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

# Solid-State Lighting Research and Development

# Multi-Year Program Plan

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Prepared for:

**Solid-State Lighting Program**
Building Technologies Office
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# DISCLAIMER

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# EXECUTIVE SUMMARY

According to a recent United States (U.S.) Department of Energy (DOE) report, lighting consumed about 18 percent of the total site electricity use in 2010 in the U.S. A second DOE report also finds that by 2025, solid-state lighting (SSL) technology offers the potential to save 217 terawatt-hours (TWh), or about one-third of current site electricity consumption used for lighting in the U.S. This projected savings corresponds to about 2.5 quadrillion British thermal units, of primary energy generation, which is approximately equal to the projected electricity generation of wind power and twelve times that of solar power in 2025. At a price of $0.10/kilowatt-hour, this would correspond to an annual dollar savings of $21.7 billion.

The energy savings projections assume significant progress in the realization of 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 to achieve the 217 TWh energy savings potential. These formidable, but achievable, targets require a number of scientific and technical improvements.

During the past year, SSL has shown some very significant advances:

- Adoption of SSL products continues to increase. For 2013, the installed base of light-emitting diodes (LEDs) in the U.S. has increased in all LED applications, more than doubling from 2012 to about 105 million units.
- Correspondingly, the annual energy cost savings from LEDs more than doubled in 2013 from the previous year, increasing to $1.8 billion. That is enough money to pay the annual lighting electricity bill for over 14 million U.S. homes.
- Cree and Philips have both announced the development of luminaire prototypes that have achieved efficacies of 200 lm/W, demonstrating the feasibility of reaching these performance levels.
- LG Chem has commercialized organic light-emitting diode (OLED) panels with efficacy levels of 60 lm/W and a color rendering index of 90.
- Konica Minolta has developed a prototype OLED panel with an efficacy of 131 lm/W and lumen maintenance, $L_{50}$, of 55,000 hours at 1,000 candelas per square meter for a device with an area of 15 square centimeters. They have also developed a flexible OLED panel with a thickness of only 70 micrometers.
- LED A-lamp pricing continues to decline, with non-dimmable 60W A19 replacement lamps now available for as little as $10 per bulb and dimmable lamps for as little as $13 per bulb. The price drops even further in regions with utility rebates.
- The City of Los Angeles has completed a four-year, citywide street lighting replacement program and has installed over 140,000 LED streetlights. The total installed base of U.S. outdoor area and roadway LEDs exceeds 3.3 million.

DOE's support for SSL is composed of three tightly integrated activities: Competitive Research and Development (R&D), Market-Based Technology Advancement, and Market Engagement.[1] The first of these activities supports competitively awarded, cost-shared R&D projects to develop advances in efficacy and performance that might not otherwise happen without DOE funding. Three areas of

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[1] For more information about the SSL Program see: http://www1.eere.energy.gov/buildings/ssl/about.html

research are supported: Core Technology Research, Product Development, and Manufacturing R&D.

Core Technology Research projects focus on applied research for technology development, with particular emphasis on meeting efficacy, performance, and cost targets. Product Development projects use knowledge gained from basic or applied research to develop or improve commercially viable materials, devices, or systems. This document, the DOE SSL Multi-Year Program Plan (MYPP), specifically addresses these two areas of research and serves to provide analysis and direction in support of advancing SSL technology. A companion document, the DOE SSL Manufacturing R&D Roadmap, addresses the third area of research and concentrates on what is needed to assure that high-quality, reduced cost products will be available in quantity and on time to meet rapidly rising demand.

The MYPP is updated annually, reflecting progress towards the goals and the shifting R&D priorities. The document provides a view of the global market for SSL and discusses in detail the barriers to adoption, particularly with regard to associated technology developments. Section 2 reviews applications where SSL is rapidly gaining traction and areas in which LEDs or OLEDs may have particular advantages. One of the greatest of the barriers to adoption is selling price, so the discussion of economic considerations gets special attention. SSL will probably always be more expensive than conventional lighting on a first-cost basis; however, higher operating efficiency and longer operating lifetimes (reduced maintenance/replacement costs) ensure that LED lighting is highly competitive on a life-cycle basis.

Section 3 examines the current state of the art for SSL technology, and includes sections on source efficacy, luminaire performance, and reliability. The various factors affecting source efficacy for LED packages and OLED panels are discussed and likely practical limits are identified. A detailed analysis is presented on the maximum projected source efficacies for warm white and cool white LED packages using a variety of architectures. Possible routes to achieving a goal of 250 lm/W are described and the key technological enablers are identified. An equivalent analysis for OLEDs identifies the various trade-offs that must be made in the design of an OLED panel to meet a goal of 190 lm/W. 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 to the state of the art for existing SSL products. From this analysis, we are able to identify the key scientific and technical breakthroughs required and use this information to help prioritize the research actions. Consideration is also given to SSL reliability and lifetime, the relationship between SSL and sustainability, and the status of global SSL R&D.

In Section 4, we derive LED and OLED performance projections, overarching DOE SSL Program milestones, and specific, priority R&D tasks and targets that will contribute to the achievement of the projections and milestones. The priority R&D tasks are identified based on inputs from technology experts and participants at the 2014 DOE SSL R&D Workshop, held from January 28th to 30th in Tampa, Florida. 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.

Three Core Technology Research tasks and two Product Development R&D tasks have been identified as priorities for LED lighting, while two Core Technology Research tasks and two Product Development R&D tasks have been identified for OLED lighting. These priorities, listed in the following table, were selected based on written input, discussions during the R&D Workshop, more detailed discussions within a selected focus group, and internal DOE discussions.

| **LED** | | **OLED** | |
|---|---|---|---|
| **Core Technology Research** | | | |
| **A.1.2** | Emitter Materials Research | **C.1.2** | Stable White Devices |
| **A.1.3** | Down-Converters | **C.6.3** | Novel Light Extraction and Utilization |
| **A.8.1** | Light Quality Research | | |
| **Product Development** | | | |
| **B.6.3** | System Reliability and Lifetime | **D.6.3** | Panel Light Extraction |
| **B.6.4** | Novel LED Luminaire Systems | **D.4.2** | OLED Luminaire |

Basic background material on LEDs and OLEDs, definitions of component parts, and information on DOE programs, metrics, and goals can also be found in in the report. Details of the legislation and policies defining the program are not included in this document but links to them may be found on the DOE's SSL website.[1]

# Multi-Year Program Plan

## SOLID-STATE LIGHTING RESEARCH AND DEVELOPMENT

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# 1 INTRODUCTION

According to a recent United States (U.S.) Department of Energy (DOE) report, lighting consumed about 18 percent of the total site electricity use in 2010 in the U.S [1]. A second DOE report also finds that by 2025, solid-state lighting (SSL) technology offers the potential to save 217 terawatt-hours (TWh), or about one-third of current site electricity consumption used for lighting in the U.S. This projected savings in site energy consumption would correspond to about 2.5 quadrillion British thermal units (Btus), or “quads”, of primary energy generation, which is approximately equal to the projected electricity generation of wind power and twelve times that of solar power in 2025 (as shown in Figure 1.1). At a price of $0.10/kilowatt-hour, this would correspond to an annual dollar savings of $21.7 billion [2].

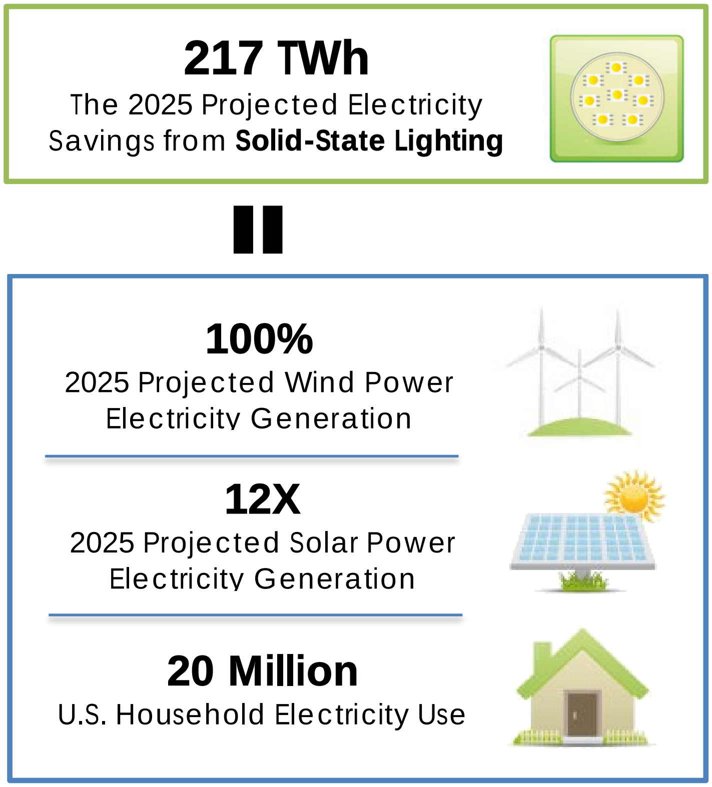

**FIGURE 1.1 2025 PROJECTED ELECTRICITY SAVINGS FROM SSL [3]**

This demonstrates that SSL provides a significant opportunity to reduce energy consumption, thereby improving domestic energy security and reducing greenhouse gas emissions. The U.S. Department of Energy has responded to this opportunity with the formation of the Solid-State Lighting Program.

By 2025, the goal of the DOE SSL Program is to 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.

The energy savings projections assume significant progress in efficient SSL sources, as well as widespread market adoption. Specifically, by 2025, this analysis assumes SSL sources will reach 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 but achievable targets. An analysis of the scientific and technical improvements necessary to achieve the 200 lm/W performance level is provided in Section 3. As we will discuss, significant progress has already been made, and market adoption is rapidly gaining momentum through product cost reductions, quality improvements, and consumer education [4].

The potential benefits described in the previous paragraphs are based on likely developments in inorganic light emitting diode (LED) technology. DOE also supports research and development (R&D) in organic light emitting diode (OLED) technology. While OLED technology is not quite at the level of LED performance or cost-competitiveness, OLEDs offer profoundly different lighting capabilities that can complement LED sources. OLEDs can be large-area, low-brightness sources that could eventually be produced on large-area flexible sheets at low cost, whereas LEDs are small, high-brightness sources produced by semiconductor manufacturing processes. Analysis of OLED technology also shows a path to high efficacy, approaching that of LEDs. The combination of low-brightness and high-brightness sources can enable more effective utilization of light, further improving energy savings by using less light to achieve the target lighting levels (known as light utilization).

This SSL R&D Multi-Year Program Plan (MYPP) strongly emphasizes improving lighting system efficiency, but also addresses other performance requirements that influence market adoption such as product life, color quality, color stability, and electronic control. Technology developments discussed in this document are also expected to be consistent with a path toward lower costs in order to promote higher levels of adoption. In addition, advancements in energy efficiency of the lighting products will also contribute to cost reductions. It has been estimated that one-third of the cost reduction of LED sources is due to improved efficiency, which not only yields more lumens per watt but also, effectively, more lumens per manufactured material or cost.

There are two companion documents to the DOE SSL MYPP. The Market-based Technology Advancement Multi-Year Plan addresses other initiatives to promote adoption such as product quality testing (Caliper), innovative product competitions (Next Generation Luminaires), and deployment activities (Gateway). The DOE SSL Manufacturing Roadmap concentrates on what is needed to assure that high-quality, reduced-cost products will be available in quantity and on time to meet rapidly rising demand [5] [6].

During the past year, SSL has shown some very significant advances:

- Adoption of SSL products continues to increase. For 2013, the installed base of LEDs in the U.S. has increased in all LED applications, more than doubling from 2012 to about 105 million units [7].
- Correspondingly, the annual energy cost savings from LEDs more than doubled in 2013 from the previous year, increasing to $1.8 billion. That is enough money to pay the annual lighting electricity bill for over 14 million U.S. homes [7].
- Cree and Philips have both announced the development of luminaire prototypes that have achieved efficacies of 200 lm/W, demonstrating the feasibility of reaching these performance levels [8] [9].
- LG Chem has commercialized organic light-emitting diode (OLED) panels with efficacy levels of 60 lm/W and color rendering index (CRI) of 90.
- Konica Minolta has developed a prototype OLED panel with an efficacy of 131 lm/W and lumen maintenance, $L_{50}$, of 55,000 hours at 1,000 candelas per square

meter (cd/m$^2$) for a device with an area of 15 square centimeters (cm$^2$). They have also developed a flexible OLED panel with a thickness of only 70 micrometers [10].
- LED A-lamp pricing continues to decline, with non-dimmable, 60W A19 replacement lamps now available for as little as $10 per bulb and dimmable lamps for as little as $13 per bulb. The price drops even further in regions with utility rebates.
- The City of Los Angeles has completed a four-year, citywide street lighting replacement program and has installed over 140,000 LED streetlights. The total installed base of U.S. outdoor area and roadway LEDs exceeds 3.3 million [7].

SSL has progressed rapidly over the past few years to the point that SSL is assumed by many to become the dominant lighting technology by 2025 [2]. However, there are still many technical and market opportunities for reaching the full performance and adoption potential of SSL more rapidly. Some of these opportunities are listed below:

- While LED lights now have a lower cost of ownership in many applications, the first cost of LED lighting discourages adoption. Advancements in more efficient technologies and manufacturing can further reduce the first cost. There is also a corresponding opportunity to educate consumers to look beyond the first cost and consider the full cost of ownership in their purchasing decision.
- Power supply units for OLEDs and LEDs that are small, efficient, and low cost are needed. There is an opportunity to reduce waste, improve recyclability, and upgradability with appropriate designs.
- Uncertainties in product lifetime and reliability are also barriers to adoption. Lumen maintenance of LED-based lighting products is becoming better understood; however, predicting catastrophic failure and unacceptable color shift is still difficult and requires new research and an improved testing and modeling framework.
- LED replacement products for a 100W A19 incandescent lamp are still not widely available.
- The development of new lighting form factors beyond replacement lamps and luminaires that take full advantage of SSL technology has not yet widely occurred. SSL beneficial form factors and systems that take advantage of the inherent controllability of SSL are expected to enable further efficiency, cost, and lighting performance improvements.
- For OLEDs, the development of control over the beam shape would allow one to increase the effectiveness of light delivery and to provide contrasting light levels.
- Next generation lighting opportunities are becoming more abundant and demand for customizable, controllable lighting is increasing.

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

Section 4 takes a deeper look at the key areas of R&D (referred to as “priority tasks”) that need attention by the community at this time. The tasks[2] have been identified, with inputs from technology experts and participants at the 2014 DOE SSL R&D Workshop (hereafter referred to as R&D Workshop), held this year from January 28th to 30th in Tampa, Florida. 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. Basic background material on LEDs and OLEDs and information on DOE programs and goals has been moved to Appendix 5, as have 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 [11] [12] [13] [14].

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[2] Appendix 5.3 contains a full list of identified SSL R&D tasks, including but not limited to priority tasks.

# 2 MARKET AND APPLICATIONS

Although still at a very early stage of adoption, SSL 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 U.S. by the year 2025 [2]. Other studies of the global market have reached similar conclusions. This section 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

According to the United Nations Environment Programme, lighting accounted for 15 percent of the total global electricity demand in 2010 [15]. IHS estimates that the global lighting market generates total annual revenue of nearly $100 billion [16]. Rising electricity prices, mounting concerns about climate change, and desire for energy independence are causing the global lighting market to shift toward energy-efficient light sources, including SSL. At this time, the global market for SSL is dominated by LED-based lighting products, while OLED lighting is currently confined to decorative luminaires and custom-built fittings, designed more to enhance the ambiance than to produce light. For this reason, the remainder of this section focuses on LED-based lighting.

Globally, IHS estimates that LED products accounted for 18 percent of lighting revenues in 2013, which corresponds to revenues of $16 billion [17]. When expressed in terms of unit sales, the greatest contribution has come from replacement lamps. Strategies Unlimited estimates that 400 million LED lamps were sold globally in 2013, suggesting that market penetration is about three percent [18]. However, estimates of global sales vary significantly, with some analyses suggesting less, while others suggest the global sale of LED lamps has reached over 800 million units. While there is uncertainty concerning today's total global unit sales of LED-based lighting products, there is agreement that revenue from LEDs is increasing. The largest global lighting company, Philips, reported that in the fourth quarter of 2013, revenues from LED-based lighting increased by 48 percent and now represents 34 percent of all their lighting sales [19]. Other companies with headquarters in Europe have reported similar results for the same time period, with LED products accounting for 33 percent of total revenues at Osram and 31.5 percent at Zumtobel [20] [21]. Among U.S.-based lighting companies, Cree's revenue, which is primarily generated through the sale of LED lighting products, rose by 42 percent for the same quarter [22].

This transition to LED lighting is widely predicted to produce an initial increase in global industry revenues, followed by a period of saturation and subsequent decline. However, different analyses assume different time periods and magnitudes for this decline. A recent example from Navigant Research for the commercial lighting sector[3] is shown in Figure 2.1.

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[3] Commercial lighting includes that for office, retail, education, healthcare, hotels/restaurants, institutional/assembly, warehouse, and transport spaces.

