year. The performance metrics have been updated to reflect current progress, but most of the goals have not changed. An efficient green emitter remains elusive, although phosphor-converted greenish-white LEDs have been used together with monochromatic red to make up much of the efficacy gap between a pc-LED and the theoretically most efficient cm-LED. The drive for higher LER requires the development of efficient narrow-band emitters/down-converters. This is particularly apparent in the red/amber spectral region where a sharper long wavelength cut-off is required for highly efficacious warm-white sources. Thus, in addition to the light emitters, work on improvements in down-conversion materials remains a priority.

Task A.1.2 addresses the need for an improved understanding of the critical materials issues impacting the development of higher-efficiency LEDs. A key focus will be on identifying the fundamental physical mechanisms underlying the phenomenon of current droop in high-performance blue LEDs. Another focus will be on improving IQE and reducing the thermal sensitivity of LEDs, especially those in the red and amber spectral regions.

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	2012 Status	2020 Targets
IQE @ 35 A/cm^2	88% (Blue) 38% (Green) 75% (Red) 13% (Amber)	90%
EQE @ 35 A/cm^2	75%(Blue) 32% (Green) 64% (Red) 11% (Amber)	81%
Power conversion efficiency[14] @ 35 A/cm^2	50% (Blue) 21% (Green) 42% (Red) 7% (Amber)	73%
Current droop – Relative EQE at 100 A/cm^2 vs. 35 A/cm^2	77%	100%
Thermal stability – Relative optical flux at 100 °C vs. 25 °C	90% (Blue) 85% (Green) 50% (Red) 25% (Amber)[15]	98% (Blue, Green) 75% (Red, Amber)

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[14] Optical power out divided by electrical power in for the LED package.

[15] This status is representative of direct emitters. Amber pc-LEDs can achieve thermal stability of up to 83 percent.

Phosphors are a key component of today's efficient LED products, but there remain a few issues where substantial improvements may be possible. Most of the conversations on A.1.3 centered around the issues of spectral efficiency and color shift. Spectral efficiency can be improved by narrowing the red phosphor emission, and new materials formulations might allow better stability of color over time.

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. Non-rare earth metal and non-toxic down-converters are encouraged.

Metrics	2012 Status	2020 Targets
Quantum yield (25°C) across the visible spectrum	90%	95%
Thermal stability – Relative quantum yield at 150 °C vs. 25 °C	90%	95%
Average conversion efficiency[16] (pc-LED)	67%	74%
Spectral full width half maximum (FWHM)	100 nm (Red)	<30 nm for all colors
Color shift over time (pc-LED)	Δu'v' <0.007 @ 6,000 hrs	Δu'v' <0.002 over life
Spectral efficiency relative to a maximum LER ~367 lm/W	92%	100%
Flux density saturation – Relative quantum yield (QY) at 1 W/mm^2 (optical flux) vs. peak QY		

The next task, light quality research, regards the quality and perception of light, which was a popular topic at the roundtables and the workshop. Participants noted the importance on gaining industry agreement on metrics for describing color rendering, on understanding differences in perception between broad-spectrum sources and sources consisting of a number of narrow spectral peaks. For some applications, color changes, differences, or poor color fidelity may limit adoption of the technology, but the applications and extent to which color issues are important are not well-

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[16] Refers to the efficiency with which phosphors create white light using an LED pump. The phosphor efficiency includes quantum efficiency and the Stokes loss of the phosphor.

quantified. There have also been various studies concerning health effects on different colors of light as well as possible efficiency-enhancing methods of using added blue light to decrease illumination needed for certain tasks.

However, the field, and potential effort, is very large, and not directly a part of the technology development. Many felt that this sort of work might not be suited to the SSL program's FOA process, but might benefit from some targeted work under DOE direction or by independent industry attention.

A.8.1 Light Quality Research		
Description: Develop improved metrics for brightness perception, color discrimination, and color preference. Employ human factors visual response or vision science studies to evaluate the impact of various spectral power distributions on the above, including line-based vs. broadband sources, violet- vs. blue-based pc-white LEDs, etc.		
Metric(s)	**2012 Status**	**2020 Target(s)**
Additional or improved color metric	Current color metrics (CRI, CQS[17], CCT, CMF[18]) inadequately describe the color of light	Development of new metrics that accurately specify color preference and color fidelity and describe improvements in energy savings, health, and productivity

4.4.2 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 system reliability and smart systems. The two tasks that do address package or luminaire design emphasize novelty: How can we better approach the issue of light sources with a new package architecture? What non-traditional luminaire designs might take best advantage of the unique attributes of LEDs?

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[17] Color Quality Scale
[18] Color Matching Function

Task B.1.1 addresses substrate development. While most products are based on sapphire or silicon carbide, several alternatives have been put forth in recent years. The industry seems to have the now-traditional options well in hand; this task suggests we broaden our view and explore potential game-changers.

B.1.1 Substrate Development

Description: Develop alternative substrate solutions that are compatible with the demonstration of low-cost, high-efficacy LED packages. Suitable GaN substrate solutions might include native GaN, GaN-on-Si, GaN templates, engineered GaN substrates, etc. Demonstrate state-of-the-art LEDs on these substrates and establish a pathway to target performance and cost.

Metrics	2012 Status	2020 Targets
Price of LED package @ state-of-the-art efficacy	\$5/klm (cool) \$9/klm (warm)	\$0.7/klm
Substrate price	Bulk: >\$2,000 (50 mm) Template/Engineered: \$100-500 (50 mm)	<\$500 (200 mm)
Current droop – Relative EQE at 100 A/cm^2 vs. 35 A/cm^2	77%	100%
Thermal stability – Relative optical flux at 100 °C vs. 25 °C	90% (Blue) 85% (Green)	98% (Blue, Green) 75% (Red, Amber)
GaN transparency (absorption coefficient)	2-10 cm^{-1}	<0.5 cm^{-1}

Task B.3.6 deals with package architecture. The key point here, as noted above, is to look for alternatives that can result in a step up in LED light source performance, not just incremental improvements.

<table>
<tr><th colspan="3">B.3.6 Package Architecture</th></tr>
<tr><td colspan="3">Description: Develop novel LED package and module architectures that can be readily integrated into luminaires. Architectures should address some of the following issues: thermal management, cost, color-efficiency, optical distribution, electrical integration, sensing, reliability, and ease of integration into the luminaire or replacement lamp while maintaining state-of-the-art efficiency. The novel packages should address technology and performance gaps within the current state of the art. Proposed approaches could employ novel phosphor conversion approaches, RGB+ architectures, system-in-package, hybrid color, chip-on-heat-sink, or other approaches to address these issues.</td></tr>
<tr><th>Metrics</th><th>2012 Status</th><th>2020 Targets</th></tr>
<tr><td>Color shift over time</td><td>Δu’v’ <0.007 @ 6,000 hrs</td><td>Δu’v’ <0.002 over life</td></tr>
<tr><td>Price of LED package @ state-of-the-art efficacy</td><td>$5/klm (cool)
$9/klm (warm)</td><td>$0.7/klm</td></tr>
<tr><td>Luminaire efficacy</td><td>100 lm/W (warm)</td><td>200 lm/W</td></tr>
<tr><td>Luminaire price</td><td></td><td></td></tr>
</table>

Discussions of the importance of a better understanding of system reliability and lifetime, the subject of task B.6.3, were extensive at the R&D workshop. While agreement that this work must be done is broad, it is less clear that the task is amenable to the FOA process. A consortium of academia and industry participants has been working on the issue for some time, working closely with a funded core technology research task on reliability. This consortium approach seems to be working well, albeit slowly, and many felt it may be a better way to coordinate work on this issue. It will still be necessary to have some directed work to provide specific inputs for the work of the consortium, but it may be advantageous for the consortium to define that work and for DOE to contract specific parts of it outside the FOA process.