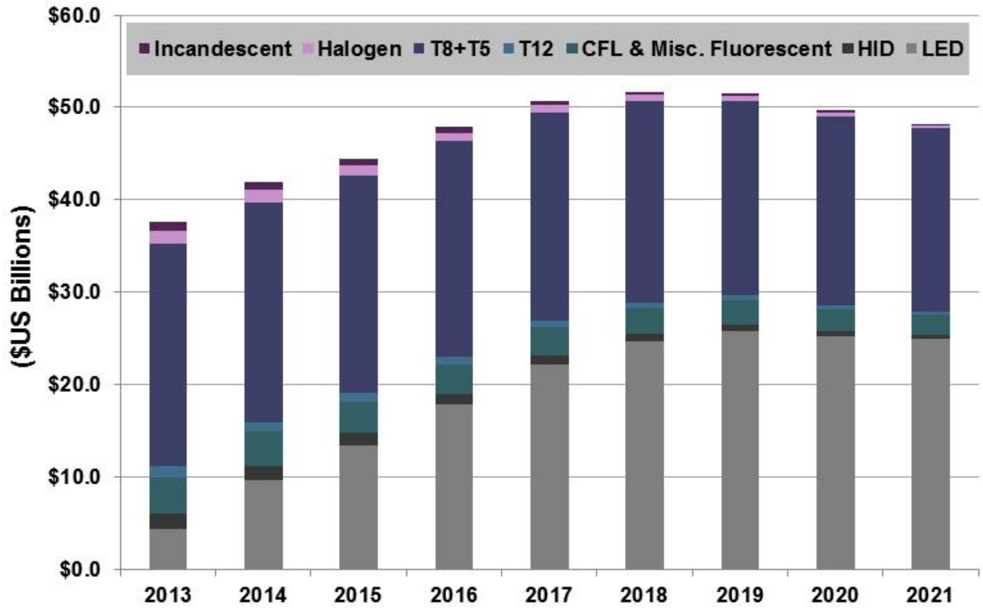

**FIGURE 2.1 GLOBAL COMMERCIAL LIGHTING REVENUE FORECAST, 2013-2020 [23]**
*Source: Energy Efficient Lighting for Commercial Markets. Prepared by Navigant Research, 2Q 2013.*

Navigant Research forecasts dramatic increases in revenue from global commercial LED sales at the expense of existing lamp technologies through 2019. From 2019 to 2021 there is a slight decrease in LED revenue, and a significant decrease in revenue from the sale of incumbent lighting technologies such as linear fluorescent lamps (including T5, T8, and T12), compact fluorescent lamps (CFL), and high-intensity discharge (HID) lamps. Despite this overall decrease in revenue, Figure 2.2 shows the forecasted unit shipments increasing through 2021, for both LED and conventional lighting. The decrease in global lighting revenue through 2021 predicted in this model is likely due to an anticipated decrease in SSL product costs, as opposed to a slowdown in unit sales [23]. However, as more longer-lived LED lamps are sold, we can expect an eventual decline in unit lamp sales since the replacement cycle for the lamps will be much longer. Added features of SSL products, such as controllability, color tuning, and smart communications, will likely add value to LED lighting products and further increase LED revenue in the coming years.

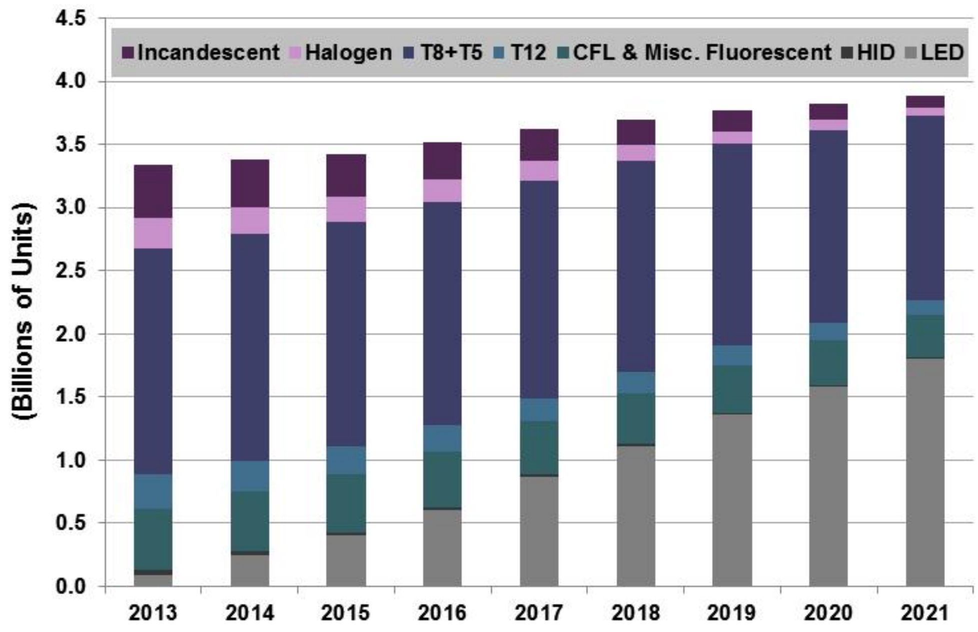

**FIGURE 2.2 FORECAST OF SHIPMENTS OF COMMERCIAL LAMPS AND LUMINAIRES, 2013-2020 [23]**
*Source: Energy Efficient Lighting for Commercial Markets. Prepared by Navigant Research, 2Q 2013.*

### 2.1.1 United States

Many of the lighting market trends seen on a global scale are similar to those within the U.S. Growing installations of energy-efficient light sources in the U.S. are 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]. This growth is occurring in all sectors and applications; however, it is most notable in the residential sector due largely to the migration away from incandescent lighting.

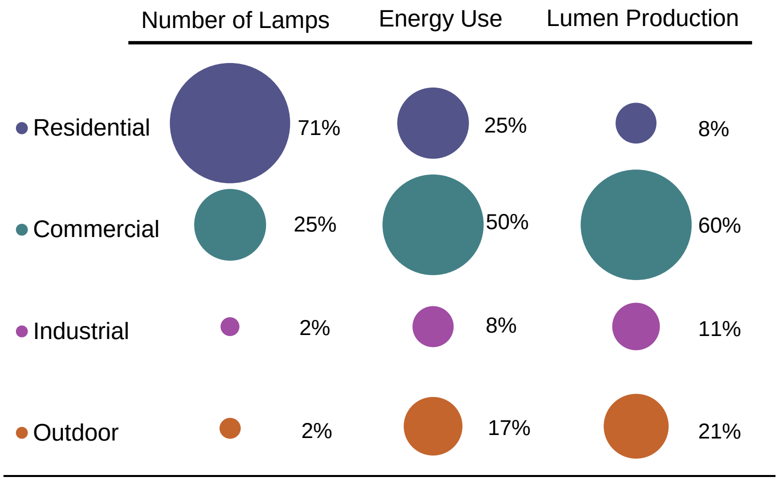

**FIGURE 2.3 U.S. LIGHTING INVENTORY, ELECTRICITY CONSUMPTION, AND LUMEN PRODUCTION, 2010 [1]**
*Source: 2010 U.S. Lighting Market Characterization. Prepared by Navigant Consulting, Inc., January 2012.*

Figure 2.3 shows that although the majority of U.S. lamps are in the residential sector, both light production and energy use are largely influenced by the commercial and outdoor sectors, due to the high output of lighting fixtures coupled with long hours of use [1]. This demonstrates a large potential for energy savings in those sectors, should LEDs displace linear fluorescent and HID lamps.

For 2013, LED penetration in the U.S. installed base was 1.3 percent for indoor and 5.8 percent for outdoor applications. This is described in more detail in Section 2.2. Adoption for indoor applications should increase in 2014, as the ban on 40W and 60W incandescent bulbs takes effect [12]. The trend toward increasing energy efficiency in the U.S. demonstrates that lighting customers are willing to modify their purchasing behavior in the face of compelling economics. The increase in energy-efficient lamps from 2001 to 2010 is illustrated in Figure 2.4 alongside DOE projections for LED penetration in 2030. Overall, DOE projects white-light LED sources to account for 74 percent of lumen-hour sales (roughly 71 percent of unit sales) in the U.S. and save 297 TWh[4] in electricity consumption by 2030 [2].

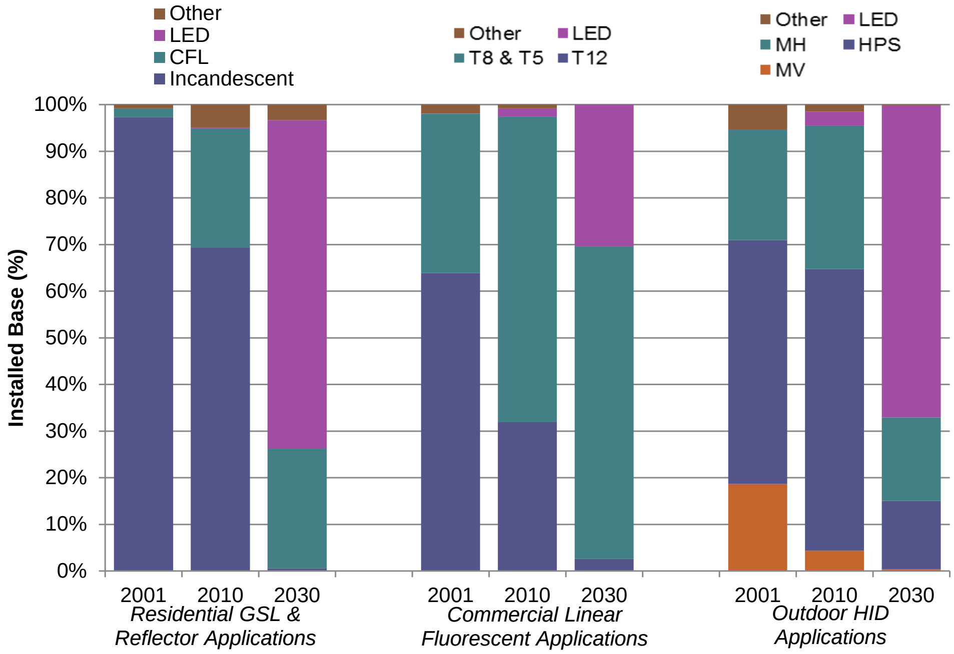

**FIGURE 2.4 U.S. MIGRATION TOWARD ENERGY-EFFICIENT LIGHT [1] [2] [24]**

### 2.1.2 Asia

Within Asia, Japan has been a driving force in purchasing LED lighting products, and leads the globe in terms of relative installations, having an estimated LED adoption rate of 15 percent in 2012 and 19 percent in 2013 [25].

Figure 2.5, from the Chinese Solid State Alliance (CSA), shows that adoption is also accelerating very rapidly in China. In 2013, the penetration of LED-based lighting in China was reported to be 8.9 percent of sales and growing rapidly, as government attention shifts from providing monetary support for investment in capital equipment to providing support for the purchase of lamps and luminaires [26].

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

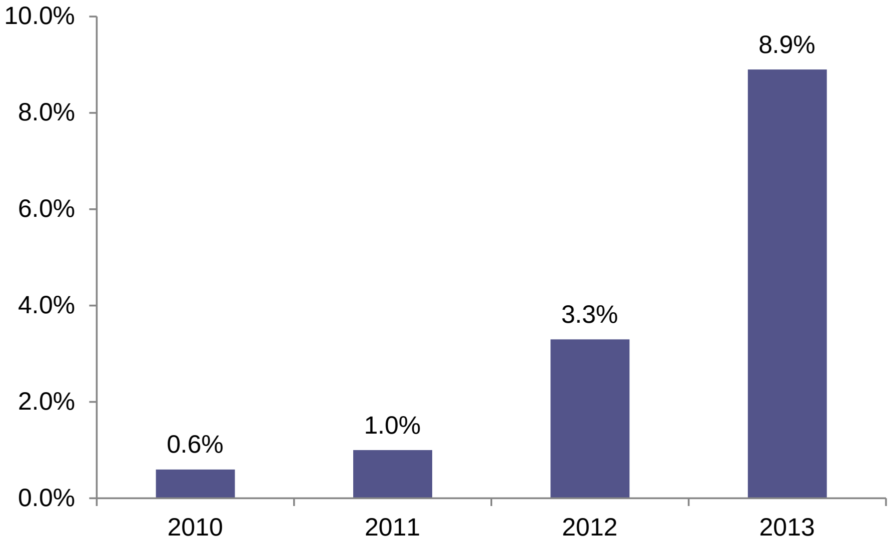

**FIGURE 2.5 MARKET PENETRATION OF LED LIGHTING IN CHINA, 2010-2013 [26]**
*Source: Industrial Data and Development Overview for China Solid State Lighting 2013. Prepared by Department of Industrial Research, CSA, January 2014.*

### 2.1.3 Europe

Penetration of LEDs in Europe has also been growing rapidly, with estimates of 184 million unit sales in 2013 [25]. Substantial market penetration is now expanding from commercial, industrial, and municipal applications into the residential sector. The lighting stock model developed by the Center for Law and Social Policy (CLASP), an international agency promoting the use of energy-efficient appliances, predicts that by 2030, LEDs will provide two-thirds of all non-residential lighting needs, as shown in Figure 2.6. This means that, although lighting demand is expected to increase, the energy use will decrease by 24 percent, leading to annual savings of up to 53 TWh [27].

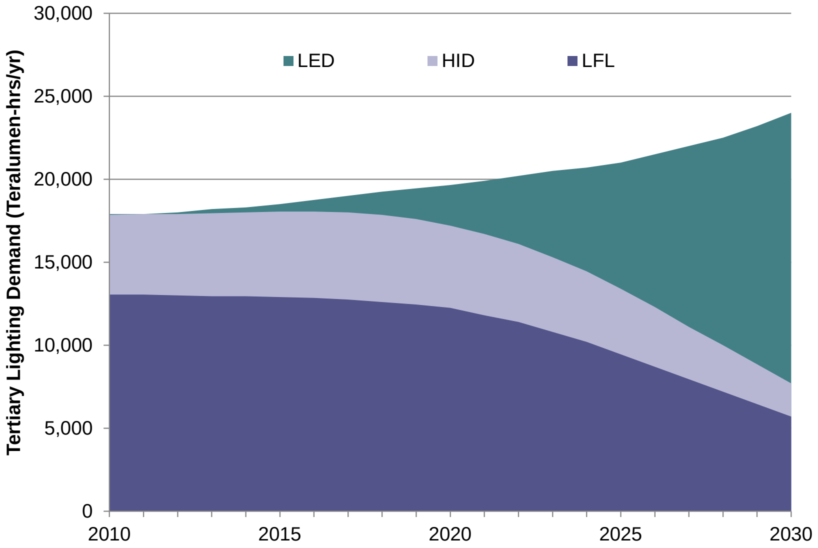

**FIGURE 2.6 EUROPEAN UNION TERTIARY LIGHTING STOCK LIGHT OUTPUT, TERALUMEN-HOURS/YEAR [27]**

*Source: Estimating Potential Additional Energy Savings from Upcoming Revisions to Existing Regulations under the Ecodesign and Energy Labelling Directives - A Contribution to the Evidence Base. Prepared by CLASP, February 2013.*

Note: The tertiary lighting sector refers to street, office, and industrial lighting (fluorescent lamps, HID lamps, and related ballasts and luminaires).

Looking within Europe, Figure 2.7 shows a reduction of about 30 percent in the energy used for residential lighting in the United Kingdom (U.K.) between 2007 and 2011. Increasing adoption of LEDs is expected to result in a further decrease, cutting the annual lighting demand by another 50 percent. Two future scenarios are shown. The “slow” progression assumes that most incandescent lamps will be replaced by halogen lamps until the next stage of European Commission regulation comes into effect in September 2016. The “gone green” scenario shows how the savings are accelerated if residential customers could be encouraged (or required) to switch directly to LEDs [28]. The anticipated rise in energy use after 2020 provides extra incentive for additional improvements in efficacy and greater adoption of lighting controls in all sectors.

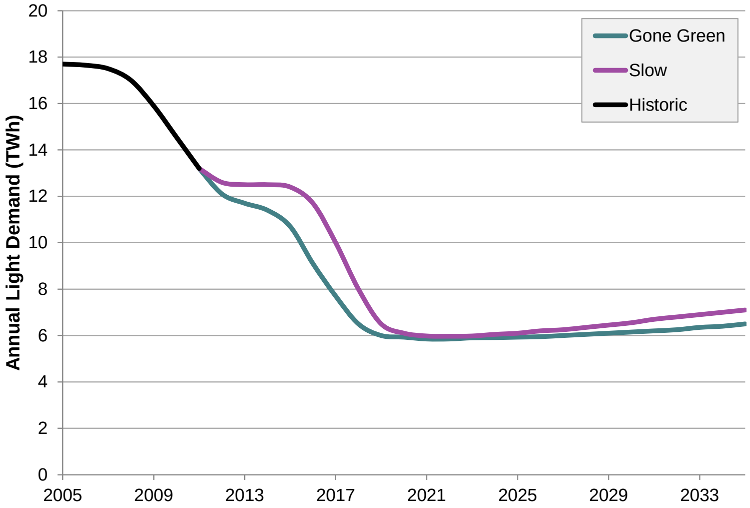

**FIGURE 2.7 U.K. RESIDENTIAL ELECTRICITY DEMAND FOR LIGHTING [28]**
*Source: UK Future Energy Scenarios: UK gas and electricity transmission. Prepared by UK National Grid, July 2013.*

### 2.1.4 Rest of the World

Reductions in lighting electricity use through SSL adoption are expected to provide substantial relief from the pressure for additional power generation in almost all developed economies. In the rest of the world, the major impact of SSL might be to provide high-quality lighting in communities where lighting has previously been inadequate. For example, over one billion people do not have access to the electricity grid and have to rely on candles and kerosene lamps [29]. The resulting light is insufficient for the performance of even simple tasks, with typical illuminance levels of 5 lux or less [30]. The use of these light sources is also dangerous due to the risk of fires and toxicity of the fuel, which contains a high proportion of heavy particulates [31]. For off-grid communities, the development of SSL sources and photovoltaic technology offers a far more affordable solution for electric light sources than developing the grid to deliver electricity.