B.6.3 System Reliability and Lifetime		
Description: Collection and analysis of system reliability data for SSL luminaires and components to determine failure mechanisms and improve luminaire reliability and lifetime (including color stability). Develop and validate accelerated test methods taking into consideration component interactions. Develop an openly available and widely usable software tool to model SSL reliability and lifetime verified by experimental data and a reliability database for components, materials, and subsystems. This task includes projects that focus on specific subsystems such as LED package, driver, and optical and mechanical components.		
Metrics	**2012 Status**	**2020 Targets**
Mean time to failure (e.g., catastrophic, L_{70}, color shift, loss of controls)	LED package lumen depreciation data	Tool to predict luminaire lifetime within 10% accuracy

Task B.6.4 describes work to develop LED luminaires with new form factors that are advantageous to LED technology, have excellent efficacy, add value to the lighting system, and integrate controls and sensors that enable additional value and energy savings. Integration of simple and effective controls, controllable power supplies, and sensors can be a key element of this work. The metrics for this task are difficult to apply and express generally, so their statuses and targets are left open. R&D proposals in this area should describe metrics for the state of the art for the particular application being addressed and describe improvements that are a result of the proposed concept and contemplated work.

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, building integration, and control integration should be considered to improve the efficiency of the light source and the efficient utilization of light. An 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	**2012 Status**	**2020 Targets**
Luminaire efficacy	100 lm/W	200 lm/W
Light utilization		
Total cost of light		

4.5 OLED Priority R&D Tasks

During the roundtable meetings in November 2012 and the workshop in January 2013, concern was expressed that the progression of OLED lighting technology from laboratory experiments to commercial products has been too slow, partly because the community has been pursuing many different options in material selection, processing technique, and device architecture. To accelerate product development and OLED adoption, the importance of cost reductions for OLED materials (for substrates, encapsulation, and electrodes) and corresponding fabrication techniques was also stressed. In particular, encapsulation materials and techniques that will allow for long-term robustness are important for OLEDs to achieve reliable lifetimes for lighting applications. Also affecting OLED device lifetime is the need for stable white materials systems. There is still a need for efficient, stable blue emitters and hosts that work in conjunction with the entire system to provide a stable white device.

Aside from research into stable organic materials and more cost-effective fabrication technology research, participants' attention was focused on the delivery of current from the edge of the panel to the light-emitting layers and the extraction of light from those layers into air.

4.5.1 OLED Core Technology Research Tasks

Task C.1.2, stable white devices, promotes the development of efficient, stable white-light OLED materials and structures to improve color quality, EQE, and lifetime while offering the potential for large-scale, low-cost production and processing. One of the greatest challenges in creating efficient, stable white OLED devices is the operating stability of blue phosphorescent emitters. The development of stable blue emitters could yield significant improvements in the luminous efficacy of phosphorescent white OLEDs. Roundtable attendees advocated leveraging the materials advancements made by the display industry for OLED lighting.

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. Color shift over time should be minimal. 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 a significant improvement in stability, while maintaining or improving other metrics.

Metrics	2012 Status	2020 Targets
Lumen maintenance (L_{70}) from 10,000 lm/m^2	15,000 hrs	>30,000 hrs
Voltage rise		<15%
Color shift over time	$\Delta u'v'$ <0.004	$\Delta u'v'$ <0.002
EQE without external extraction enhancement	~22%	25-30%
Voltage @ 2 mA/cm^2	~3.4 V	<3 V
CRI	70-90	>90

Task C.3.1, fabrication technology research, addresses OLED cost reductions through the development of new techniques for materials deposition, encapsulation, and device fabrication. Techniques that significantly change the cost structure for OLEDs need to be developed such as solution-processable techniques, equipment that drastically improves materials utilization, and low-cost, reliable encapsulation techniques.

C.3.1 Fabrication Technology Research		
Description: Develop new practical techniques for materials deposition, device fabrication, or encapsulation of OLED panels with performance consistent with the Manufacturing Roadmap. Methods should use technologies showing the potential for scalability and reduced cost (for example, by enabling significant advances in yield, quality control, substrate size, process time, and materials usage).		
Metrics	**2012 Status**	**2020 Targets**
Relative reduction in material cost and total cost of ownership (TCO)	1 relative cost	1/10 cost
Material utilization	5-50%	>70%
Thickness uniformity	5% variation over small areas	<5% variation over 200 cm^2
Yield of good panels		>90%

Task C.6.3, novel light extraction approaches, was selected for the investigation of unique light extraction techniques that could potentially allow for a breakthrough in extraction enhancement. Light extraction remains one of the largest obstacles to realizing OLED performance targets of efficacy and lifetime and also plays into the brightness and cost of OLED panels. While scalable improvements of up to 2x (as compared to an OLED on standard ITO/glass substrate) have been demonstrated, the long-term goal is a 3x improvement in extraction efficiency. This task seeks novel approaches that can lead to a scalable, low-cost 3x improvement in extraction efficiency.

C.6.3 Novel Light Extraction Approaches		
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 (for example, extraction layers should not lead to voltage increases, reduction in device efficacy, angular dependence of color). The proposed solution could involve modifications within the OLED stack, within or adjacent to the transparent electrode, 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. The approach should provide potential for low cost and should be demonstrated in a device of at least 1 cm^2 in size to demonstrate applicability and scalability to large-area (panel-size) devices.		
Metrics	**2012 Status**	**2020 Targets**
Extraction efficiency	40% (laboratory, small area)	70%
Angular variation in color		$\Delta u'v' < 0.002$

4.5.2 OLED Product Development Tasks

Task D.2.2 was prioritized because standard electrode materials are high cost and do not necessarily provide uniform current distribution across the panel. The current distribution structures must ensure a uniform distribution of the current across the panel and minimize energy loss. The difficulty in accomplishing this arises from the requirement that at least one of the two electrodes must be transparent. Indeed, the value of an OLED luminaire may be enhanced significantly if the whole structure is transparent. It has become apparent that limitations of the optical transmittance and sheet resistance of transparent conductors make it extremely unlikely that current can be distributed uniformly over large panels, say with size greater than 10 cm x 10 cm, using homogeneous transparent conducting sheet. Thus, compound structures will be required, for example using wire grids to carry current across the panel while injection into the organic stack is accomplished through thin transparent films.

D.2.2 Low-Cost Electrode Structures

Description: Demonstrate a high-efficiency OLED panel employing a cost-effective electrode technology on low-cost glass. The electrode technology should distribute the current uniformly over a large OLED panel, while maintaining high overall optical transparency. In addition to sheets of transparent conducting materials, the structures may involve wire grids or series connections between the anodes and cathodes of panel segments. The inner surfaces should be smooth enough to enable the deposition of thin organic layers and should not lead to shorting during device operation. The proposed approach should be scalable and should demonstrate or discuss compatibility with state-of-the-art extraction techniques.

Metrics	2012 Status	2020 Targets
Luminance uniformity	80% at 1,000 cd/m^2	85% at 3,000 cd/m^2
Optical transparency	80%	85% from 450 nm to 620 nm
Optical absorption	~5%	<1% from 450 nm to 620 nm
Surface roughness (peak-to-valley)	20 nm	<10 nm
Incremental cost	\$20-50/m^2	<\$10/m^2

Task D.6.3, like C.6.3, is prioritized because the problem of light extraction remains the greatest fundamental barrier to the successful commercialization of OLED lighting. Because photons are created in a region of high refractive index in a very thin planar layer, most of the light suffers total internal reflection before emerging into air, which has a much lower index. It is urgent that a practical solution be found to suppress the total internal reflection without compromising the thin planar structure of OLED panels; thus, this topic has been included amongst the solicitations in both core technology research and product development. The workshop attendees recommended that attention should be focused on attaining a solution that can be brought to market within 3-4 years.

D.6.3 Panel Light Extraction and Utilization

Description: Demonstrate manufacturable approaches to improve light extraction efficiency for OLED panels while providing some control over the angular distribution of the intensity of the emitted light in order to maximize the useful light for specific applications. 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). The proposed solution could involve modifications within the OLED stack, within or adjacent to the transparent electrode, and/or external to the device. The approach should be demonstrated over large areas (>25 cm^2) and must be amenable to low-cost manufacture.

Metrics	2012 Status	2020 Targets
Extraction efficiency	40%	70%
Incremental cost		<$10/$m^2$
Angular variation in color		$\Delta u'v' < 0.002$

4.6 Current SSL Project Portfolio

DOE received $25.8 million from Congress for SSL R&D in the 2012 fiscal year (FY2012, which began in October 2011) and has requested $24.2 million in funding for FY2013. These levels are consistent with congressional appropriations from previous years, which has hovered around $25 million each year. In FY2009 an additional, one time, funding of $50 million was provided through the American Recovery and Reinvestment Act (ARRA) of 2009 to be used to accelerate the SSL R&D Program and jumpstart the manufacturing R&D initiative.

The active DOE SSL R&D Portfolio as of April 2013, shown in Figure 4.3, includes 17 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 $47.2 million in government and industry investment.

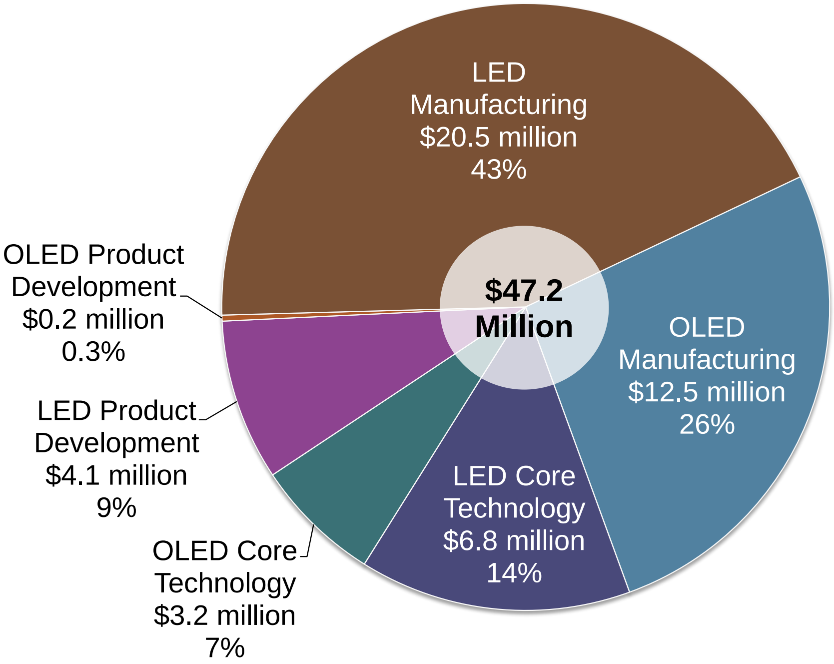

FIGURE 4.3 DOE SSL TOTAL PORTFOLIO SUMMARY, APRIL 2013

Figure 4.4 provides a graphical breakdown of the funding for the current SSL project portfolio as of April 2013. DOE is currently providing $30.8 million in funding for the projects, and the remaining $16.4 million is cost-shared by project awardees. Of the 17 projects active in the SSL R&D portfolio, 11 focus on LED technology and six focus on OLEDs.

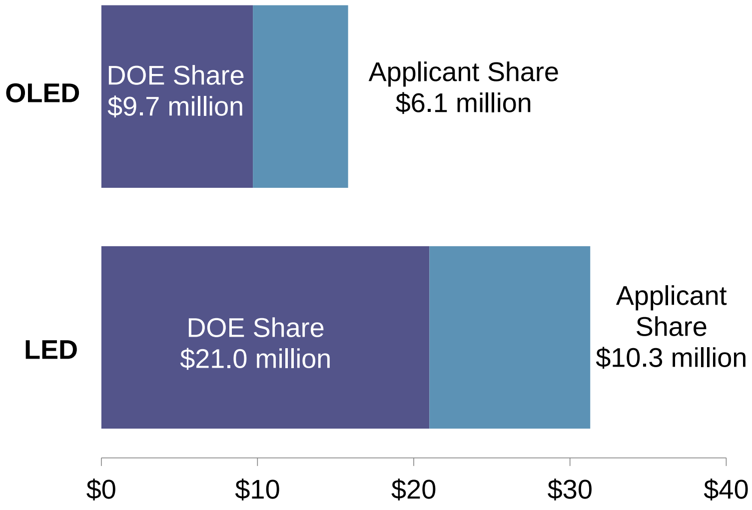

FIGURE 4.4 FUNDING OF SSL R&D PROJECT PORTFOLIO BY FUNDER, APRIL 2013

DOE supports SSL R&D in partnership with industry, small business, academia, and national laboratories. Figure 4.5 provides the approximate level of R&D funding contained in the current SSL portfolio among the four general groups of SSL R&D partners.

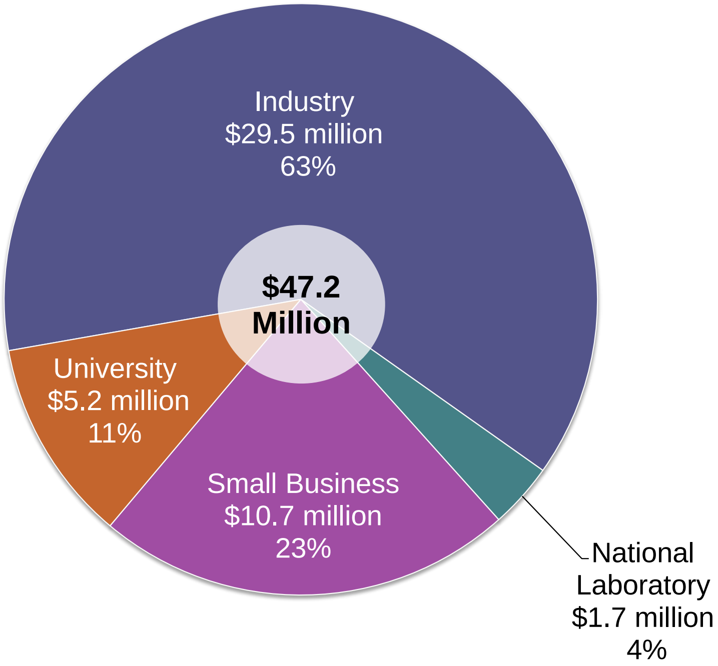

FIGURE 4.5 DOE SSL TOTAL PORTFOLIO SUMMARY BY RECIPIENT GROUP, APRIL 2013

Table 4.8 and Table 4.9 show the total number of SSL R&D core technology research and product development projects and total project funding for each. Both tables show the categories in which there are active projects that DOE funded or has selected for funding, keeping with the evolving priorities. Table 4.10 lists these projects.