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

### 2.1.5 Summary

There is a vast global market for SSL products. Most regions of the world, even with government policy support, still have experienced less than ten percent adoption of LED-based lighting products on a unit basis. Increased adoption driven by scientific and technological improvements represents an enormous energy savings opportunity for the world and an enormous market opportunity for LED lighting manufacturers, and component and materials providers.

## 2.2 Applications for Solid-State Lighting

In the U.S., today's LED installed base is over 20 times larger than just three years earlier [7] [32]. While this growth is significant, the performance and quality of modern LED lamps and luminaires has improved even more dramatically. LED-based lighting solutions are constantly evolving and the first iterations of products hardly resemble those on the market today. The rapid innovation of LED technology creates challenges when characterizing the general lighting market; however, DOE makes an effort to profile domestic lighting applications in which LEDs are competitive and well positioned to gain ground against traditional light sources. This analysis is presented in the "Adoption of Light-Emitting Diodes in Common Lighting Applications: Snapshot of 2013 Trend" [7].[5] From 2012 to 2013, it was found that the U.S. installed base of LEDs had increased in all applications, more than doubling to about 105 million units. As the number of LED installations continues to grow, so does the energy savings. Annual source energy savings from LEDs in 2013 more than doubled from the previous year to 188 TBtu, which is equivalent to an annual energy cost savings of about $1.8 billion.

Although these current savings are significant, LEDs have not even begun to scratch the surface of their potential. Future annual energy savings could approach 4,060 TBtu (4.1 quadrillion Btu or quads), if all current general illumination applications switched to LEDs "overnight." Energy savings of this magnitude would result in annual energy cost savings of about $39 billion. Table 2.1 below provides a summary of U.S. installations and associated energy savings from this most recent analysis.

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

**TABLE 2.1 U.S. INSTALLED BASE AND ENERGY SAVINGS OF LED LIGHTING BY APPLICATION [7]**

| Application[1] | 2013 LED Installed[2] Penetration % | 2013 LED Units Installed[2] Millions | 2013 Energy Savings TBtu (TWh) | Energy Savings Potential TBtu (TWh) |
|---|---|---|---|---|
| **A-Type** | 1.1% | 34.2 | 40.5<br>(3.9) | 802<br>(77.3) |
| **Directional** | 3.4% | 33.3 | 79.7<br>(7.7) | 395<br>(38.0) |
| **Small Directional** | 16% | 7.5 | 15.3<br>(1.5) | 71.9<br>(6.9) |
| **Decorative** | 0.7% | 8.3 | 2.3<br>(0.2) | 269<br>(25.9) |
| **Linear Fixture** | 0.7% | 4.9 | 7.3<br>(0.7) | 1,052<br>(101) |
| **Industrial** | 2.1% | 1.8 | 9.2<br>(0.9) | 789<br>(76.0) |
| **Other[3]** | 0.5% | 3.8 | 7.4<br>(0.7) | 178<br>(17.1) |
| **Total Indoor** | **1.3%** | **95.5** | **162<br>(15.6)** | **3,556<br>(342)** |
| **Area/Roadway** | 7.1% | 3.3 | 13.8<br>(1.3) | 256<br>(24.7) |
| **Parking Garage** | 2.4% | 0.8 | 6.5<br>(0.6) | 140<br>(13.5) |
| **Building Exterior[3]** | 7.9% | 4.7 | 5.4<br>(0.5) | 59.3<br>(5.7) |
| **Other[3]** | 2.9% | 0.7 | 1.2<br>(0.1) | 48.6<br>(4.7) |
| **Total Outdoor** | **5.8%** | **9.5** | **26.9<br>(2.5)** | **504<br>(48.6)** |
| **Total All** | **1.4%** | **105** | **188<br>(18.1)** | **4,060<br>(391)** |

Notes:

1. Descriptions of each application group are provided in Appendix 5.2.3.
2. Installations are the total cumulative number of LED lamps and luminaires that have been installed as of 2013.
3. The “other” and “building exterior” applications were not analyzed in 2012.

OLED technology has yet to gain a measurable share of the general lighting market, but the OLED community is making strides toward commercializing products for certain applications. Most OLED prototypes have yet to attain light output levels suitable for many general lighting applications. Initial products have been largely decorative in nature although some OLED products have been developed for task lighting applications, such as desk or table lamps and automotive interior lighting.

### 2.2.1 LED Replacement Lamps

In 2013, replacement lamp applications were responsible for most of the LED lighting market, both domestically and globally [7], with omnidirectional A-type lamps, directional parabolic aluminized reflector (PAR) and multifaceted reflector (MR) lamps comprising 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 [25], largely driven by lighting efficiency standards and regional regulatory phase-outs, as discussed in Section 2.1. In the U.S., it is estimated that LED A-type lamps accounted for about 33 percent of LED lighting installations in 2013, closely followed by LED reflector lamps at about 21 percent [7]. Compared to the A-type, which produces omnidirectional light, reflector lamps provide directional light and are commonly used in recessed can, accent, retail-display, and track-lighting fixtures. In retail-display applications, LED reflector lamps are already installed on a significant scale, which is evident in the high penetration level and large installed LED lamp base observed in these applications. In 2013, growth in the retail-display and commercial markets was primarily fueled by the uptake of LEDs in commercial downlighting applications in Europe and, to a lesser extent, the U.S., Japan, and the rest of the world [33]. Global LED reflector lamp shipments were forecasted to surpass shipments of all other reflector lamp technologies by 2017 and climb to 58 percent by 2020 [25]. While LED A-type and reflector lamps represent the majority of LED installations in the U.S., they still represent less than 2 percent of the total installed stock.

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 impact on regional lighting markets.

### 2.2.2 LED Luminaires

Luminaires are defined as fully integrated lighting products designed to replace an entire fixture (not just the lamp). An example of an LED luminaire would be a fully integrated 2’ X 2’ troffer replacement. In many instances, integrated LED luminaires can have superior performance compared with replacement lamps, since any design constraints imposed by an existing form factor or available space are usually less severe.

Commercial and industrial applications are an important market for LED luminaires as they represent about 30 percent of all lighting installations, but are responsible for well over half of the total electricity consumption for all lighting in the U.S. Conversely, general service replacement lamp applications represent nearly 70 percent of all installations but are responsible for only slightly over 30 percent of the total lighting energy consumption [1]. This distinction is largely due to the high operating hours and light output of luminaire fixtures. Commercial and industrial lighting applications therefore present a significant opportunity for LED luminaires, with the potential to offer significant energy and life-cycle cost savings beyond that of LED lamps. By 2025, the annual energy savings associated with commercial and industrial luminaires is expected to approach 1.25 quads, based on the assumption that they account for half of the total energy savings of 2.5 quads [7].

LED luminaires are a rapidly growing segment of the overall LED lighting market and are beginning to prove themselves as a good choice for a variety of commercial applications including troffer, panel, suspended, strip, pendant lighting, and industrial low- and high-bay fixtures. Although the installed stock of LED luminaires jumped from an estimated 6.5 million units in 2012 to nearly 20 million units in 2013, they still represent only about one percent of all luminaires installed in U.S.

commercial and industrial applications [7] [32]. Assuming the continued performance improvement and decrease in price, LED luminaires could reach close to 15 percent of the installed stock by 2020 [2].

### 2.2.3 Outdoor LED Lamps and Luminaires

Outdoor lighting is another rapidly growing sector for LED luminaires, especially in roadway, area, and parking lot applications. LEDs are competitive in these applications because they offer longer lifetimes, energy savings, and better lumen maintenance than incumbent HID technologies. This drastically reduces costly maintenance and repair and gives LED luminaires a competitive life-cycle cost. Navigant Research estimates that the average maintenance cost of LED luminaires in general outdoor lighting applications is less than half that of their HID counterparts. The installed inventory of LED luminaires in highway, road, and parking lot applications in the 2012 world market was around 2.4 percent. Europe, which constitutes nearly 40 percent of the total global street lighting market with around 90 million installations, has currently less than one-half-million LED fixtures installed in this application [34].

In 2013, DOE estimates that LED luminaires in area, roadway, parking, exterior building, and other outdoor applications accounted for roughly 5.8 percent of the U.S. outdoor installed base[6] [7]. Growth in LED outdoor lighting has continued, with programs such as Los Angeles' LED Street Lighting Energy Efficiency Program leading the charge. With over 140,000 LED streetlights installed in the last four years, this effort is one of the largest LED street lighting retrofits undertaken to date [35]. Each year a growing number of U.S. cities undergo major LED retrofit projects – one of the most recent is for the city of Detroit, Michigan which announced its plan in February 2014 to overhaul the city's entire street lighting system with an installation of over 42,000 LED streetlights [36]. In addition, the DOE SSL GATEWAY program has demonstrated installations of outdoor SSL systems in several areas across the country.[7]

### 2.2.4 OLED Luminaires

Although some early proponents of OLED lighting envisaged large luminous areas, such as OLED wallpaper or OLED curtains, OLEDs are now mostly being used in modular form, as arrays of small panels of area 100 $\text{cm}^2$ or less. These panels can be configured either in two- or three-dimensional forms, offering light sculptures as a new form of architectural lighting. Figure 2.8 shows two examples of OLED luminaires, the Acuity Trilia (left) and Lumen Being (right). In the Lumen Being luminaire, the relative intensity of the individual panels can be varied and controlled by gestures or personal devices, such as smart phones.

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[6] Excludes traffic signal applications.

[7] More information on specific projects is available at: www.ssl.energy.gov/gatewaydemos_results.html.

**FIGURE 2.8 OLED PANEL-BASED LUMINAIRES CONFIGURED AS 2-D (LEFT) AND 3-D (RIGHT) LIGHT SCULPTURES**
*Source: Acuity Brands*

Currently, OLEDs can be difficult to use as the primary source of lighting in a room due to their limited light output and high cost. Many proponents are recommending their use in wall sconces and task lights, for example in desk lamps or under-cabinet lighting, in conjunction with ambient lighting. The low brightness of OLEDs allows them to be placed close to the task surface without being uncomfortable to the user, and improves light utilization. Methods of shaping the OLED light distribution may be required for efficient light utilization at greater distances.

### 2.2.5 Emerging Applications

Although SSL products have made meaningful inroads into the existing lighting market, the fundamental technology underlying SSL offers the promise of expanding the total lighting market through new lighting capabilities and controls. SSL is fundamentally fully and instantaneously dimmable (with appropriately designed power supplies). SSL also has the potential for fully controllable color tuning with the ability to match any desired color point or color quality. These two attributes could enable a vast array of new lighting applications. Some of these new and growing applications for SSL are listed below:

- Spectrally controlled lighting for desired human physiological responses such as lighting to make people more alert or to facilitate sleep
- Spectrally optimized lighting for greenhouse crop growth
- Efficient lighting designed for livestock production
- Lighting spectrally tuned for very specific inspection or enhanced visibility functions

In general, these applications use SSL primarily for the productivity enhancement and will leverage the full spectrum “palette” of colors offered by LED sources, the ability to control these sources in real time, and the general cost-effectiveness of using LED lighting. While the DOE SSL Program is focused on providing efficient, low-cost SSL products with excellent lighting performance, these new applications may be harnessed to further accelerate adoption of energy-saving products for general illumination and may provide energy savings and productivity benefits in applications beyond general illumination. A note of caution is warranted for these new applications, as there is a possibility that some claims of enhanced productivity will outstrip the scientific backing for such claims.

## 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) ensure that LED lighting is highly competitive on a life-cycle basis. A life-cycle cost analysis (LCCA) gives the total cost of a lighting system, including all expenses incurred over the life of the system. The payback period is the time it takes the consumer to recover the higher purchase cost of a more energy-efficient product as a result of lower operating costs. In a commercial setting with long hours of daily operation, this payback period might already be as short as one year.[8]

### 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)** | $16 |
| **CFL 6” Downlight (13W; T4; ~500 lumens)** | $10 |
| **LED 6” Downlight (11.5W; 625 lumens)** | $43 |
| **OLED Panel** | $500 |
| **OLED Luminaire** | $1,400 |

On a normalized light output basis, an A19 LED lamp is currently around seven times the initial price of a halogen bulb and around 60 percent more than the price of an equivalent dimmable CFL. Nevertheless, on a life-cycle basis, an LED lamp reaches cost parity with a halogen lamp after only 1,700 hours (around 18 months at three hours per day). The availability of utility rebates can reduce

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

the price of an A19 LED lamp to as low as $6/klm, creating a 500-hour payback period when compared to a halogen lamp (less than six months at 3 hours per day) and rendering the dimmable CFL largely redundant.

The first OLED products are only now becoming commercially available, and as the table above shows, these products are not yet cost competitive. Although lines designed for volume production are being brought up to full production, yields and throughput are still below planned levels.

### 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 levels. The selected data is based on available datasheets and represents devices in the highest flux bins where this is reported (taking the average value within that bin) or typical flux values for the total available distribution. Chosen devices fall within specified ranges of correlated color temperature (CCT), stated in Kelvin (K), and CRI. In all cases, the price, expressed in units of $/klm, and efficacy, expressed in units of lm/W, have been determined at a fixed current density of 35 amperes per square centimeter (A/cm$^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.

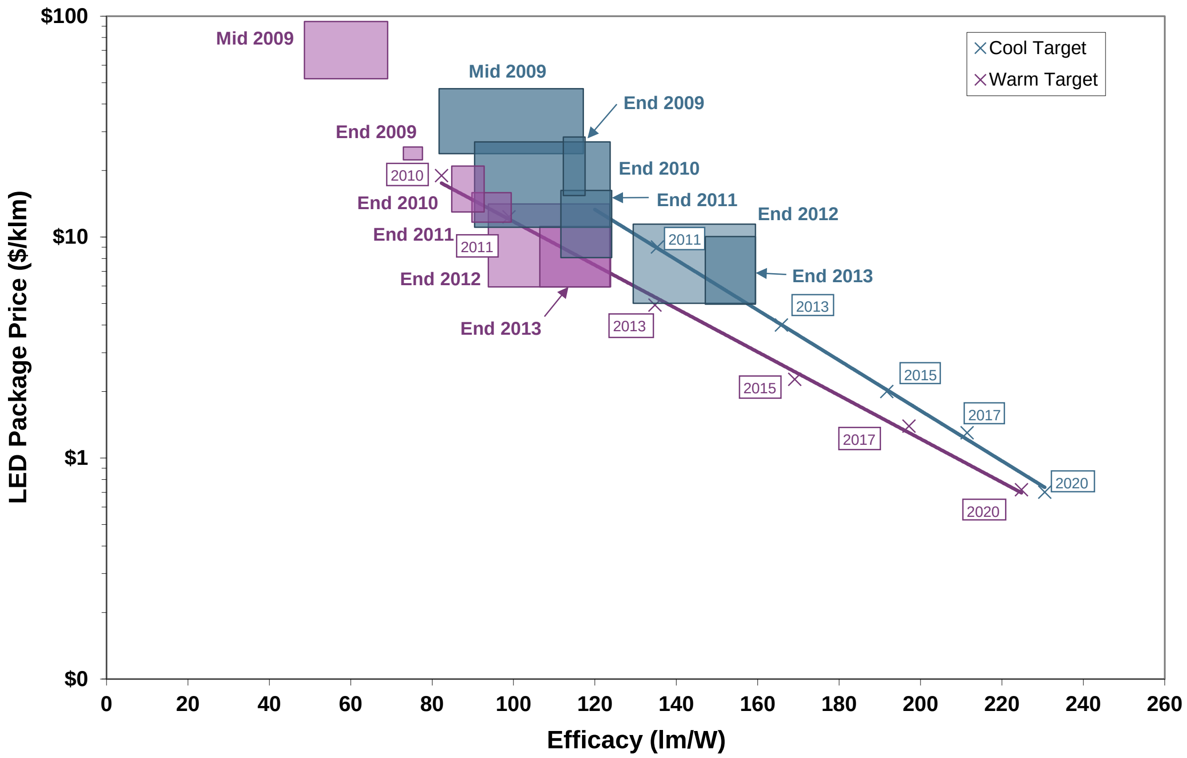

**FIGURE 2.9 PRICE-EFFICACY TRADE-OFF FOR LED PACKAGES AT 35 A/CM$^2$ AND 25°C**

Notes:

1. Cool-white packages assume CCT = 4746-7040K and CRI >70; warm-white packages assume CCT = 2580-3710K 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.