TABLE 4.8 SSL R&D PORTFOLIO: CORE TECHNOLOGY RESEARCH PROJECTS, APRIL 2013

Task	Number of Projects	Funding ($ million)
Light-Emitting Diodes	**4**	**$6.8**
Emitter Materials	2	$2.6
Down-Converters	1	$2.1
Optimizing System Reliability	1	$2.1
Organic Light-Emitting Diodes	**3**	**$3.2**
Novel Materials	3	$3.2
Total	**7**	**$10.0**

TABLE 4.9 SSL R&D PORTFOLIO: PRODUCT DEVELOPMENT PROJECTS, APRIL 2013

Task	Number of Projects	Funding ($ million)
Light-Emitting Diodes	**3**	**$4.1**
Semiconductor Materials	2	$3.9
LED Thermal Management	1	$0.2
Organic Light-Emitting Diodes	**1**	**$0.2**
Panel Outcoupling	1	$0.2
Total	**4**	**$4.2**

TABLE 4.10 SSL R&D PORTFOLIO: CURRENT RESEARCH PROJECTS, APRIL 2013[19]

	Research Organization	Project Title
LED	Applied Nanotech	CarbAl™ Based Circuit Board for Power LED Packaging
	Cree, Inc.	High Efficiency Integrated Package
	Philips Lumileds	High Power Warm White Hybrid LED Package for Illumination
	Research Triangle Institute	Solid-State Lighting Luminaire Reliability Model
	Sandia National Laboratories	Semi-polar GaN Materials Technology for High IQE Green LEDs
	Soraa	Light Emitting Diodes on Semipolar Bulk GaN Substrate with IQE >80% at 150 A/cm^2 and 100 °C
	SUNY Buffalo	High Efficiency Colloidal Quantum Dot Phosphors
OLED	Arizona State University	High Efficiency and Stable White OLED Using a Single Emitter
	Universal Display	Novel Low Cost Single Layer Outcoupling Solution for OLED Lighting
	University of Florida	High Triplet Energy Transporting Materials and Increased Extraction Efficiency for OLED Lighting
	University of Rochester	Development and Utilization of Host Materials for White Phosphorescent OLEDs

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[19] See Appendix 5.4 for a discussion of patents awarded through DOE-funded projects.

5 APPENDICES

5.1 Program Organization

DOE has made a long-term commitment to advance the development and market introduction of energy-efficient white-light sources for general illumination. SSL differs fundamentally from today's lighting technologies, and its unique attributes drive the need for a coordinated approach that guides technology advances from laboratory to marketplace. DOE has developed a comprehensive national strategy to support R&D that advances SSL technology, products, and the underlying science, conducted under several programs: the Basic Energy Sciences (BES) Program, the Advanced Research Projects Agency–Energy (ARPA-E), and the Energy Efficiency and Renewable Energy (EERE) Building Technologies Office (BTO) SSL Program. Of these, the SSL Program within EERE BTO is the only program that exclusively funds SSL R&D. For more information on BES and ARPA-E efforts, please visit the following, respectively: www.science.energy.gov/bes and www.arpa-e.energy.gov.

5.1.1 DOE Solid-State Lighting Program Goals

The SSL Program was created in response to a directive in Section 912 of the Energy Policy Act of 2005 to *"support research, development, demonstration, and commercial application activities related to advanced solid-state lighting technologies based on white light emitting diodes"* [8]. Accordingly, DOE has set forth the following mission statement and goal for the SSL Program:

> Mission: *Guided by a government-industry partnership, DOE's mission is to create a new, U.S.-led market for high-efficiency, general illumination products through the advancement of semiconductor technologies, to save energy, reduce costs, and enhance the quality of the lighted environment.*
>
> Goal: *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 percent with lighting that accurately reproduces sunlight spectrum.*

Guided by this mission and goal, DOE annually develops a portfolio of SSL activities, shaped by input from industry leaders, research institutions, universities, trade associations, and national laboratories. The Program strategy is comprehensive, with three distinct, interrelated thrusts (and accompanying roadmaps): core technology research and product development, manufacturing R&D, and market development support.

This MYPP guides SSL core technology research and product development over the next few years and informs the development of annual SSL R&D funding opportunities. This plan is a living document, updated annually to incorporate new analyses, technological progress, and new research priorities as science evolves. The SSL Manufacturing Roadmap and Multi-Year Market Development Support Plan are published as separate documents at apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_manuf-roadmap_august2012.pdf and apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_5year-plan_2012-16.pdf, respectively.

5.1.2 Significant SSL Program Accomplishments to Date

RECENT PROGRAM HIGHLIGHTS

The following is a list of the SSL Program's recent highlights and relevant dates. More information on each can be found by following the accompanying URL.

Highlight	Date	Link to More Information
DOE Hosts Tenth Annual SSL R&D Workshop	January 2013	www.ssl.energy.gov/longbeach13_highlights.html
DOE Hosts Seventh Annual DOE SSL Market Introduction Workshop	July 2012	www.ssl.energy.gov/pittsburgh2012_highlights.html
DOE Hosts Fourth Annual DOE SSL Manufacturing R&D Workshop	June 2012	www.ssl.energy.gov/sanjose2012_highlights.html
DOE Conducts Broad-Based Education Outreach at LIGHTFAIR®	May 2012	www.ssl.energy.gov/news_detail.html?news_id=18340
DOE Reopens L Prize® PAR 38 Competition	March 2012	www.lightingprize.org
Next Generation Luminaires™ Announces LED Design Competition Winners	February, March 2012	www.ngldc.org
"Review of the Life-Cycle Energy Consumption of Incandescent, Compact Fluorescent, and LED Lamps"	February 2012	http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/2012_LED_Lifecycle_Report.pdf
"Energy Savings Potential of Solid-State Lighting in General Illumination Applications"	January 2012	http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_energy-savings-report_jan-2012.pdf
"2010 U.S. Lighting Market Characterization"	January 2012	http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/2010-lmc-final-jan-2012.pdf
Lighting Facts® Expands Product List and Online Resources	N/A	www.lightingfacts.com

RECENT RESEARCH HIGHLIGHTS

With DOE's support, considerable progress has been made in the advancement of SSL technology. Researchers working on projects supported by the DOE's SSL R&D Program have won several prestigious national research awards and have achieved several significant accomplishments in the area of SSL. The following list serves to highlight some of the significant achievements that have been reported since April 2012 resulting from DOE-funded projects. More detail is available on DOE's website at: www.ssl.energy.gov/highlights.html.