Figure 2.9 charts the evolution of LED package efficacy and price. Each time period is characterized by a rectangle with an area bound by the highest efficacy and lowest price products. Efficacies as high as 159 lm/W (cool white) and 123 lm/W (warm white) have been reported during 2013 as well as prices as low as $5/klm (cool white) and $6/klm (warm white). The MYPP price-efficacy projections are also included in Figure 2.9 for comparison purposes and are summarized in Table 2.4. The values achieved for efficacy and price are beginning to lag the projections and are not achieved simultaneously for the same device. As expected, higher efficacy products continue to demand higher prices, and lower prices correlate with reduced performance. However, while peak efficacy values have not increased significantly over the past year, prices for the highest performing products have continued to fall, and the spread in efficacy values has narrowed.

TABLE 2.3 SUMMARY OF LED PACKAGE PRICE AND PERFORMANCE PROJECTIONS

| Metric | 2013 | 2015 | 2017 | 2020 | Goal |
|---|---|---|---|---|---|
| **Cool-White Efficacy (lm/W)** | 166 | 192 | 211 | 231 | 250 |
| **Cool-White Price ($/klm)** | 4 | 2 | 1.3 | 0.7 | 0.5 |
| **Warm-White Efficacy (lm/W)** | 135 | 169 | 197 | 225 | 250 |
| **Warm-White Price ($/klm)** | 5.1 | 2.3 | 1.4 | 0.7 | 0.5 |

We have chosen to normalize the values used in this and previous reports to a specific current density and operating temperature in order to set projections and track progress. More recently, with the introduction of an ever-widening portfolio of package designs, it has become increasingly difficult to apply this method of normalization. In certain cases, the total die area cannot be accurately determined and in others the required current density cannot be achieved. The definition of a single current density for multi-die packages with mixed die types is problematic. Even where the specified current density can be achieved, it does not always correspond to the optimum operating conditions for that package and often provides a pessimistic indicator of package performance in a real application. For example, Cree reports an efficacy of 200 lm/W for their MK-R product at 1W and 25°C (6500K). The same package has a normalized efficacy of 149 lm/W. Changing the measurement conditions also impacts the normalized price. At 200 lm/W the normalized price is $40/klm but drops to $4/klm at 149 lm/W. A new normalization method needs to be introduced to cater to the different package designs and provide realistic real-word performance.

A more useful normalization method might take account of what is important in a real application, which involves a trade-off between lumen output, efficacy, and price. As the die cost has reduced, it has become more cost effective to operate a larger number of LED packages at lower current densities to achieve higher efficacy at the same lumen output. Lower current densities create less heat and allow for simpler and cheaper packaging to be employed. Mid-power LED packages are a good example. A typical 3535 or 5630 package[9] costs 10 to 15 cents in modest volumes and produces around 30 lumens at 100 mA (300 mW), yielding an efficacy of 100 lm/W at a price in the $3/klm to $4/klm range.

Ultimately, it might be argued that the die area doesn’t matter, because what is important is the number of lumens emitted from a given package emitting area (lm/mm$^2$), the cost of those lumens (lm/$), and the efficacy (lm/W). Further work is required to identify a suitable normalization procedure that can be applied across the whole gamut of package types.

### 2.3.3 LED Lamp and 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 dimmable A19 60W-equivalent (800 lm)

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[9] 3535 and 5630 packages are types of mid-power LEDs with package dimensions of 3.5 mm x 3.5 mm and 5.6 mm x 3.0 mm respectively.

replacement lamp for our projections. Figure 2.10 shows how the lowest 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 2.10 is the current MYPP projection. During 2013 we have continued to see a reduction in prices as manufacturing costs are reduced and competition intensifies. The retail price has dropped to a low of around $13, corresponding to a normalized price of $16/klm, in good agreement with the MYPP projection. Retail prices are projected to fall further during 2014 and approach the $10 range ($12.5/klm), which many believe may be a critical tipping point resulting in widespread adoption of such products in a residential setting. Generous rebates are available from many utilities, which can reduce the retail price to as low as $4.97, or $6/klm, helping to accelerate the adoption of LED-based A19 lamps.

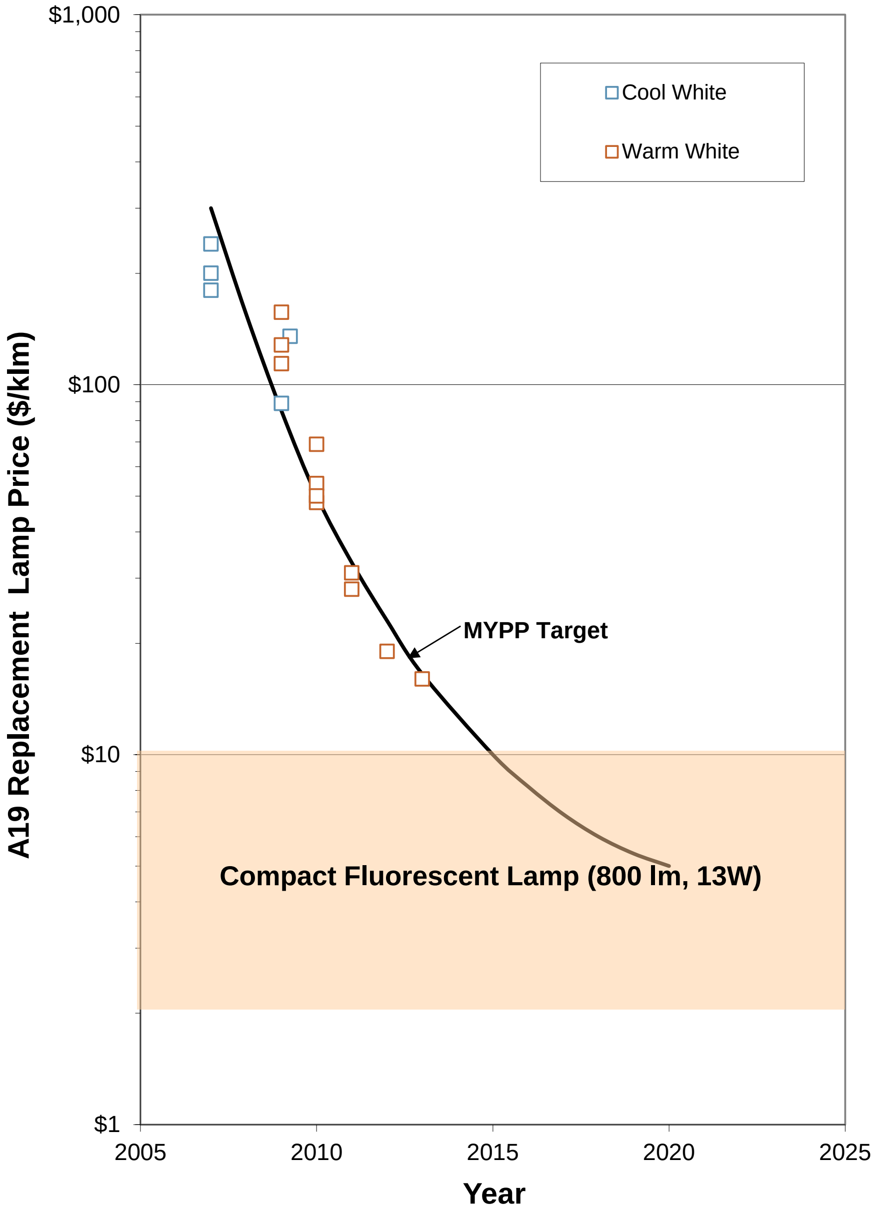

**FIGURE 2.10 A19 REPLACEMENT LAMP PRICE PROJECTION (60W EQUIVALENT; DIMMABLE)**
Note: The shaded region illustrates the price range for a typical equivalent performance CFL (13W, self-ballasted CFL, non-dimmable at bottom, and dimmable at top).

Typical prices for LED replacement lamps over the past two years are summarized in Table 2.5. Prices have continued to fall for each of the lamp types reported in the table, with reductions of between 10 and 20 percent over the last year. For existing product designs, it will become increasingly difficult to achieve further price reductions and new designs are constantly being introduced to realize lower prices while minimizing performance compromises. The energy usage is reduced by around a factor of four for LED-based MR16 and PAR38 lamps and a factor of six 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 2.4 TYPICAL SPECIFICATIONS AND PRICES FOR LED-BASED REPLACEMENT LAMPS**

| LED Lamp Type | Light Output (Lumens) | Power Input (Watts) | Nominal Equivalent (Watts) | Prices ($/klm) | |
|---|---|---|---|---|---|
| | | | | 2012 | 2013 |
| **A19** | 800 | 10 | 60 | 19 | 16 |
| **PAR38** | 900 | 18 | 75 | 44 | 37 |
| **MR16** | 500 | 10 | 35 | 44 | 36 |
| **6” Downlight** | 625 | 11.5 | 65 | 48 | 43 |

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 to 10,000 lumens (i.e., typical replacements for 150W HPS or 175W MH lamps) has dropped from around $150/klm to around $50/klm, and the efficacy has increased from around 50 lm/W to an average of 80 lm/W [37].

As a specific example, the City of Los Angeles replaced 141,089 streetlights between 2009 and 2013 [38]. Over the course of the program, the average price of each light reduced from $432 to $245, while efficacy improved from 42 lm/W to 81 lm/W. Average energy savings are 63.1 percent and carbon emissions have been reduced by 47,583 metric tons a year. Annual financial savings for the city are in excess of $7 million. The smaller size of the LED sources also led to a significant improvement in the distribution of light and much less emission of light into neighboring houses and into the night sky. The lights are proving to be very reliable. The incidence of early failures was reduced from 10 percent, typical of HID lamps, to 0.3 percent. The lumen depreciation of the LEDs evaluated during trials in 2007 has been less than 13 percent over a six-year period.

Due to the efforts of the Municipal Solid-State Streetlight Consortium, even small municipalities can benefit from the experience gained in large cities such as Los Angeles and can install reliable LED systems with payback periods in the range of five to eight years [39].

### 2.3.4 OLED Panel and Luminaire Prices

Although samples of OLED panels have been available since 2009, most have been produced on R&D lines and are very expensive on a $/klm basis. Fabrication lines designed specifically for higher volumes have been built by LG Chem and First-O-Lite, and the main R&D lines operated by OSRAM and Philips have been upgraded to enable commercial production. Prices should drop substantially as these factories move into full production.

The retail prices of luminaires are even higher than for the panels. Decorative luminaires, such as the K-Blade desk light from Riva 1920, which uses a Lumiblade panel from Philips, and the Bonzai from Blackbody, are priced in the range of $3,000/klm to $5,000/klm [40] [41]. More functional luminaires for commercial applications are now priced at around $1,500/klm.

**FIGURE 2.11 K-BLADE AND BONSAI TABLE LAMPS**
*Sources: Riva, Black-Body*

### 2.3.5 Summary

Achieving widespread adoption of SSL lamps and luminaires will depend on the ability to simultaneously satisfy performance and economic requirements. Demonstrating higher efficiency than conventional sources is not enough; the products must also be cost competitive. In this section we illustrate the historical and projected decline in price for LED packages, lamps, and luminaires. On a first-cost basis, LED lamps and luminaires remain more expensive than conventional sources; however, the true economic benefit is only realized when we take account of the reduced operating costs and longer lifetime. A LCCA shows that LED products are becoming increasingly competitive, with payback periods of one year or less in many applications. Conversely, commercial OLED products are in the beginning stages of development and prices remain high; therefore, a LCCA is premature.

## 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. For many applications, LED-based light sources can have a lower total cost of lighting (since consumers would require fewer replacement purchases due to the long life of LED products). However, this requires that SSL sources achieve their lifetime claims. SSL is also a relatively new technology with extreme lifetimes and new failure mechanisms, so the reliability of these products is not well understood. While lumen maintenance is well understood for LED packages, this does not fully describe the anticipated lifetime of the complete luminaire and its full range of possible failure modes. Failure mechanisms such as color shift, optics degradation, power supply failure, and solder detachment, 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 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 inorganic LEDs. 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 $R_9$ values, and a range of CCTs. However, the perception remains that LED lighting products have fundamentally worse color quality than conventional sources. This perception may be based on the very first, low color-quality LED lighting products, or due to the incorrect use of an LED product in a specific 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 allows for full coverage of the visible spectrum; however, red emission in the infrared regime and the lack of efficient, long-life blue emitters limit options in terms of optimizing the trade-off 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 consumer demands.

3. Lighting System Performance: For lighting products, lamps in particular, consumers have come to expect full interchangeability 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 luminance 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.

In order for SSL to reach its full energy savings potential, improvements to more than just efficacy and prices will be required. Enhanced understanding and definition of reliability will improve customer confidence in SSL products, enable more informed engineering trade-offs by manufacturers, and help to convince consumers that more expensive SSL products are worth the extra investment. Understanding and communicating color quality will likewise help to demonstrate the value of SSL products and provide confidence that SSL products can light an area with appropriate and consistent color quality at the time of installation and over the lifetime. Finally SSL products that will work with existing fixtures and dimming circuits will also increase customer confidence and promote the adoption of SSL technology. As we have seen from the introduction of CFL technology, maximizing adoption and resulting energy savings requires more than just providing a more efficient source at a reasonable cost. Consumers must be satisfied with the overall value of the lighting product in addition to the energy savings. For every consumer and lighting application, the relative importance of cost of ownership, first cost, efficacy, color quality, reliability, and lighting system performance will be different, but improvements to all will certainly result in better products, increased adoption, and greater energy savings.

# 3 TECHNOLOGY STATUS

In this section, we consider the factors affecting source efficacy for LED packages and OLED panels, and identify likely practical limits for both technologies. 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 products. This section 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

In general, LED luminaires are already more efficient than incandescent lamps, halogen lamps, and most CFLs, and they are competitive with linear fluorescent luminaires. Initial OLED luminaire products have similar efficacy to that of CFLs 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 luminaires 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 analysis presented in this section has been revisited following solicited inputs from experts as well as discussions at the R&D Workshop regarding the technical challenges of meeting a 250 lm/W goal using different package architectures [42].

The performance of white-light LED packages depends on the basic LED architecture, but also the CCT of the package, the CRI objective, and the spectral power density. 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 (4746K to 7040K) with CRI greater than 70 and the other for warmer CCT (2580K to 3710K) with CRI greater than 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 the principal types of LED package: (i) the color-mixed LED (cm-LED), (ii) the phosphor-converted LED (pc-LED), and (iii) the hybrid LED. The hybrid LED combines one or more monochromatic LED sources with a pc-LED.

#### 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 optical watt. Simulation work by Yoshi Ohno and Wendy Davis at the National Institute of Standards and Technology (NIST) has shown that LED emission spectra with good color quality and LER values in the range of 350 to 450 $\mathrm{lm/W_{optical}}$ can be achieved [43] [44] [45]. If we call the theoretical best value $\mathrm{LER_{max}}$ and LER is the practically achieved result from a light source, then $\mathrm{LER/LER_{max}}$ is the spectral efficiency of a given source. In this section, we have used NIST's model (version 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.

Typical simulated optical spectra for a color-mixed (red-green-blue [RGB] and red-green-blue-amber [RGBA]), phosphor-converted, and hybrid (phosphor-converted plus monochromatic red source) LED are shown in Figure 3.1. The spectrum from a conventional incandescent black-body source is included for comparison. For each spectrum we can optimize the peak wavelengths, spectral widths, and intensities in order to determine $LER_{max}$ for any given color temperature and color rendering index. In this analysis, we have chosen to optimize for a warm-white source with CCT of 3000K, CRI of 85, and $R_9$ greater than zero. Relaxing the criterion for CRI or $R_9$ would result in a higher $LER_{max}$ but would compromise the quality of light.

For theoretical peak performance, once the optimum spectrum and corresponding LER have been determined, we can calculate the theoretical maximum luminous efficacy of the LED. For monochromatic sources the efficacy is determined by multiplying the contribution to LER from each peak in the spectrum by the power conversion efficiency (PCE) of that source. The PCE values used in this analysis assume operation at a current density of 35 A/cm$^2$ and temperature of 25°C. For the phosphor-converted source, it is necessary to integrate over the envelope of the phosphor spectrum with each point multiplied by the down-conversion quantum efficiency and Stokes loss[10]. However, in order to simplify the analysis, we have chosen to represent the phosphor by a single overriding conversion efficiency and a single value for Stokes loss based on the peak of the emission spectrum. This is a rather imprecise assumption because the emission is rather broad and asymmetrical, particularly for the green phosphor; however it should provide a reasonable estimate for our purpose. For the hybrid LED we combine both methods to determine LED efficacy.

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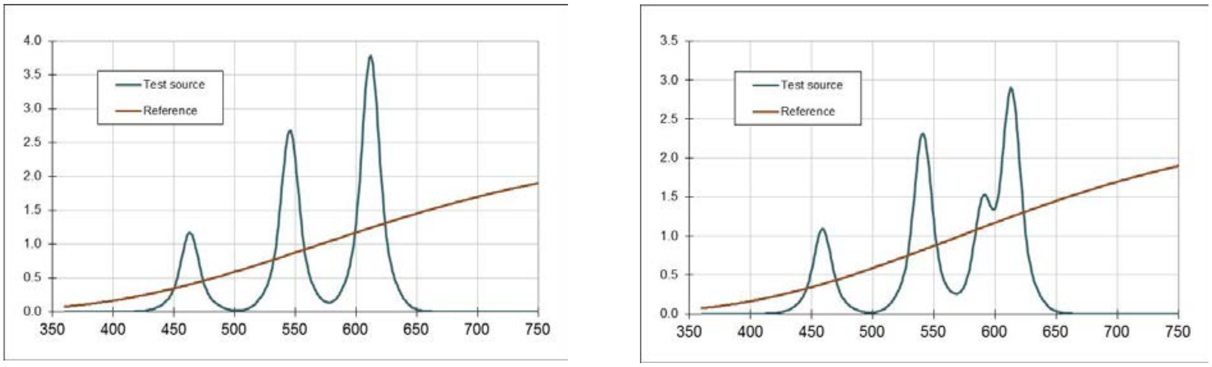
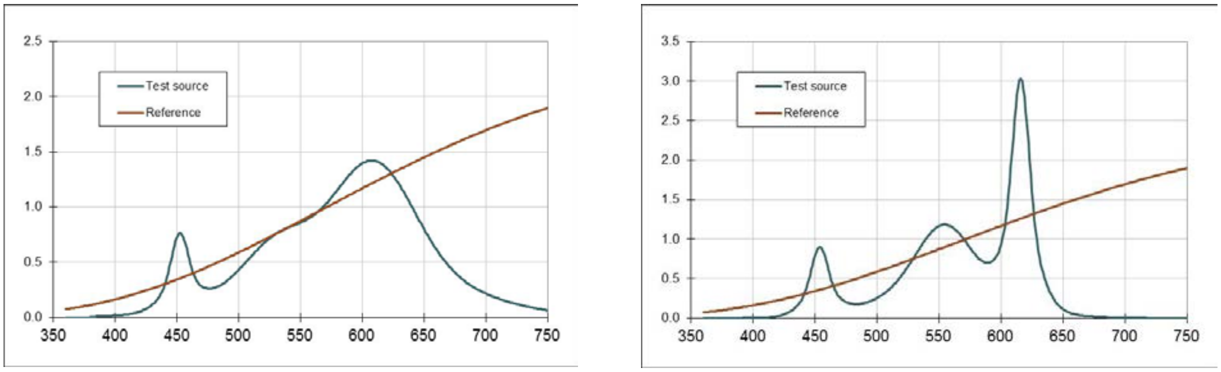
[10] Stokes loss arises from the difference in energy between the absorbed and emitted photons of the phosphor material.



Typical Color-Mixed RGB LED Spectrum

Typical Color-Mixed RGBA LED Spectrum



Typical Phosphor-Converted LED Spectrum

Typical Hybrid LED Spectrum

**FIGURE 3.1 TYPICAL SIMULATED OPTICAL SPECTRA FOR EACH APPROACH COMPARED TO BLACK-BODY CURVE (3000K, 85 CRI, $R_9$>0)**

Table 3.1 and Table 3.2 show the result of the analysis for a cm-LED. An LER of around 400 lm/W is calculated for both a three-color RGB and four-color RGBA spectrum. In each case we have assumed a moderate full width at half-maximum (FWHM) of 20 nanometers (nm) for each source. In order to calculate the luminous efficacy of the source, we require PCE values for the individual monochromatic LED sources. In the tables we have provided two sets of data based on typical current values and on 2020 targets. Using these values, we obtain a current efficacy of 133 lm/W for RGB and 85 lm/W for RGBA. These efficacies increase to 191 and 153 lm/W, respectively, using the 2020 target values. These projections do not include any additional losses for color-mixing. The lower efficacy for an RGBA configuration is primarily due to the low PCE value for the amber source. Increasing the PCE for amber and/or green LEDs to 55 percent to match the target for the red LED would increase the efficacy for both configurations to around 230 lm/W. In order to achieve a target value closer to 250 lm/W, it will be necessary to increase the PCE for red, green, and amber LEDs to 60 percent.

TABLE 3.1 ESTIMATED EFFICACIES FOR AN RGB CM-LED WITH CCT OF 3000K AND CRI OF 85 ($R_9$>0)

| Emissions | Blue LED | | Green LED | | Red LED | |
|---|---|---|---|---|---|---|
| Peak Wavelength (nm) | 463 | | 546 | | 612 | |
| FWHM (nm) | 20 | | 20 | | 20 | |
| PCE (%) | Current | Target | Current | Target | Current | Target |
| | 55 | 80 | 22 | 35 | 44 | 55 |
| LER (lm/W) | 400 | | | | | |
| Efficacy (lm/W) | Current | | | Target | | |
| | 133 | | | 191 | | |

TABLE 3.2 ESTIMATED EFFICACIES FOR AN RGBA CM-LED WITH CCT OF 3000K AND CRI OF 85 ($R_9$>0)

| Emissions | Blue LED | | Green LED | | Amber LED | | Red LED | |
|---|---|---|---|---|---|---|---|---|
| Peak Wavelength (nm) | 459 | | 539 | | 590 | | 615 | |
| FWHM (nm) | 20 | | 20 | | 20 | | 20 | |
| PCE (%) | Current | Target | Current | Target | Current | Target | Current | Target |
| | 55 | 80 | 22 | 35 | 8 | 20 | 44 | 55 |
| LER (lm/W) | 402 | | | | | | | |
| Efficacy (lm/W) | Current | | | | Target | | | |
| | 85 | | | | 153 | | | |

Table 3.3 shows the result of the analysis for a pc-LED. 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 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 three-color LED NIST model, assuming a broader FWHM of 100 nm for the green phosphor and 110 nm for the red phosphor.

**TABLE 3.3 ESTIMATED EFFICACIES FOR A PC-LED WITH CCT OF 3000K AND CRI OF 85 ($R_9>0$)**

| Emissions | Blue LED | | Green Phosphor | | Red Phosphor | |
|---|---|---|---|---|---|---|
| Peak Wavelength (nm) | 454 | | 536 | | 612 | |
| FWHM (nm) | 20 | | 100 | | 110 | |
| | Current | Target | Current | Target | Current | Target |
| PCE (%) | 55 | 80 | - | - | - | - |
| Effective Phosphor Conversion Efficiency (%)[*] | - | - | 44 | 67 | 37 | 56 |
| LER (lm/W) | 316 | | | | | |
| Efficacy (lm/W) | Current | | | Target | | |
| | 123 | | | 189 | | |

[*] *Combining Stokes losses, phosphor quantum efficiency, and PCE of the blue LED pump.*

For a CCT of 3000K and CRI of 85 we obtain a maximum LER of 316 lm/W, resulting in a current efficacy of 123 lm/W. The target efficacy based on a broad phosphor emission is 189 lm/W; however, this target value should be adjusted to reflect projected improvements in phosphor FWHM. For example, a reduction in FWHM for the red phosphor to 50 nm increases LER to 361 lm/W and efficacy to 223 lm/W. Reducing both green and red phosphors to 50 nm increases LER to 375 lm/W and efficacy to 232 lm/W. Further reducing the phosphor FWHMs to our target value of 30 nm yields an LER of 395 lm/W and efficacy of 247 lm/W.

As a practical example, an approximate fit was made to the spectrum reported for a phosphor-converted Luxeon TX package at 3000K and 85 CRI. The best fit used a slightly narrower green phosphor and suggested an LER of around 320 lm/W and an efficacy of 124 lm/W. This latter value is in excellent agreement with a reported efficacy of 122 lm/W at 35 A/cm$^2$.

The lack of a practical narrow red phosphor has prompted the development of a hybrid approach where the red phosphor is replaced by a monochromatic red LED, which has a narrow FWHM in the range of 20 nm. An analysis of the hybrid approach is provided in Table 3.4. The LER in this case is around 368 lm/W, resulting in an efficacy of around 165 lm/W. Based on target values for device performance, the efficacy rises to around 231 lm/W while still relying on a broad green phosphor. Reducing the green phosphor FWHM to our 30 nm target increases the efficacy to 244 lm/W.

This analysis clearly demonstrates the advantages offered by narrow green and red emission spectra and establishes the hybrid approach as a promising alternative in the short term due to the ready availability of a narrow red source. Yet despite the obvious advantages offered by the red LED source, conventional devices based on AlGaInP exhibit very different thermal behavior to the GaN-based blue LEDs, necessitating control systems and adding complexity.

**TABLE 3.4 ESTIMATED EFFICACIES OF A HYBRID-LED WITH CCT OF 3000K AND CRI OF 85 ($R_9$>0)**

| Emissions | Blue LED | | Green Phosphor | | Red LED | |
|---|---|---|---|---|---|---|
| Peak Wavelength (nm) | 460 | | 539 | | 612 | |
| FWHM (nm) | 20 | | 100 | | 20 | |
| | Current | Target | Current | Target | Current | Target |
| PCE (%) | 55 | 80 | - | - | 44 | 55 |
| Effective Phosphor Conversion Efficiency (%)* | - | - | 45 | 68 | - | - |
| $LER_{max}$ (lm/W) | 368 | | | | | |
| Efficacy (lm/W) | Current | | | Target | | |
| | 165 | | | 231 | | |

**Combining Stokes losses, phosphor quantum efficiency, and PCE of the blue LED pump.*

A similar analysis of the three main package architectures has also been performed for cool-white LEDs at 6200K and CRI of 70. This analysis yields an LER of 325 lm/W for a pc-LED using broad phosphors, resulting in a current efficacy of 143 lm/W and target efficacy of 217 lm/W, although it was not possible to obtain a positive value for $R_9$. Reducing the FWHM for the green and red phosphors to 30 nm increases LER to 359 lm/W and increases the efficacy to 241 lm/W ($R_9$ greater than zero). This slightly lower peak efficacy for a cool-white architecture is most likely a consequence of the simplified model being employed.

Due to the small amount of red in these spectra there is a relatively small difference between phosphor-converted and hybrid approaches. The narrower spectrum and slightly higher conversion efficiency associated with a red LED does provide a six to seven percent efficacy advantage for the hybrid approach using current values but there is no significant advantage using target values. It is the reduction in green phosphor FWHM that has the most marked impact on efficacy.

The analysis for a cool-white cm-LED yields an LER of 360 lm/W, a current efficacy of 120 lm/W, and target efficacy of 178 lm/W. As was the case for the warm-white cm-LED, the low PCE for the green LED significantly limits the device efficacy. Increasing the PCE for the green LED to 55 percent to match the red LED source increases the efficacy to 222 lm/W. Increasing both red and green LED PCE's to 65 percent pushes the efficacy up to 250 lm/W.

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

- The hybrid approach offers the highest efficacy in the short term due to the ready availability of narrow red LED sources, although high thermal sensitivity of the red LED creates additional practical problems.
- The phosphor-converted approach can match the hybrid approach provided efficient narrow-band red and green phosphors (FWHM less than 50 nm) can be developed.

- The color-mixed approach will only realize its potential advantage over the phosphor-converted or hybrid alternatives when green and yellow/amber LEDs can be achieved with power conversion efficiencies in the 60 to 70 percent range.
- The maximum projected LED efficacy at 35 A/cm$^2$ and 25°C is around 250 lm/W.

In a practical application, the current density and operating temperature will most likely deviate from the values used to perform the above analyses and this will impact the efficacy. Reducing the operating current to minimize current droop can produce as much as a 15 to 20 percent increase in efficacy. An increased operating temperature, as typically experienced in a lamp or luminaire, will produce a reduction in lumen output and a corresponding reduction in efficacy. Many LED packages are now routinely measured at 85°C to be closer to the device operating temperature and typically exhibit a 10 to 13 percent reduction in efficacy over 25°C operation. Reducing the sensitivity of internal quantum efficiency (IQE) to current density (i.e., current droop) is a significant opportunity for improved efficacy and cost reduction. Similarly, reducing thermal sensitivity of the LED package would allow LEDs to be driven harder and thus emit more light without compromising efficacy. These and other loss channels are described in more detail in the next section.

### LED PACKAGE EFFICACIES

Figure 3.2 summarizes an analysis of the various sources of efficiency loss in a pc-LED package. For each loss channel, Figure 3.2 shows an estimate of the present efficiency and an estimate of the remaining potential improvement to reach the 2020 target (at a package temperature of 25°C and a nominal current density of 35 A/cm$^2$). Package loss channels include some that are intrinsic to the blue pump diode (e.g., electrical efficiency, IQE, extraction efficiency), and others that refer primarily to the phosphor (e.g., conversion efficiency, scattering/absorption efficiency).

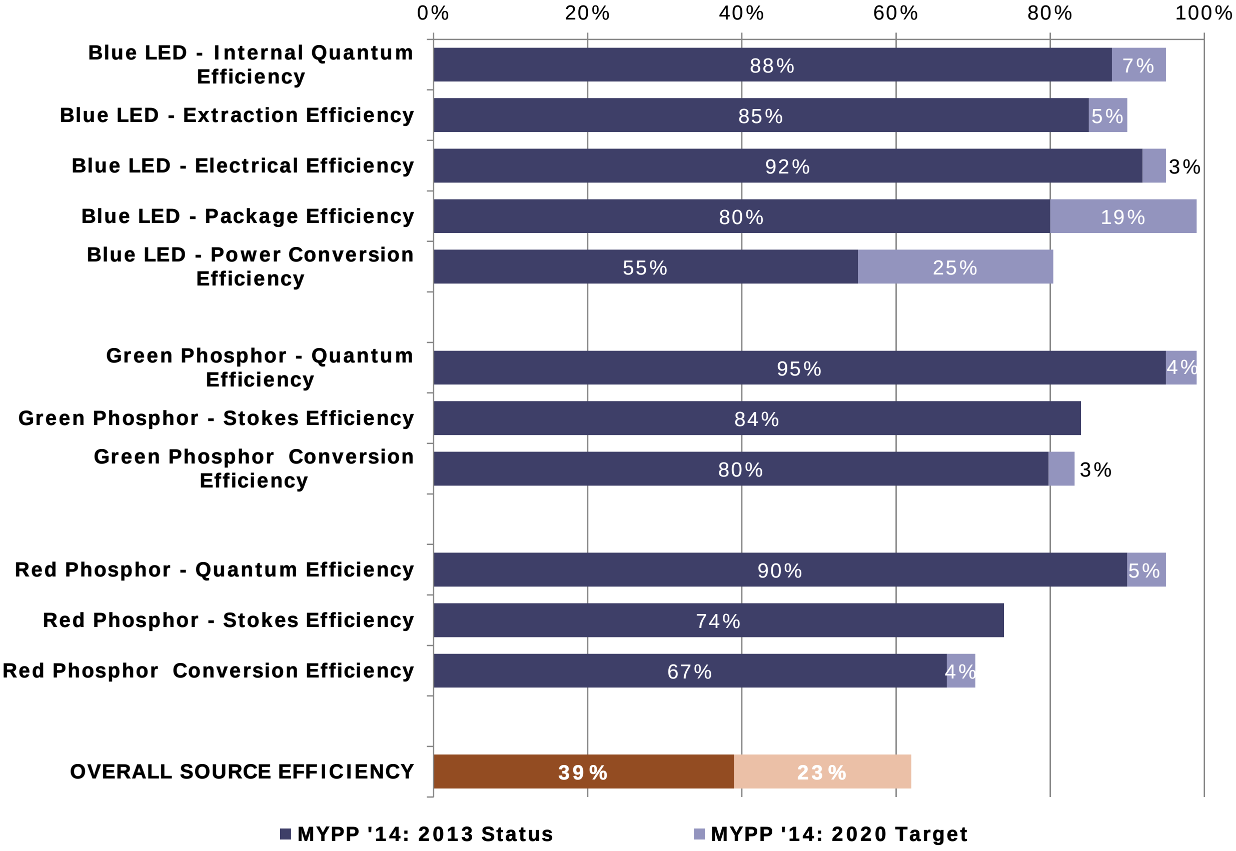


**FIGURE 3.2 WARM-WHITE PC-LED PACKAGE LOSS CHANNELS AND EFFICIENCIES**

Notes:

1. LED package efficiencies are reported at 25°C and 35 A/cm$^2$.
2. The analysis assumes a CCT of 3000K and CRI of 85. Different choices of CCT/CRI will lead to slightly different results.

The efficiencies and efficacy of pc-LEDs are summarized in Table 3.5. Although it is uncertain whether all of these targets can actually be realized in a commercial, marketable product, they suggest that there is significant potential for an improvement over today's LED performance.

TABLE 3.5 SUMMARY OF WARM-WHITE PC-LED PACKAGE EFFICIENCIES AND EFFICACIES

| Metric | | 2013 Status | 2020 Target | Goal |
|---|---|---|---|---|
| **LER (lm/W)** | | 316 | 375 | 395 |
| **Blue LED** | Internal Quantum Efficiency | 88% | 95% | 95% |
| | Extraction Efficiency | 85% | 90% | 90% |
| | Electrical Efficiency | 92% | 95% | 95% |
| | Package Efficiency | 80% | 99% | 99% |
| | Power Conversion Efficiency | 55% | 80% | 80% |
| **Green Phosphor** | Quantum Efficiency | 95% | 99% | 99% |
| | Stokes Efficiency | 84% | | |
| | Conversion Efficiency | 80% | 83% | 83% |
| **Red Phosphor** | Quantum Efficiency | 90% | 95% | 95% |
| | Stokes Efficiency | 74% | | |
| | Conversion Efficiency | 67% | 71% | 71% |
| **Overall Source Efficiency** | | 39% | 62% | 62% |
| **PC-LED Efficacy (lm/W)** | | 123 | 232 | 247 |

Figure 3.3 provides a similar analysis to the above for a cm-LED. The performance is characterized using three colors: red, green, and blue. Although 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 (direct-emitting) LEDs seriously limits the capability of cm-LEDs today.