Research Highlight	Date
Ultratech Develops an Improved Lithography Tool for LED Wafer Manufacturing	November 2012
Veeco Develops a Tool to Reduce Epitaxy Costs and Increase LED Brightness	October 2012
Philips Lumileds Is Exploring the Use of Silicon Substrates to Lower the Cost of LEDs	October 2012
Applied Materials Develops an Advanced Epitaxial Growth System to Bring Down LED Costs	October 2012
WhiteOptics' Low-Cost Reflector Composite Boosts LED Fixture Efficiency	April 2012
DuPont Displays Develops Low-Cost Method of Printing OLED Panels	April 2012
UDC Teaming with Acuity to Make Commercial-Sector PHOLED Luminaire	April 2012
OSRAM SYLVANIA Develops High-Efficiency LED Troffer Replacement	April 2012
Philips Light Sources & Electronics is Developing an Efficient, Smaller, Cost-Effective Family of LED Drivers	April 2012

5.2 Definitions

This appendix defines and describes the various components and efficiency metrics associated with LED and OLED general illumination luminaires. Understanding each component of a luminaire and its contribution to overall luminaire efficiency helps to highlight the opportunities for energy efficiency improvements and thereby to define priorities for DOE’s SSL R&D Portfolio.

5.2.1 Light-Emitting Diodes

LED COMPONENTS[20]

Component level (no power source or driver)

- *LED* refers to a p-n junction semiconductor device (also referred to as chip) that emits incoherent UV, visible, or infrared radiation when forward biased.
- *LED Package* refers to an assembly of one or more LEDs that includes wire bond or other type of electrical connections (thermal, mechanical, or electrical interfaces) and optionally an optical element. Power source and ANSI standardized base are not incorporated into the device. The device cannot be connected directly to the branch circuit.
- *LED Array* or *Module* refers to an assembly of LED packages (components), or dies on a printed circuit board or substrate, possibly with optical elements and additional thermal, mechanical, and electrical interfaces that are intended to connect to the load side of a LED driver. Power source and ANSI standard base are not incorporated into the device. The device cannot be connected directly to the branch circuit.

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[20] Definitions provided by ANSI/IES RP-16-10 Nomenclature and Definitions for Illuminating Engineering with permission from the Illuminating Engineering Society of North America.

Subassemblies and systems (including a driver)

- *LED Lamp* refers to an assembly with an ANSI standardized base designed for connection to an LED luminaire. There are two general categories of LED lamps:
    - *Integrated LED Lamp* refers to an integrated assembly comprised of LED packages (components) or LED arrays (modules), LED driver, ANSI standard base and other optical, thermal, mechanical and electrical components. The device is intended to connect directly to the branch circuit through a corresponding ANSI standard lamp-holder (socket).
    - *Non-integrated LED lamp* refers to an assembly comprised of an LED array or packages and ANSI standard base. The device is intended to connect to the LED driver of an LED luminaire through an ANSI standard lamp-holder (socket). The device cannot be connected directly to the branch circuit.
- *Light engine* consists of an integrated assembly comprised of LED packages or LED arrays, driver, and other optical, thermal, mechanical, and electrical components. The device is intended to connect directly to the branch circuit through a custom connector compatible with the LED luminaire for which it was designed and does not use an ANSI standard base.
- *Driver* refers to a device comprised of a power source and LED control circuitry designed to receive input from the branch circuit and operate an LED package, array, or lamp.
    - *Power supply* refers to an electronic device capable of providing and controlling current, voltage, or power within design limits.
    - *Control circuitry* refers to electronic components designed to control a power source by adjusting output voltage, current or duty cycle to switch or otherwise control the amount and characteristics of the electrical energy delivered to an LED package or array. LED control circuitry does not include a power source.
- *LED Luminaire* refers to a complete lighting unit consisting of LED Packages or Arrays and a matched driver together with parts to distribute light, to position and protect the light-emitting elements, and to connect the unit to a branch circuit. The LED luminaire is intended to connect directly to a branch circuit.

LED EFFICIENCY METRICS

Component level

- *Package efficacy* refers to the ratio of lumens out of the LED package to the power applied to the LED package at room temperature, thus not including the driver, luminaire optical or thermal losses.
- *Electrical efficiency* accounts for the efficiency with which electrical charge carriers injected into the LED package find their way to the active region of the LED device. Ohmic (resistive) losses associated with the semiconductor layers and the LED package materials represent the most important loss mechanism. A reduction in electrical efficiency is associated with an increase in the energy (voltage) required to create photons over and above the intrinsic bandgap energy (voltage) of the semiconductor active region.
- *Internal quantum efficiency*, IQE, is the ratio of the photons emitted from the active region of the semiconductor chip to the number of electrons injected into the active region.[21]
- *Light extraction efficiency* is the ratio of photons emitted from the semiconductor chip into the encapsulant to the total number of photons generated in the active region. This includes the effect of power reflected back into the chip because of index of refraction difference, but excludes losses related to phosphor conversion.

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[21] The internal quantum efficiency is difficult to measure, although it can be measured indirectly in various ways, for example using a methodology described by S. Saito, et al., Phys. Stat. Sol. (c) 5, 2195 (2008).

- *External quantum efficiency*, EQE, is the ratio of extracted photons to injected electrons.[22] It is the product of the IQE and the extraction efficiency.
- *EQE current droop* represents the difference in EQE (at 25°C) between the peak value, typically occurring at very low current density, and that reported at a nominal current density of 35 A/cm^2. Current droop is considered to be a reduction in IQE as the current density is increased but can be most readily characterized through EQE measurement.
- *Phosphor conversion efficiency* refers to the efficiency with which phosphors convert the wavelength of the absorbed light. The phosphor efficiency includes quantum efficiency of the phosphor and the Stokes loss of the conversion process. This efficiency is relevant only to pc-LEDs.
- *Color-mixing* refers to losses incurred while mixing colors in order to create white light (not the spectral efficacy, but just optical losses). This efficiency is relevant only to color-mixed or hybrid LEDs.
- *Scattering/Absorption* accounts for the scattering and absorption losses in the phosphor and encapsulant of the package. The efficiency can be described as the ratio of the photons exiting the encapsulant to the photons injected into the encapsulant.
- *Spectral efficiency* is the ratio of the luminous efficacy of radiation (LER) of the actual spectrum to the maximum possible LER (LER_{max}), as determined by the modeling of an optimized spectrum with appropriate color quality. The actual spectrum may be limited by the response of the phosphor, or when optimal wavelengths for a color-mixed or hybrid LED are not available.

Subassemblies and systems

- *Luminaire efficacy*, a key metric for the DOE SSL R&D Program, is the ratio of *lumen output* to the electrical power applied to the *luminaire*.
- *Driver efficiency* represents the efficiency of the electronics in converting input power from 120 V alternating current to low-voltage direct current as well as any controls needed to adjust for changes in conditions (e.g. temperature or age) so as to maintain brightness and color or for active control of the lighting system.
- *Additional EQE current droop* represents the ratio of EQE (at 25 °C) at a current density of 100 A/cm^2 as compared with 35 A/cm^2. Packages are often operated at higher current densities in order to minimize the number of packages required to achieve a specific lumen output. Increasing the current density currently results in reduced efficiency due to additional EQE current droop. Reducing the droop sensitivity of the LED can reduce this additional loss.
- *Flux thermal stability* is the ratio of the lumens emitted by the LED package in thermal equilibrium under continuous operation in a luminaire to the lumens emitted by the package as typically measured and reported in production at 25 °C.[23] These thermal losses can be reduced by minimizing temperature rise through innovative thermal management strategies or perhaps by reducing the thermal sensitivity of the LED package itself.
- *Phosphor thermal stability* is the ratio of phosphor conversion efficiency at thermal equilibrium under continuous operation in a luminaire to the phosphor conversion efficiency

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[22] The external quantum efficiency can be measured experimentally using the expression $\eta_{ex} = (P_{opt} / h\nu) / (I / q)$ where P_{opt} is the absolute optical output power, $h\nu$ is the photon energy, I is the injection current and q is the electron charge.