Because the cm-LED does not suffer from Stokes loss, it is theoretically capable of higher efficacies than the pc-LED, although the benefit may be offset by the need for color-mixing optics. There may also be stability issues for color-mixed luminaires that must be taken into account, as these increase driver complexity and cost. As discussed earlier, other options exist for obtaining different color temperatures or CRI using a hybrid approach. In fact, high-efficacy warm-white luminaires employing this hybrid approach have been on the market since 2009; however, hybrid LEDs also exhibit stability issues.

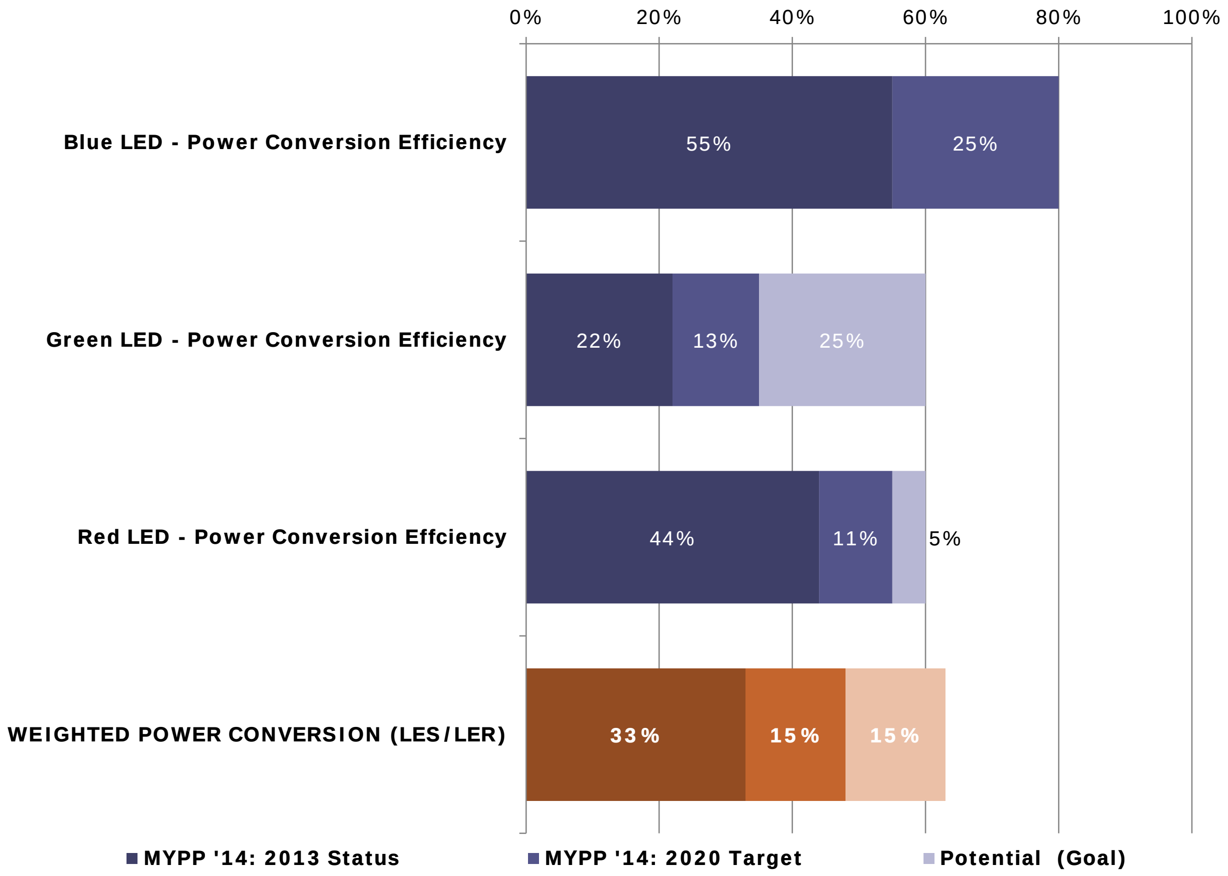


**FIGURE 3.3 WARM-WHITE RGB CM-LED PACKAGE LOSS CHANNELS AND EFFICIENCIES**

Notes:

1. Efficiencies are as typically reported at 25°C and 35 A/cm$^2$.
2. The analysis assumes a CCT of 3000K 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.

Table 3.6 provides an overall summary of the efficiency and resulting efficacy for a cm-LED. Ultimately, a color-mixed approach using narrow line-width sources offers the prospect of the highest possible efficacies. Present performance for the cm-LED is strongly affected by the low efficiency of green and/or amber LEDs, and to meet the goal of 250 lm/W will require very significant advances in PCE for both sources. Reaching this goal may not be possible using existing materials, systems, and designs and, as a consequence, the need for work on innovative approaches remains an important priority. In principle, the 250 lm/W goal can also be met using the phosphor-converted and hybrid approaches, provided sufficiently narrow phosphor sources can be developed. Consequently the development of efficient and stable narrow-band down-converters remains another important priority.

TABLE 3.6 SUMMARY OF WARM-WHITE CM-LED PACKAGE EFFICIENCIES AND EFFICACIES

| Metric | | 2013 Status | 2020 Target | Goal |
|---|---|---|---|---|
| **LER (lm/W)** | | 400 | | |
| **Blue LED** | Power Conversion Efficiency[1] | 55% | 80% | 80% |
| **Green LED** | Power Conversion Efficiency | 22% | 35% | 60% |
| **Red LED** | Power Conversion Efficiency | 44% | 55% | 60% |
| **Weighted Power Conversion (LES/LER)** | | 33% | 39% | 63% |
| **CM-LED Efficacy (lm/W)** | | 133 | 191 | 250 |

[1] See Table 3.5 for a detailed breakdown of efficiency channels.

### 3.1.2 OLED Panel Efficacy

Highly efficient, large-area prototype OLED panels have been recently demonstrated. Konica Minolta has shown a 15 cm$^2$ panel with an efficacy of 131 lm/W at 1,000 cd/m$^2$ and 118 lm/W at 3,000 cd/m$^2$ [46]. Panasonic has successfully scaled their technology to an area of 25 cm$^2$, achieving efficacy of 112 lm/W at 1,000 cd/m$^2$ and 98 lm/W at 3,000 cd/m$^2$ [47]. Lumen maintenance (L$_{50}$) for both panels is acceptable at 55,000 hours for the Konica Minolta panel and over 100,000 hours for the Panasonic panel when operated at 1,000 cd/m$^2$.

These high-efficacy prototypes are promising, but 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. The availability of high-efficacy panels has allowed luminaire manufacturers such as Acuity to focus on improvements in color quality and lifetime, offering CRI of 89, CCT at 3000K, and lumen maintenance (L$_{70}$) at 18,000 hours from 3,000 cd/m$^2$. Progress has also been made on reducing panel-to-panel color variations to around four standard deviations in color matching in luminaires with multiple panels.

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

#### SPECTRAL EFFICIENCY

The relatively broad line-width of red emission from OLEDs makes it difficult to achieve excellent color quality and high efficacy simultaneously. Figure 3.4 shows the values of LER and CRI for three OLED spectra. With a typical line-width for the red emitter, a peak below 600 nm gives high LER but CRI below 90, whereas a peak above 600 nm gives high CRI with lower LER. In the spectrum shown in the center, the main red peak has been narrowed, perhaps due to interference effects in the organic stack, but a secondary peak has been introduced around 660 nm. This gives good color quality with less decrease in LER.

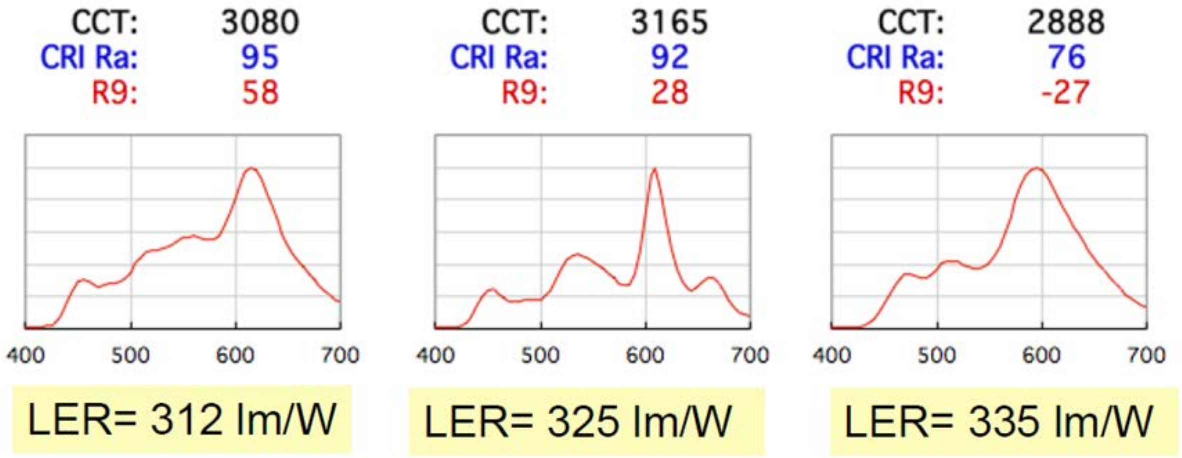


**FIGURE 3.4 EMISSION SPECTRA FROM OLED PANELS [48]**
*Source: Yoshi Ohno, 2013*

### 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:

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

Under ideal conditions, the minimum drive voltage required to enable the spectrum to be extended to approximately 450 nm in the blue region is approximately 2.8 volts (V). The drive voltage must also be sufficient to produce the desired current density, which is a few mA/cm$^2$ for a single-stack device. Toshiba has produced luminance of 1,000 cd/m$^2$ in their 70 millimeter (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 less than five percent at 3,000 cd/m$^2$.

The electrical efficiency can be improved through the use of tandem structures because the conductivity of the various organic materials can be adjusted so that the voltage drop across the lower energy emission layer is less than that of the blue. In the Panasonic panel with a two-stack structure, luminance of 1,000 cd/m$^2$ is achieved at 5.5 V and 3,000 cd/m$^2$ is obtained at 6.0 V, leading to an improvement in electrical efficiency of about 15 percent. First O-Lite has reported luminance of 1,320 cd/m$^2$ from a triple stack with a drive voltage of 7.4 V, demonstrating an electrical efficiency of over 90 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 LG Chem's achievement of $L_{70}$ at 18,000 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 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 stable blue fluorescent emitters with lower IQE are combined with red and green phosphorescent molecules. Recent experiments have suggested that this leads to an IQE of about 75 percent. In fluorescent emitters with small singlet-triplet separations, thermally activated up-conversion of triplet to singlet states may yield delayed fluorescence, resulting in higher IQE; however, it is too early to know whether this phenomenon can be exploited to give systems with high efficacy and long lifetime.

### EXTRACTION EFFICIENCY

Extraction efficiency is the ratio of visible photons emitted from the panel to the photons generated in the emissive region. Absorption and trapping of photons in the electrodes, transparent substrate, and inner layers lead to reductions in light extraction efficiency and account for the largest efficiency losses in OLED panels. For simple OLEDs, the fraction of light emitted to air is typically in the range of 20 to 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 several 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
- Bend the light towards the normal through the inclusion of micro-lens arrays or patterned interfaces between layers of different refractive index
- Add scattering centers or rough interfaces so that light makes many attempts to escape, each time at a different angle
- Reduce surface plasmonic losses at the metal/organic interface by reducing the coupling of light into surface plasmon modes (e.g. increasing the distance between the emitter and the

metal electrode, horizontally oriented dipoles), making metal-free devices, or Bragg scattering the surface plasmon polariton modes into visible light with texturing at the interface

- Reduce Fresnel reflections by using graded refractive index schemes

Research along these lines has been mostly responsible for the improvement achieved in laboratory devices during the past two years, but many of the proposed solutions do not seem compatible with inexpensive manufacturing of large panels.

### TRADE-OFFS AGAINST COST REDUCTION AND FLEXIBILILTY

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 3.7, which shows solution processed results in the last row. The rate of lumen depreciation of red and green emitters has been reduced to acceptable levels, but significant improvements are necessary for phosphorescent blue emitters.

This shortfall in efficacy has delayed the introduction of OLEDs on flexible substrates and the application 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 RECENT OLED PROGRESS

Table 3.7 summarizes some of the laboratory results reported since the last year’s update of this MYPP document.

**TABLE 3.7 OLED LABORATORY PANELS REPORTED IN 2013 AND 2014**

| Developer | Efficacy (lm/W) | Luminance (cd/m$^2$) | Area (cm$^2$) | CRI (Ra) | CCT (K) | L$_{70}$ (1000 hours) | Drive (V) |
|---|---|---|---|---|---|---|---|
| **Konica Minolta** | 131<br>118 | 1,000<br>3,000 | 15 | 82 | 2800 | 27.5[1] | |
| **SEL/Sharp** | 113<br>105 | 1,000<br>5,000 | 81 | | 3270 | 400[1] | 8[3]<br>8.4[3] |
| **Panasonic** | 110<br>98 | 1,000<br>3,000 | 25 | 81 | 2600 | 40<br>10 | 5.5[2]<br>6.0[2] |
| **UDC** | 70<br>60 | 1,000<br>3,000 | ~200 | 85<br>86 | 3030<br>2880 | 165<br>25 | 7.1[3]<br>7.8[3] |
| **LG Chem** | 82 | 3,000 | 16[4] | 84 | 2900 | 30 | 8.5[3] |
| **CDT/Sumitomo** | 56<br>48 | 1,000<br>3,000 | 13 | 80<br>82 | 2900 | | 4.3[5]<br>4.8 |

Notes:

1. Scaled from data provided for L$_{50}$ assuming L$_{50}$ is two times L$_{70}$
2. Tandem device producing two photons per injected electron
3. Triple stack device producing three photons per injected electron
4. This technology has been scaled up to yield similar performance in 76 cm$^2$ panels.
5. Single-stack device with solution processed layers up to the emissive layer and an evaporated ETL/cathode

Table 3.8 provides estimates of the efficiency factors for three types of panels operating at 3,000 cd/m$^2$.

**TABLE 3.8 COMPONENTS OF OLED PANEL EFFICACY**

| Metric | LG Chem[1] | Panasonic[2] | CDT/Sumitomo[3] |
|---|---|---|---|
| **Electrical Efficiency** | 80% | 75% | 46% |
| **Internal Quantum Efficiency** | 75% | 85% | 72% |
| **Extraction Efficiency** | 42% | 50% | 46% |
| **Spectral Efficiency** | 90% | 85% | 89% |
| **Panel Efficiency** | 23% | 27% | 14% |
| **Panel Efficacy (lm/W)** | 82 | 98 | 48 |

Notes:

1. A hybrid triple stack with fluorescent blue emitters and phosphorescent red and green
2. A double stack with all phosphorescent emitters
3. A single stack with polymer/oligomer emitters

Figure 3.5 shows OLED loss channels and compares state-of-the-art performance to the program goal indicating how much improvement might be possible. The values for 2013 refer to the LG Chem laboratory panel, with a triple stack giving an efficacy of 82 lm/W, as shown in Table 3.8. The goal corresponds to an LER of 360 lm/W and a panel efficacy of 190 lm/W.

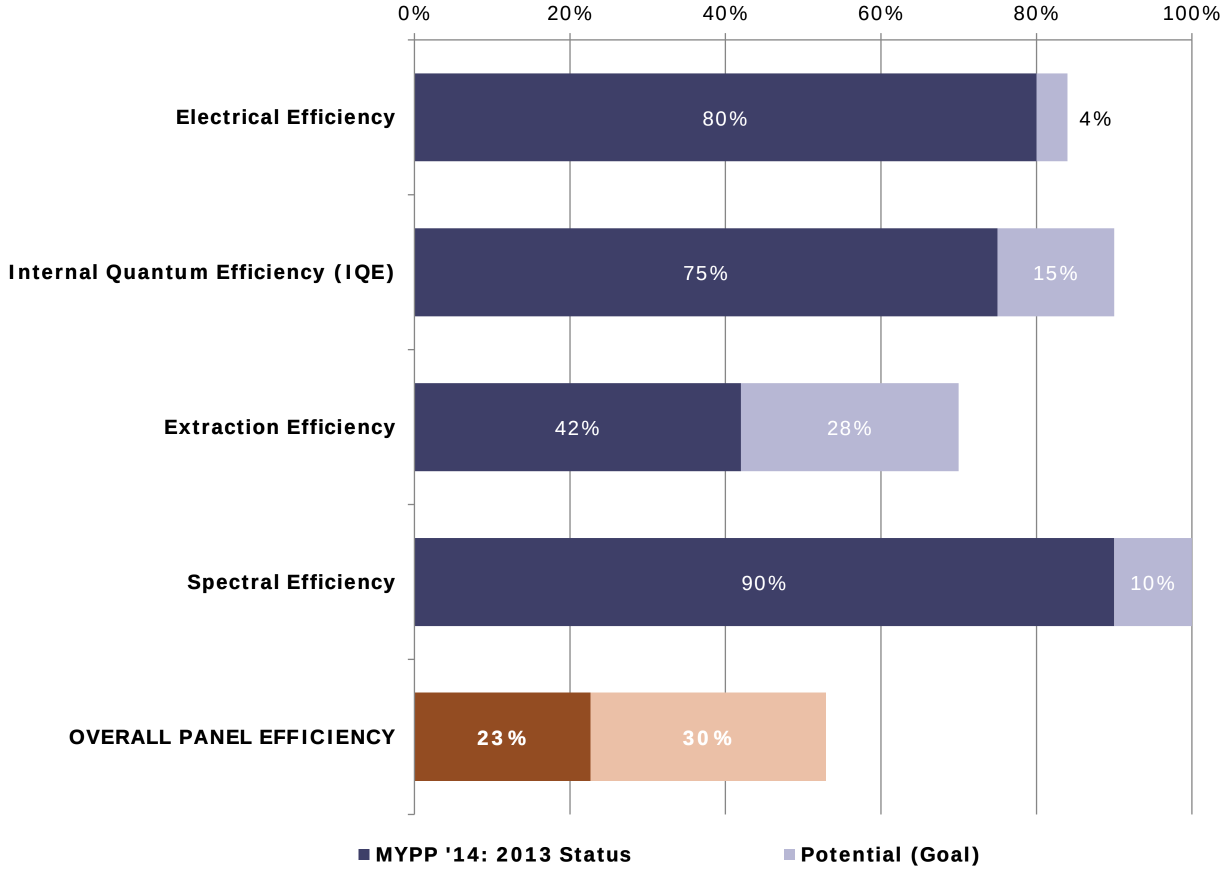


FIGURE 3.5 OLED PANEL LOSS CHANNELS AND EFFICIENCIES

## 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 3.6 shows projected efficacies for LED sources compared to high-efficiency HID and linear fluorescent sources. As shown in the figure, LED products are expected to surpass the efficacy of the most efficient conventional lighting technologies within a few years and are projected to reach efficacy levels of greater than 200 lm/W within a decade. Table 3.9 compares the current performance of some SSL luminaire products with conventional lighting technologies. Projections for the efficiency breakdown of LED and OLED luminaires are provided in Table 3.10 and Table 3.11, respectively. These figures and 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, which vary according to 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 2700K to 6500K 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.

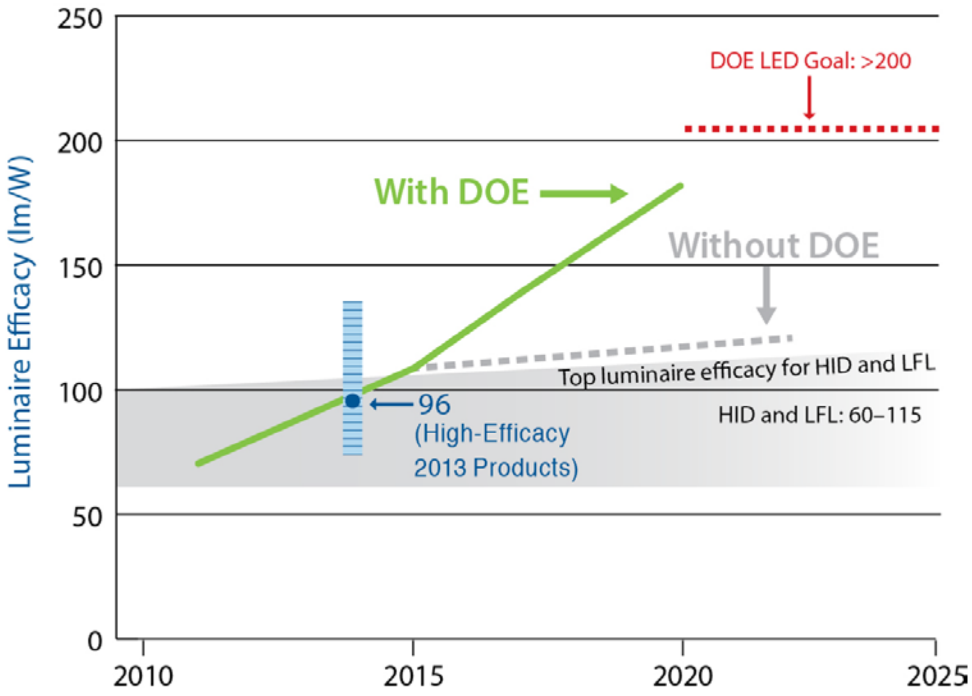


**FIGURE 3.6 COMPARISON OF SSL AND INCUMBENT LIGHT SOURCE EFFICACIES**

*Source: LED Lighting Facts Product Database*

TABLE 3.9 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 6” Downlight (Warm-White)[3]** | 87 | 3500 | 60,000 |
| **LED Troffer 2' x 4' (Warm-White)[4]** | 131 | 3000 | 75,000 |
| **LED High/Low-Bay Fixture (Warm-White)[5]** | 119 | 3500 | 75,000 |
| **OLED Luminaire[6]** | 52 | 3500 | 15,000 |
| **HID (High Watt) System[7]** | 115 | 3100 | 15,000 |
| **Linear Fluorescent System[7]** | 108 | 4100 | 25,000 |
| **HID (Low Watt) System[7]** | 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 database for Cree LRP38-10L-30K lamp.
3. Based on Lighting Facts database for Hubbell Lighting Prescolite LB6LEDA10L35K WH.
4. Based on Lighting Facts database for Cree CS24-40LHE-30K luminaire.
5. Based on Lighting Facts database for Cree CS18-80LHE-35K luminaire.
6. Based on Acuity Brands luminaires.
7. 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 3.7 and Table 3.10. The overall system can be particularly sensitive to thermal management. Because 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, and 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 this further. For example, some streetlight designs have integrated specific lens functionality into the primary optic/encapsulant of the LED package, thereby removing the secondary optic and eliminating optical losses at the additional interfaces.

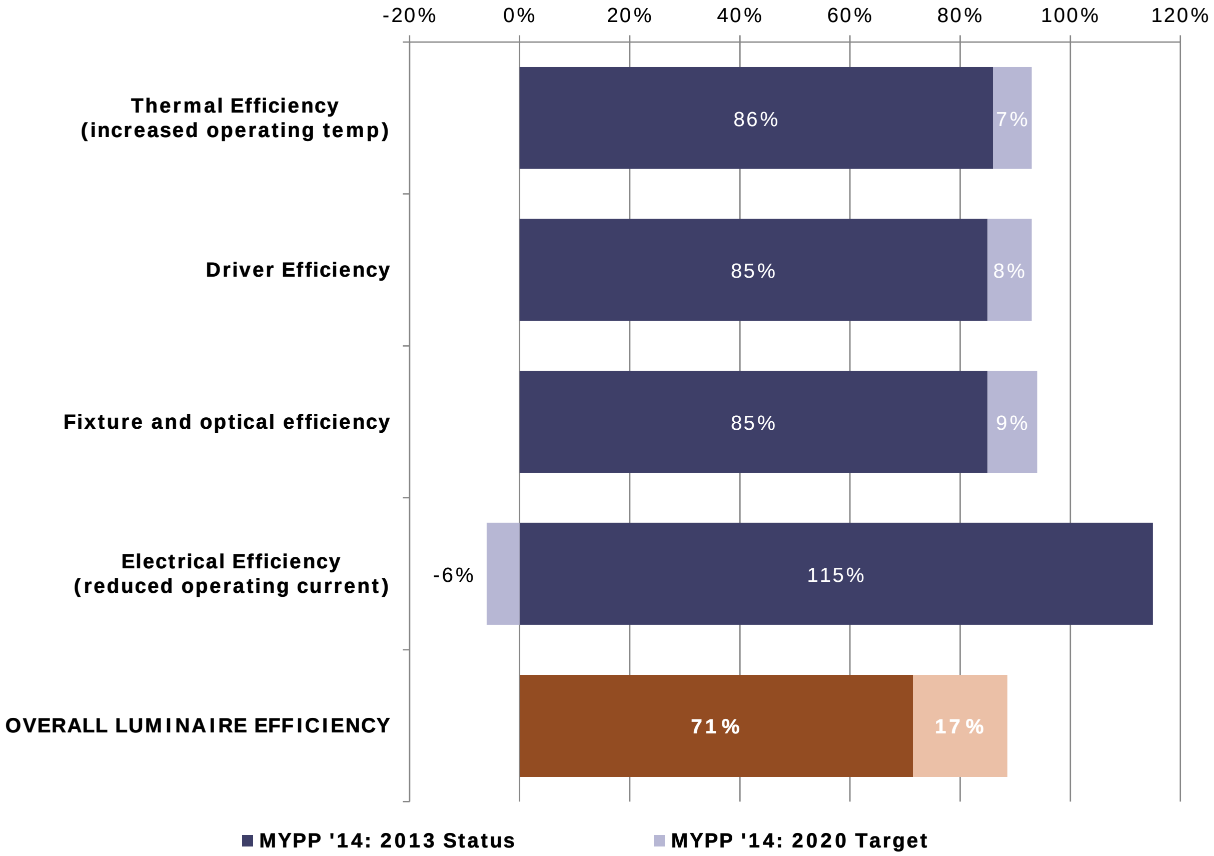


FIGURE 3.7 LED LUMINAIRE EFFICIENCY FACTORS

**TABLE 3.10 BREAKDOWN OF WARM-WHITE[1] LED LUMINAIRE EFFICIENCY PROJECTIONS**

| Efficiency Channel | 2013 | 2015 | 2020 | Goal |
|---|---|---|---|---|
| **Package Efficacy Projection[2] (lm/W)** | 135 | 169 | 225 | 250 |
| **Thermal Efficiency (increased $T_{op}$)** | 86% | 88% | 93% | 95% |
| **Driver Efficiency** | 85% | 87% | 93% | 96% |
| **Fixture/Optical Efficiency** | 85% | 89% | 94% | 96% |
| **Electrical Efficiency (reduced $I_{op}$)** | 115% | 113% | 109% | 105% |
| **Overall Luminaire Efficiency** | 71% | 77% | 89% | 92% |
| **Luminaire Efficacy[3] (lm/W)** | 96 | 130 | 200 | 230 |

Notes:

1. Warm-white packages and luminaires have CCT = 2580-3710K and CRI>80.
2. Package efficacy projections are for the warm-white, pc-LED, per Figure 4.1.
3. Luminaire efficacy is obtained by multiplying the resultant luminaire efficiency by the package efficacy.

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.

The driver 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(s). If a luminaire is dimmable, the power supply must also be able to convert the dimmed input into an appropriately dimmed LED output. The efficiency of the power supply 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.

The electrical efficiency refers to the benefit obtained by driving the LED package at a lower current density to minimize droop, giving an approximate 15 percent boost over the 35 $A/cm^2$ current density. Reduced operating currents can also help improve the thermal efficiency of the luminaire, although the larger number of packages required generally has a cost implication. System-level optimization of the various trade-offs can lead to higher efficacies than those suggested in Table 3.10.

Example OLED luminaires are shown in Figure 3.8. In luminaires that are available commercially at this time, the only additional efficiency loss arises in the driver, which leads to a loss of around 15 percent. Panel efficacies are computed at operating temperature, which is usually just a few degrees above ambient. No exterior optics are added, so that the light distribution remains close to Lambertian. Thus, the efficacy of the luminaire is approximately 85 percent of that of the panel. We assume that the efficiency of OLED drivers will improve along with that of LEDs, but with a two-year time lag.

In future applications, beam shaping may be required to focus the light where it is most needed or to avoid glare. It seems unlikely that this will be accomplished within the panel, so that exterior optical elements may be needed in the luminaire.

The anticipated evolution of luminaire efficiency is shown in Table 3.11. The optical losses will depend on the application, so that the value in the table represents an average.

**TABLE 3.11 BREAKDOWN OF OLED LUMINAIRE EFFICIENCY PROJECTIONS**

| Metric | 2013 | 2015 | 2020 | Goal |
|---|---|---|---|---|
| **Panel Efficacy[1] (lm/W)** | 60 | 100 | 160 | 190 |
| **Optical Efficiency of Luminaire** | 100% | 100% | 90% | 90% |
| **Efficiency of Driver** | 85% | 85% | 90% | 95% |
| **Total Efficiency from Device to Luminaire** | 85% | 85% | 81% | 86% |
| **Resulting Luminaire Efficacy[1] (lm/W)** | 51 | 85 | 130 | 162 |

Notes:

1. Efficacy projections assume CRI >80, CCT 2580-3710K.

The effective efficiency of a luminaire is also affected by light utilization, which represents how well the generated light from the luminaire reaches the target application and provides suitable illumination. 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 lamps, to those that maximize application efficiency as well as optical, electrical, and thermal efficiency.

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.

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 energy efficiency and match the lighting performance of existing conventional lighting technologies, but also add significant value. SSL luminaires can add value in terms of color quality and control, integration with lighting controls, and form factors for enhanced lighting application and building design. Adding these features to LED and OLED luminaires will help enable consumers to accept the cost of SSL products and embrace the full potential (including energy savings) of this lighting technology.

FIGURE 3.8 OLED LUMINAIRES FROM ACUITY, SELUX, AND TAKAHATA ELECTRONICS

## 3.3 SSL Reliability and Lifetime

Apart from being highly efficacious, SSL products may provide useful light output for a very long time in comparison with conventional lighting technologies. At this time there is insufficient information about OLED behavior over long periods of operation, but there is every indication that this promise will be fulfilled by many LED products. Life testing of the DOE L-prize-winning A-lamp from Philips has continued, and as of late April 2013, the lamps showed no signs of degradation after more than 25,000 hours of operation at an elevated temperature [49]. However, this is one of the best products currently available, and other available products do exhibit early failure. Some may lack proper thermal management, use poor materials, or have other flaws, but our understanding of the reasons for failure is still incomplete.

For products with lifetimes of many years, even decades, failures may be very slow to appear under normal operation. Therefore, detecting these failures in the laboratory is very difficult, but it is important to understand and to be able to estimate useful product life. LED products are generally more expensive than their traditional predecessors, so the ability to recover the first cost over the life of the product is important to consumers. Once the first cost of the product is recovered, operation of the LED product will offer energy savings compared to conventional technologies for the remainder of its useful life. This is a key advertising point to encourage the adoption of LEDs.

Our knowledge of failure mechanisms has advanced, but is not complete. Previously it was thought that the degradation of lumen output of the LED source itself would be the determinant of lifetime of completed products. The LED package useful life is often cited as the point at which the lumen output has declined by 30 percent, referred to as 70 percent lumen maintenance or $L_{70}$. In 2008, the Illuminating Engineering Society (IES) published IES LM-80, an approved method for measuring the lumen maintenance of solid-state (LED) light sources, arrays, and modules [50]. As integrated lamps and luminaires appeared on the market, it was at first assumed that one could carry over the LM-80 test data on the sources to the entire product. Now, after further research, it is thought that electronic or driver failures, or degradation of optical components, may occur long before LED lumen depreciation results in failure. Especially when driven at lower drive currents or operated at lower temperatures, lumen depreciation can be slow to reach 30 percent. Many researchers have put a great deal of effort into devising a way to project the time at which $L_{70}$ will be reached, and IES has documented a forecasting procedure, IES TM-21 [51]. This technical memorandum stipulates that the projections may not exceed a set multiple of the actual hours of testing data taken, which helps avoid exaggerated claims. An approach similar to IES LM-80 is also being developed for an entire lamp or luminaire product; however, while lumen depreciation may be difficult to measure in the packaged LEDs, it may be nearly impossible or perhaps prohibitively expensive and time-consuming to do so in complete products. Furthermore, lumen depreciation may not even be the dominant failure mechanism in complete products, as there are many other potential failure modes.

Components and subsystems such as the drivers, optical lenses, or reflectors can fail independently of the LED package. Apart from assembly or material defects, which cause a small probability of random short-term failure, eventual failure of attachments, optical, electrical, or other materials and components may occur under normal operation before the light source. Additionally, overheating caused by poor luminaire design can shorten the life of an LED package dramatically, and moisture incursion can be an important mechanism of failure and determinant of life for an outdoor luminaire. 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 conventional commercial lighting products, an early failure rate due to defects in manufacture or installation of perhaps ten percent of product may be acceptable. However, with the higher prices of LED products, customers expect a much lower early failure rate (where even one percent may be too high) in addition to a longer useful life.

The LED Systems Reliability Consortium (LSRC), sponsored by DOE and the Next Generation Lighting Industry Alliance (NGLIA), is a group of industry, academic, and government representatives with the objective of advancing our knowledge of the failure and lifetime of LED systems (e.g., luminaire, lamp, and light engine). In 2011, the consortium published "LED LUMINAIRE LIFETIME: Recommendations for Testing and Reporting (second edition)," which, taking all failure mechanisms into consideration, provides a working definition of luminaire lifetime and identifies testing that might be necessary to provide a useful estimate of life [52]. The publication concludes that measuring full luminaires, though required in principle, is prohibitively expensive. The document strongly recommends that industry cooperate to develop accelerated tests at the materials, component, or subsystem level, along with suitable means to simulate full system failure rates. Under the Core Technology Research program, DOE awarded funding to Research Triangle Institute (RTI) to begin testing products to determine failure modes and develop software approaches to simulate failure rates. Subsequently, RTI has partnered with the LSRC to make available additional product testing, provide suggestions for experimental design, and assist in interpreting the results and progress. Product testing under conditions of very high stress, intended to accelerate the occurrence of failures, has proceeded over the past two years, providing new insight into the likely nature of eventual product failure in the field under normal operation. A report by RTI summarizing the results of this testing was recently posted on the DOE SSL website [53].