[23] Standard LED package measurements use relatively short pulses of current to eliminate thermal effects, keeping the device at 25 °C (or other controlled point). In standard operation, however, the LED is driven under CW (continuous wave) conditions. Under these conditions, in thermal equilibrium the device operates at a case temperature typically 100 degrees or so higher than room temperature.

measure at 25 °C. This additional cause of efficiency loss as the phosphor temperature increases is relevant only to the pc-LED.

- *Luminaire optical efficiency* is the ratio of the lumens emitted by the luminaire to the lumens emitted by the LED package in thermal equilibrium. This efficiency loss arises from optical losses in diffusers, reflectors, beam shaping optics or shields or objects in the light path (for purposes of this analysis, spectral effects in the fixture and optics are ignored, although this may not always be appropriate).

5.2.2 Organic Light-Emitting Diodes

OLED COMPONENTS

Component level

- *Pixel* is a small area device (usually less than 1 cm^2) used for R&D. The pixel contains the basic assembly of thin films, including the two electrodes, layers that facilitate the injection and transport of charge, and one or more emissive layers in the center. The emissive layers consist of organic materials while the conductive layers may contain a mixture of organic and inorganic materials. The pixel can also include minimal packaging for environmental protection and electrical connection points to the device. The pixel may create white or monochromatic light.
- *Panel* refers to an OLED with a minimum area of 50 cm^2. OLED panels require current-conducting structures to ensure uniform emission of light across the panel. Panels may also incorporate packaging, thermal management, and elements to enhance light extraction. When panels are fabricated on a glass or plastic substrate, the usual procedure is to employ a transparent anode next to the substrate through which the light escapes, as the cathode can then be made from opaque metal and a foil, glass, or multilayer barrier cover can be used to encapsulate the device. It is also possible to manufacture an OLED with a highly transparent top electrode (typically with up to 80 percent transmission across the visible spectral region). These structures can make use of robust, low-cost, flexible metal foil substrates, or can be built on transparent substrates to make transparent devices.

Subassemblies and systems

- *Luminaire* refers to the complete lighting system, intended to be directly connected to an electrical branch circuit. It consists of an assembly of one or more interconnected OLED panels along with the OLED electrical driver, mechanical fixture, and optics, if necessary, to deliver the appropriate distribution of light.
- The *driver* converts the available electrical power to the appropriate voltage, current, and waveform for the device and includes any necessary electronic controls, for example to enable dimming or to modify the color of the emitted light.

OLED EFFICIENCY METRICS

Component level

- *Electrical efficiency* accounts for the efficiency with which electrical charge carriers injected into the OLED panel find their way to the active region of the OLED device. Ohmic (resistive) losses associated with current spreading across the panel electrodes and at interfaces as well as within the organic layers represent the most important loss mechanism. Any excess in the energy (voltage) required to create photons over and above the optical energy gap also reduces the electrical efficiency.

- *Internal quantum efficiency*, IQE, is the ratio of the photons created in the emissive region of the OLED to the number of electrons injected into the organic stack. This can be over 100 percent if additional electron-hole pairs are created within the stack.
- *Light 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.
- *Spectral efficiency* is the ratio of the LER of the actual spectrum to the maximum luminous efficacy of radiation (LER_{max}), as determined by the CCT and CRI and the intrinsic spectral properties of the source.

Subassemblies and systems

- *Driver efficiency* represents the efficiency of the electronics in converting input power from external alternating current to low-voltage direct current as well as any controls needed to adjust for changes in conditions (e.g., temperature or age) so as to maintain brightness and color or for active control of the lighting system.
- *Fixture and optical efficiency* is the ratio of the lumens emitted by the luminaire to the lumens emitted by the OLED panel. This efficiency loss arises from optical losses in diffusers, reflectors, beam shaping optics or shields or objects in the light path.

5.3 MYPP Task Structure

Priority tasks shown in red.

LED Core Technology Research Tasks

- A.1.0 Emitter Materials
  - A.1.1 Alternative substrates
  - **A.1.2 Emitter materials research**
  - **A.1.3 Down converters**
- A.2.0 Device Materials and Architectures
  - A.2.1 Light extraction approaches
  - A.2.2 Novel emitter architectures
- A.3.0 Device Packaging
  - A.3.4 Thermal control research
- A.4.0 LED Fabrication
  - A.4.4 Manufacturing simulation
- A.5.0 Optical Components
  - A.5.1 Optical component materials
- A.6.0 Luminaire Integration
  - A.6.2 Thermal components research
  - A.6.3 System reliability methods
- A.7.0 Electronic Components
  - A.7.4 Driver electronics
  - A.7.5 Electronics reliability research
- A.8.0 Light Quality
  - **A.8.1 Light quality research**

LED Product Development Tasks

- B.1.0 Emitter Materials
  - **B.1.1 Substrate development**
  - B.1.2 Semiconductor materials
  - B.1.3 Phosphors
- B.2.0 Device Materials and Architectures
  - B.2.3 Electrical
- B.3.0 Device Packaging
  - B.3.1 LED package optics
  - B.3.2 Encapsulation
  - B.3.4 Emitter thermal control
  - B.3.5 Environmental sensitivity
  - **B.3.6 Package architecture**
- B.4.0 LED Fabrication
  - B.4.1 Yield and manufacturability
  - B.4.2 Epitaxial growth
  - B.4.3 Manufacturing tools
- B.5.0 Optical Components
  - B.5.1 Light utilization
  - B.5.2 Color maintenance
  - B.5.3 Diffusion and beam shaping
- B.6.0 Luminaire Integration
  - B.6.1 Luminaire mechanical design
  - B.6.2 Luminaire thermal management
  - **B.6.3 System reliability and lifetime**
  - **B.6.4 Novel LED luminaire systems**
- B.7.0 Electronic Components
  - B.7.1 Color maintenance
  - B.7.2 Color tuning
  - B.7.3 Lighting systems and controls

OLED Core Technology Research Tasks

- C.1.0 Materials and Device Architectures
  - C.1.1 Novel device architectures
  - **C.1.2 Stable white devices**
  - C.1.3 Material and device architecture modeling
  - C.1.4 Material degradation
  - C.1.5 Thermal characterization of materials and devices
- C.2.0 Substrate and Electrode
  - C.2.2 Electrode research
- C.3.0 Fabrication
  - **C.3.1 Fabrication technology research**
- C.4.0 Luminaire Integration
  - C.4.3 Optimizing system reliability
- C.5.0 Electronic Components
- C.6.0 Panel Architecture
  - **C.6.3 Novel light extraction approaches**

OLED Product Development Tasks

- D.1.0 Materials and Device Architectures
  - D.1.1 Implementation of materials and device architectures
  - D.1.5 Device failure
- D.2.0 Substrate and Electrode
  - D.2.1 Substrate materials
  - **D.2.2 Low-cost electrode structures**
- D.3.0 Fabrication
  - D.3.1 Panel manufacturing technology
  - D.3.2 Quality control
- D.4.0 Luminaire Integration
  - D.4.1 Light utilization
  - D.4.2 Breakthrough OLED luminaire
  - D.4.3 System reliability methods
  - D.4.4 Luminaire thermal management
  - D.4.5 Electrical interconnects
- D.5.0 Electronic Components
  - D.5.1 Color maintenance
  - D.5.2 Smart controls
  - D.5.3 Driver electronics
- D.6.0 Panel Architecture
  - D.6.1 Large area OLEDs
  - D.6.2 Panel packaging
  - **D.6.3 Panel light extraction and utilization**
  - D.6.4 Panel reliability
  - D.6.5 Panel mechanical design

LED Core Technology Research Tasks

Task		Description
A.1.1	Alternative substrates	Explore alternative practical substrate materials and growth for high-quality epitaxy so that device quality can be improved.
A.1.2	Emitter materials research	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.
A.1.3	Down converters	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. Non-rare earth metal and non-toxic down-converters are encouraged.
A.2.1	Light extraction approaches	Devise improved methods for raising chip-level extraction efficiency and LED system optical efficiency. Photonic crystal structures or resonant cavity approaches would be included.
A.2.2	Novel emitter materials and architectures	Devise novel emitter geometries and mechanisms that show a clear pathway to efficiency improvement; demonstrate a pathway to added chip-level functionality offering luminaire or system efficiency improvements over existing approaches; explore novel architectures for improved efficiency, color stability, and emission directionality including combined LED/converter structures. (Possible examples: nano-rod LEDs, lasers, micro-cavity LEDs, photonic crystals, luminaire-on-a-chip.)
A.3.4	Thermal control research	Simulation of solutions to thermal management issues at the package or array level. Innovative thermal management solutions.
A.4.4	Manufacturing simulation	Develop manufacturing simulation approaches that will help to improve yield and quality of LED products.
A.5.1	Optical component materials	Develop optical component materials that last at least as long as the LED source (50k hours) under lighting conditions that would include: elevated ambient and operating temperatures, UV- and blue-light exposure, and wet or moist environments.
A.6.2	Thermal components research	Research and develop novel thermal materials and devices that can be applied to solid-state LED products.
A.6.3	System reliability methods	Develop models, methodology, and experimentation to determine the system lifetime of the integrated SSL luminaire and all of the components based on statistical assessment of component reliabilities and lifetimes. Includes investigation of accelerated testing.
A.7.4	Driver electronics	Develop advanced solid-state electronic materials and components that enable higher efficiency and longer lifetime for control and driving of LED light sources.
A.7.5	Electronics reliability research	Develop designs that improve and methods to predict the lifetime of electronics components in the SSL luminaire.

A.8.1	Light quality research	Develop improved metrics for brightness perception, color discrimination, and color preference. Employ human factors visual response or vision science studies to evaluate the impact of various spectral power distributions on the above, including line-based vs. broadband sources, violet- vs. blue-based pc-white LEDs, etc.

LED Product Development Tasks

Task		Description
B.1.1	Substrate development	Develop alternative substrate solutions that are compatible with the demonstration of low-cost, high-efficacy LED packages. Suitable GaN substrate solutions might include native GaN, GaN-on-Si, GaN templates, engineered GaN substrates, etc. Demonstrate state-of-the-art LEDs on these substrates and establish a pathway to target performance and cost.
B.1.2	Semiconductor materials	Reduce the operating voltage of LED chips or arrays by increasing lateral conductivity or architectural improvements or package design, etc.
B.1.3	Phosphors	
B.2.3	Electrical	Reduce the operating voltage of LED chips or arrays by increasing lateral conductivity or architectural improvements or package design, etc.
B.3.1	LED package optics	Beam shaping or color-mixed at the LED package or array level.
B.3.2	Encapsulation	Develop a thermal/photo-resistant encapsulant that exhibits long life and has a high refractive index.
B.3.4	Emitter thermal control	Demonstrate an LED or LED array that maximizes heat transfer to the package so as to improve chip lifetime and reliability.
B.3.5	Environmental sensitivity	Develop and extensively characterize a packaged LED with significant improvements in lifetime associated with the design methods or materials.
B.3.6	Package architecture	Develop novel LED package and module architectures that can be readily integrated into luminaires. Architectures should address some of the following issues: thermal management, cost, color-efficiency, optical distribution, electrical integration, sensing, reliability, and ease of integration into the luminaire or replacement lamp while maintaining state-of-the-art efficiency. The novel packages should address technology and performance gaps within the current state of the art. Proposed approaches could employ novel phosphor conversion approaches, RGB+ architectures, system-in-package, hybrid color, chip-on-heat-sink, or other approaches to address these issues.
B.4.1	Yield and manufacturability	Devise methods to improve epitaxial growth uniformity of wavelength and other parameters so as to reduce binning yield losses. Solutions may include in-situ monitoring and should be scalable to high-volume manufacture.
B.4.2	Epitaxial growth	Develop and demonstrate growth reactors and monitoring tools or other methods capable of growing state-of-the-art LED materials at low cost and high reproducibility and uniformity with improved materials-use efficiency.
B.4.3	Manufacturing tools	Develop improved tools and methods for die separation, chip shaping, and wafer bonding, and testing equipment for manufacturability at lower cost.

LED Product Development Tasks

Task		Description
B.5.1	Light utilization	Maximize the ratio of useful light exiting the luminaire to total light from the LED source. This includes all optical losses in the luminaire; including luminaire housing as well as optical losses from diffusing, beam shaping, and color-mixing optics. Minimize artifacts such as multi-shadowing or color rings.
B.5.2	Color maintenance	Ensure luminaire maintains the initial color point and color quality over the life of the luminaire. Product: Luminaire/ replacement lamp
B.5.3	Diffusion and beam shaping	Develop optical components that diffuse and/or shape the light output from the LED source(s) into a desirable beam pattern and develop optical components that mix the colored outputs from the LED sources evenly across the beam pattern.
B.6.1	Luminaire mechanical design	Integrate all aspects of LED luminaire design: thermal, mechanical, optical, and electrical. Design must be cost-effective, energy-efficient, and reliable.
B.6.2	Luminaire thermal management	Design low-cost integrated thermal management techniques to protect the LED source, maintain the luminaire efficiency and color quality.
B.6.3	System reliability and lifetime	Collection and analysis of system reliability data for SSL luminaires and components to determine failure mechanisms and improve luminaire reliability and lifetime (including color stability). Develop and validate accelerated test methods taking into consideration component interactions. Develop an openly available and widely usable software tool to model SSL reliability and lifetime verified by experimental data and a reliability database for components, materials, and subsystems. This task includes projects that focus on specific subsystems such as LED package, driver, and optical and mechanical components.
B.6.4	Novel LED luminaire systems	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, building integration, and control integration should be considered to improve the efficiency of the light source and the efficient utilization of light. An 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.
B.7.1	Color maintenance	Develop LED driver electronics that maintain a color setpoint over the life of the luminaire by compensating for changes in LED output over time and temperature, and degradation of luminaire components.
B.7.2	Color tuning	Develop efficient electronic controls that allow a user to set the color point of the luminaire.
B.7.3	Lighting systems and controls	Develop integrated lighting controls that save energy over the life of the luminaire. May include methods to maximize dimmer efficiency. May include sensing occupancy or daylight, or include communications to minimize energy use, for example.

OLED Core Technology Research Tasks

Task		Description
C.1.1	Novel device architectures	Device architectures to increase EQE, reduce voltage, and improve device lifetime that are compatible with the goal of stable white light. Explores novel structures like those that use multi-function components, cavities or other strategies to optimize light extraction. Could include studying material interfaces.
C.1.2	Stable white devices	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. Color shift over time should be minimal. 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 a significant improvement in stability, while maintaining or improving other metrics.
C.1.3	Material and device architecture modeling	Developing software simulation tools to model the performance of OLED devices using detailed material characteristics.
C.1.4	Material degradation	Understand and evaluate the degradation of materials during device operation.
C.1.5	Thermal characterization of materials and devices	Involves modeling and/or optimizing the thermal characteristics of OLED materials and device architectures with the goal of developing less thermally sensitive and hydrolytically more stable materials and devices.
C.2.2	Electrode research	Develop a novel electrode system for uniform current distribution across a >200 cm^2 panel. Solutions must have potential for substantial cost reduction with long life while maintaining high OLED performance. Work could include more complex architectures such as grids or patterned structures, p-type and n-type degenerate electrodes, two-material electrodes, electrodes that reduce I*R loss, flexible electrodes, or other low-voltage electrodes.
C.3.1	Fabrication technology research	Develop new practical techniques for materials deposition, device fabrication, or encapsulation of OLED panels with performance consistent with the Manufacturing Roadmap. Methods should use technologies showing the potential for scalability and reduced cost (for example, by enabling significant advances in yield, quality control, substrate size, process time, and materials usage).
C.4.3	Optimizing system reliability	Research techniques to optimize and verify overall luminaire reliability. Develop system reliability measurement methods and accelerated lifetime testing methods to determine the reliability and lifetime of an OLED device, panel, or luminaire through statistical assessment of luminaire component reliabilities and lifetimes.

OLED Core Technology Research Tasks

Task		Description
C.6.3	Novel light extraction approaches	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 (for example, extraction layers should not lead to voltage increases, reduction in device efficacy, angular dependence of color). The proposed solution could involve modifications within the OLED stack, within or adjacent to the transparent electrode, 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. The approach should provide potential for low cost and should be demonstrated in a device of at least 1 cm^2 in size to demonstrate applicability and scalability to large-area (panel-size) devices.

OLED Product Development Tasks

Task		Description
D.1.1	Implementation of materials and device architectures	Develop materials and device architectures that can concurrently improve robustness, lifetime, efficiency, and color quality with the goal of stable white light over its lifetime. The device should be pixel-sized, demonstrate scalability, and have a lumen output of at least 50 lumens.
D.1.5	Device failure	Understand the failure modes of an OLED at the device level.
D.2.1	Substrate materials	Demonstrate an OLED with reasonable performance and low degradation using a substrate material that is low cost and shows reduced water and oxygen permeability. Other considerations may include processing and operational stability, weight, cost, optical and barrier properties, and flexibility.
D.2.2	Low-cost electrode structures	Demonstrate a high-efficiency OLED panel employing a cost-effective electrode technology on low-cost glass. The electrode technology should distribute the current uniformly over a large OLED panel, while maintaining high overall optical transparency. In addition to sheets of transparent conducting materials, the structures may involve wire grids or series connections between the anodes and cathodes of panel segments. The inner surfaces should be smooth enough to enable the deposition of thin organic layers and should not lead to shorting during device operation. The proposed approach should be scalable and should demonstrate or discuss compatibility with state-of-the-art extraction techniques.
D.3.1	Panel manufacturing technology	Develop and demonstrate methods to produce an OLED panel with performance consistent with the roadmap using integrated manufacturing technologies that can scale to large areas while enabling significant advances in yield, quality control, substrate size, process time, and materials usage using less expensive tools and materials than in the OLED display industry and can scale to large areas.
D.3.2	Quality control	Develop characterization methods to help define material quality for different materials and explore the relationship between material quality and device performance. Develop improved methods for monitoring the deposition of materials in creating an OLED panel.

OLED Product Development Tasks

Task		Description
D.4.1	Light utilization	Supports maximizing the ratio of useful light exiting the luminaire to total light from the OLED sources. This includes optical losses in the luminaire as well as from beam distribution and color-mixing optics.
D.4.2	Breakthrough OLED luminaire	Emphasizes the need to employ the unique properties of OLEDs through new luminaires and form factors. Designs should capture the value proposition features of OLEDs.
D.4.3	System reliability methods	Develop models, methodology, and experimentation to determine the lifetime of the integrated OLED luminaire and all of the components.
D.4.4	Luminaire thermal management	Design integrated thermal management techniques to extract heat from the luminaire in a variety of environments and operating conditions. Thermal management should maintain the OLED source temperature as well as enhance the luminaire color and efficiency performance.
D.4.5	Electrical interconnects	Develop standard connections for integration of OLED panels into the luminaire.
D.5.1	Color maintenance	Develop OLED driver electronics that maintain a color setpoint over the life of the luminaire by compensating for changes in OLED output over time and temperature, and degradation of luminaire components.
D.5.2	Smart controls	Develop integrated lighting controls and sensors that save energy over the life of the luminaire.
D.5.3	Driver electronics	Develop efficient, long-life OLED driver electronics and power converters that efficiently convert line power to acceptable input power of the OLED source(s) and maintain their performance over the life of the fixture. These can include energy-saving functionality such as daylight and occupancy sensors and communication protocols for external lighting control systems.
D.6.1	Large area OLEDs	Demonstrate a high-efficiency OLED panel, with a white light output of at least 200 lm and an area of at least 200 cm^2. The OLED panel should have high brightness and color uniformity as well as a long operating lifetime. The panel should employ low-cost designs, processes, and materials and demonstrate a potential for high-volume manufacturing.
D.6.2	Panel packaging	Demonstrate manufacturable approaches to improve light extraction efficiency for OLED panels while providing some control over the angular distribution of the intensity of the emitted light. 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, angular dependence of color). The proposed solution could involve modifications within the OLED stack, within or adjacent to the transparent electrode, and/or external to the device. The approach should be demonstrated over large areas (> 25 cm^2) and must be amenable to low-cost manufacture.

OLED Product Development Tasks

Task		Description
D.6.3	Panel light extraction and utilization	Demonstrate manufacturable approaches to improve light extraction efficiency for OLED panels while providing some control over the angular distribution of the intensity of the emitted light in order to maximize the useful light for specific applications. 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). The proposed solution could involve modifications within the OLED stack, within or adjacent to the transparent electrode, and/or external to the device. The approach should be demonstrated over large areas (>25 cm^2) and must be amenable to low-cost manufacture.
D.6.4	Panel reliability	Analyze and understand failure mechanisms of OLED panels and demonstrate a packaged OLED panel with significant improvements in operating lifetime. Specific issues may include enhanced thermal management to support operation at higher luminance levels, or the dependence of shorting on layer thickness and uniformity.
D.6.5	Panel mechanical design	Integrate all aspects of OLED luminaire design: thermal, mechanical, optical, and electrical. The design must be cost-effective, energy-efficient and reliable.

5.4 Patents

As of January 2013, 58 SSL patents have been awarded to research projects funded by DOE. Since December 2000, when DOE began funding SSL research projects, a total of 159 patent applications have been submitted, ranging from large businesses (55) and small businesses (61) to universities (36) and national laboratories (7). These patents are listed on DOE's website at: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/patents_factsheet_feb2013.pdf.

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