It is the intention of the LSRC to continue this work, and additional tests are now being defined to further investigate failure mechanisms specific to lighting. Testing has increased concern about color shift in limiting the useful life of certain classes of products and applications where color is important. Accordingly, more emphasis will be placed on understanding the causes for color shift, which may result from the LEDs or from optical components or materials, and trying to find means to predict how it may affect performance. Discussions of how simulations to predict useful life may be derived from testing of materials and components are also ongoing. The LSRC plans to publish a third version of their "Recommendations" document later this year, updating our understanding of useful life and providing new testing and reporting recommendations.

Progress on understanding OLED lifetime has been impeded by the absence of significant product presence in the marketplace. Although some laboratory work has been done to investigate OLED failures, further understanding is unlikely until significant numbers of products can be tested for substantial periods of time. One possibility is that the large quantities of portable electronic devices using smaller 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. However, there is no substitute for testing lighting products, and it is likely that some different design approaches and testing methods will need to be developed to ensure an acceptable level of OLED product reliability. At the R&D Workshop, Acuity Brands Lighting reported that yields have been largely improving, and thousands of panels have been tested for up to four weeks without failure. If yields continue to improve, they will be able to eliminate their currently mandatory burn-in period, which is costly and time consuming.

## 3.4 SSL Sustainability

Much of the development of SSL technology has been justified by the understanding that SSL can be much more efficacious than conventional lighting. Although SSL has not yet reached what is believed to be its full potential in terms of efficacy, there are already LED lighting products that exceed the efficacy of nearly all conventional lighting technologies, as shown in Table 3.9. The DOE-sponsored life-cycle assessment (LCA) shows that LED products reduce the total life-cycle energy consumption, including energy consumed during manufacturing, transportation, and use of the products as shown in Figure 3.9. [54]. While SSL products reduce the energy required for lighting, they can do so without compromising the lighting performance.

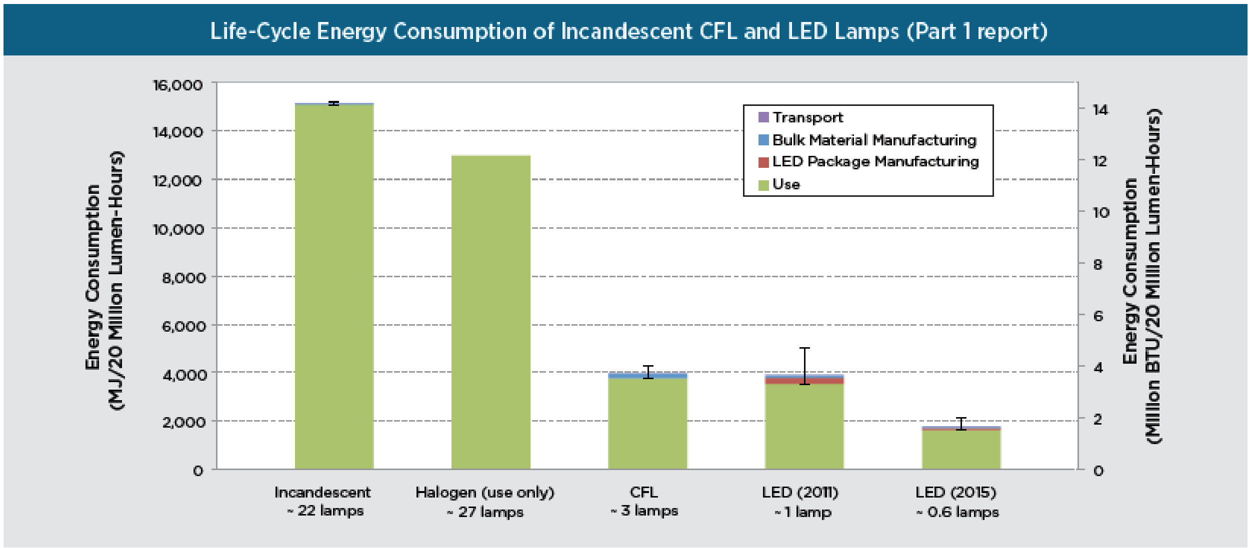


**FIGURE 3.9 ENERGY CONSUMPTION COMPARISON FROM DOE LCA STUDY [54]**
*Source: Life-Cycle Assessment of Energy and Environmental Impacts of LED Lighting Product. Prepared by EERE Building Technologies Office, April 2013.*

The DOE-sponsored LCA studies have shown that SSL can reduce energy use from lighting and maintain performance levels without using large amounts of toxic or rare-earth materials. Unlike fluorescent lighting technology, LEDs and OLEDs do not require mercury or lead, and they make more effective use of rare-earth materials. The DOE LCA showed that in terms of air, resource, water, and soil impacts, LED-based SSL has far less negative impact than incandescent lighting and marginally less than CFLs. Additionally, and LED lighting has further room to improve. The LCA indicates that SSL represents an advancement in sustainability for lighting, particularly as further improvements in efficiency are realized. As discussed in Section 1, the energy consumption impacts of SSL are enormous and are already making an impact. The reduction in energy use from lighting in the U.S. enables improved energy security, reduced energy demand, economic benefits of lower energy consumption, and reduced greenhouse gas emissions. Although SSL products are demonstrating exceptional sustainability, more could be done to even further limit environmental impacts. The following are some of the efforts that are being pursued:

- Lighting that reduces the ecological impacts of providing light at night, such as the Coastal Light offered by Lighting Science Group, which provides a spectrum designed to minimize disruption of sea turtle hatching.[11]
- Streetlights designed to minimize light pollution. The International Dark-Sky Association suggests guidelines to reduce the amount of unusable upward emitted light at night [55]. LED lighting products with their improved optical distribution can significantly reduce the amount of light wasted upward into the atmosphere.
- “De-materializing” or reducing the amount of material, particularly energy-intensive materials such as aluminum, used for SSL products. With thoughtful new design, the opportunity exists

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[11] More information on the Coastal Light can be found at https://www.lsgc.com/fixtures/sea-turtle-friendly-led-fixture/.

to dramatically reduce the amount of materials required for an LED lamp or luminaire products. A good example is the Philips SlimStyle lamp, which has no heat sink.[12]

- Understanding the product life cycle to allow for reusing, recycling, or salvaging luminaires or components at the end of product life.
- Improved manufacturing efficiency. As manufacturing innovations are applied to SSL products, we can expect improved manufacturing efficiency in terms of yield, materials utilization efficiency, and energy efficiency.

## 3.5 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.

### 3.5.1 LED-Based SSL Technology

The primary source of R&D funding in Europe is business enterprise, with the government contributing around 35 percent. SSL R&D activity in Europe is generally coordinated through industry consortia such as the European Photonics Industry Consortium[13] and voluntary cross-border associations such as Photonics21.[14] Much of the government funding in SSL is channeled through European Union (EU) 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 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 [56]. They will use the inputs they received to develop a European strategy on SSL. Recently, the EU launched its Horizon 2020 research program with a budget of €80 billion ($110 billion), which covers the next seven-year period.

Active EU collaborative R&D projects[15] in the field of LED-based SSL during 2013 include NWS4LIGHT (nanowire LEDs), CYCLED (life-cycle analysis), HERCULES (light quality), NPLC-LED (thermal management), SSL4EU (multi-chip LED light sources), 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). New projects started during 2013 and early 2014 include HI-LED (Human-centric intelligent LED light engine) and LASSIE-FP7 (LED module development). These projects have a combined total project value of approximately $54 million, with funding of $39 million provided by the EU. Projects are typically of two or three years in duration.

According to the NGLIA, the Chinese central government spends around $1 billion annually on SSL R&D alone, with the provinces providing additional incentives [57]. This is around 0.5 percent of the country’s total R&D spending, which, according to Battelle, was around $199 billion in 2012, with the government contributing around 25 percent [58].

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[12] More information on the Philips Slim Style A-shape lamp can be found at http://www.usa.philips.com/c-p/046677433147.

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

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

[15] For more information, see: www.cordis.com.

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 equipment (up to $1.8 million per machine). Consequently, China's installed base of such equipment has risen rapidly from around 135 in 2009 to around 1,090 by the end of 2013 [26]. A total of 13 industrial science parks have been established throughout the country for SSL R&D and manufacturing.

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 [59].

In the Republic of Korea (hereafter referred to as South Korea) the private sector is likewise a key player in R&D activities, contributing around 75 percent of R&D funding in 2011 [60]. The major contributors to South Korea's R&D activity are their domestic global companies in high-technology industries, such as Samsung Electronics, LG Electronics, Hynix, and Hyundai Automobile. Until recently, the white LED activity had 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 contrast with other developed countries. In 2010, the industry provided as much as 84 percent of the funding for R&D. Assuming a similar percentage in 2012 when total R&D spending was reported as $158 billion [61], we can estimate the government contribution to be around $25 billion. The amount spent specifically on SSL R&D is not known.

In summary, global government support of R&D in LED-based SSL remains significant. In some geographical regions the industrial sector has established significant momentum of its own and the percentage of government support is gradually reducing, although continued support for pre-competitive R&D remains an important government action. In other regions with a less developed industrial sector, governments have recognized the strategic importance of SSL and are investing heavily in R&D and manufacturing infrastructure in a concerted effort to establish a strong industrial base.

### 3.5.2 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 Flex-O-Fab, which is promoting the development of a robust supply chain for the manufacture of OLEDs on flexible substrates, using either roll-to-roll or sheet-to-sheet processing [62]. The Ecole Polytechnique in Switzerland is working with eight companies from six countries. The EU is supplying $9.8 million towards a total budget of $15.6 million.

Flexible lighting is also the theme of the IMOLA (intelligent light management for OLED on foil applications) project.[16] 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. The European project ENAB-SPOLED involves six partners, and is coordinated by Germany-based OLED lighting developer Novaled. The project will see both commercial and academic partners work to develop solution processable OLEDs and a functional luminaire demonstrator based on the technology.
The project has already been given $5.5 million of funding by Germany's Federal Ministry of Education and Research, the U.K.'s Technology Strategy Board, and the Austrian Research Promotion Agency.

The German Ministry of Education and Research has provided about $150 million over a six-year period, with the goal of encouraging corporate investment of about $520 million. For example, the goal of the Olympus project is the production of durable OLED luminaires with efficacy above 100 lm/W. The project runs through September 2015, with a budget of $47 million, and is coordinated by Osram with support from BJB, Ledon, Merck, and Trilux. The cyCESH project is focused on the development of solution-processable materials by Cynora, Novaled, and the University of Regensburg. This three-year project has a budget of $8.4 million.

The greatest investments in OLED technology have been made in South Korea. Samsung's OLED investments have recently averaged about $5 billion per year [63]. 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 Chem.

Although the South Korean government has provided some funding for companies, primarily to encourage the development of the OLED supply chain, its principal contribution has been to support universities and research institutes. Despite the small size of the country, South 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, including those 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.

While corporate financing remains strongly focused on inorganic LED devices that can have a more immediate impact on the market, governments across the world acknowledge that the special

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

characteristics of OLEDs could broaden the adoption of SSL technology, and therefore are beginning to offer significant OLED research support.

# 4 RESEARCH AND DEVELOPMENT PLAN

This section 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 section 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 Section 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. The projections are based on best-in-class performance, normalized to particular operating conditions in order to track progress; however, 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 section, are a number of metrics specific to that task and individual goals that together will enable us to achieve the goals of the program.

### 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 based on experience to date. To show anticipated progress over time, we use a logistic fit and assume an upper asymptote of 250 lm/W, as explained in Section 3.1.1. All of the data points are for pc-LED solutions and the curves have been fit using the best-in-class qualified data points. No projection is provided for cm-LEDs due to the lack of data points.

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.

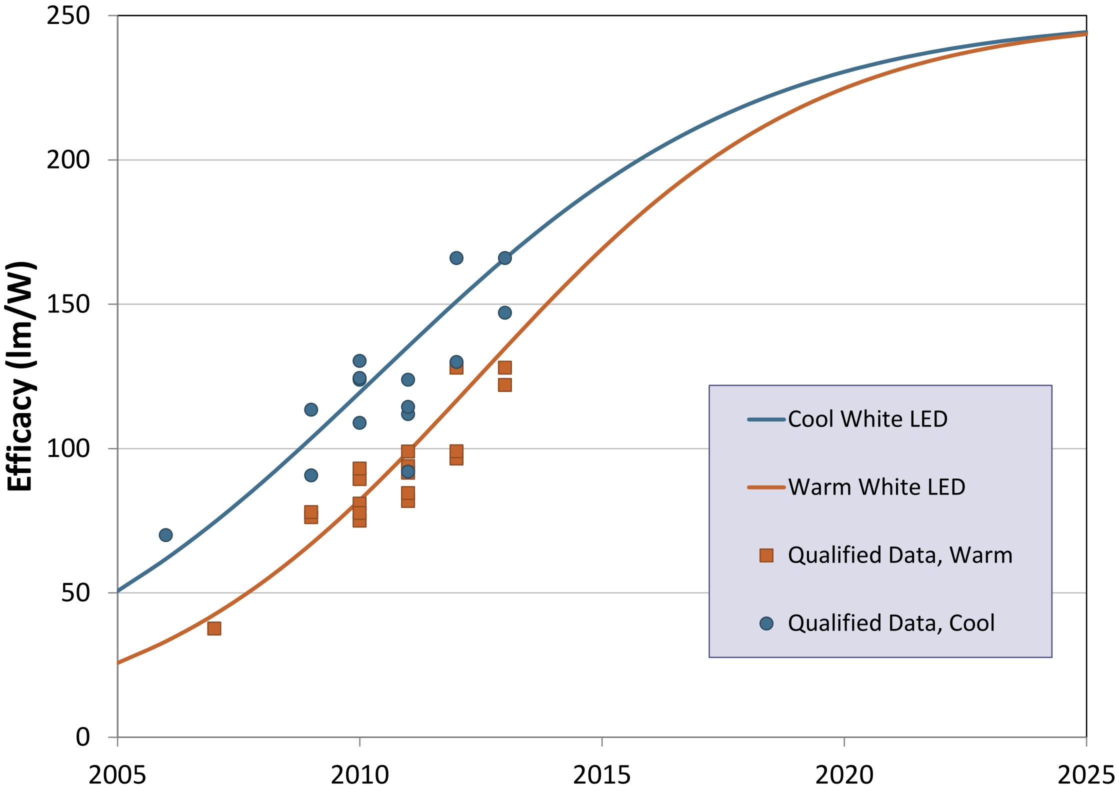

FIGURE 4.1 WHITE-LIGHT PC-LED PACKAGE EFFICACY PROJECTIONS FOR COMMERCIAL PRODUCT

All products produced to date use phosphor-converted or hybrid architectures. Hybrid LEDs will meet the asymptote more quickly than pc-LEDs due to the ready availability of narrow line-width red LED sources. Pc-LEDs will gradually approach the goal as narrower phosphors are developed (less than 50 nm). Cm-LEDs offer the prospect of even higher efficacies, provided green and amber LED sources can be developed with power conversion efficiencies in excess of 60 percent.

**TABLE 4.1 COMPARISON OF PROJECTIONS FOR LED PACKAGE EFFICACY (LM/W) WITH THE OUTCOME OF ANALYSES REPORTED IN SECTION 3.1.1**

| Package Type | Projection Method | 2013 | 2015 | 2017 | 2020 | Goal |
|---|---|---|---|---|---|---|
| **Cool White** | Curve Fit to Data | 166 | 191 | 211 | 231 | 250 |
| | pc-LED Analysis | 143 | - | - | 217 | 241 |
| | hybrid-LED Analysis | 151 | - | - | 223 | 240 |
| **Warm White** | Curve Fit to Data | 135 | 169 | 197 | 225 | 250 |
| | pc-LED Analysis | 123 | - | - | 232 | 247 |
| | hybrid-LED Analysis | 165 | - | - | 231 | 244 |

### 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 Chem, as shown in Table 4.2.

**TABLE 4.2 LG CHEM PERFORMANCE ROADMAP AT 3,000 CD/M$^2$ [64]**

| Metric | 2013 | 2014 | 2015 | 2016 |
|---|---|---|---|---|
| **Efficacy (lm/W)** | 80 | 100 | 120 | 140 |
| **$L_{70}$ Lumen Maintenance (1,000 hours)** | 20 | 30 | 40 | 60 |
| **Maximum Area (mm)** | 140 x 140 | 320 x 320 | - | - |
| **Minimum Thickness (mm)** | 1.0 | 0.45 | 0.3 | 0.2 |

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$^2$ and CRI ≥ 80 with CCT between 2580 and 3710K. Where these parameters are known the data point is considered qualified.

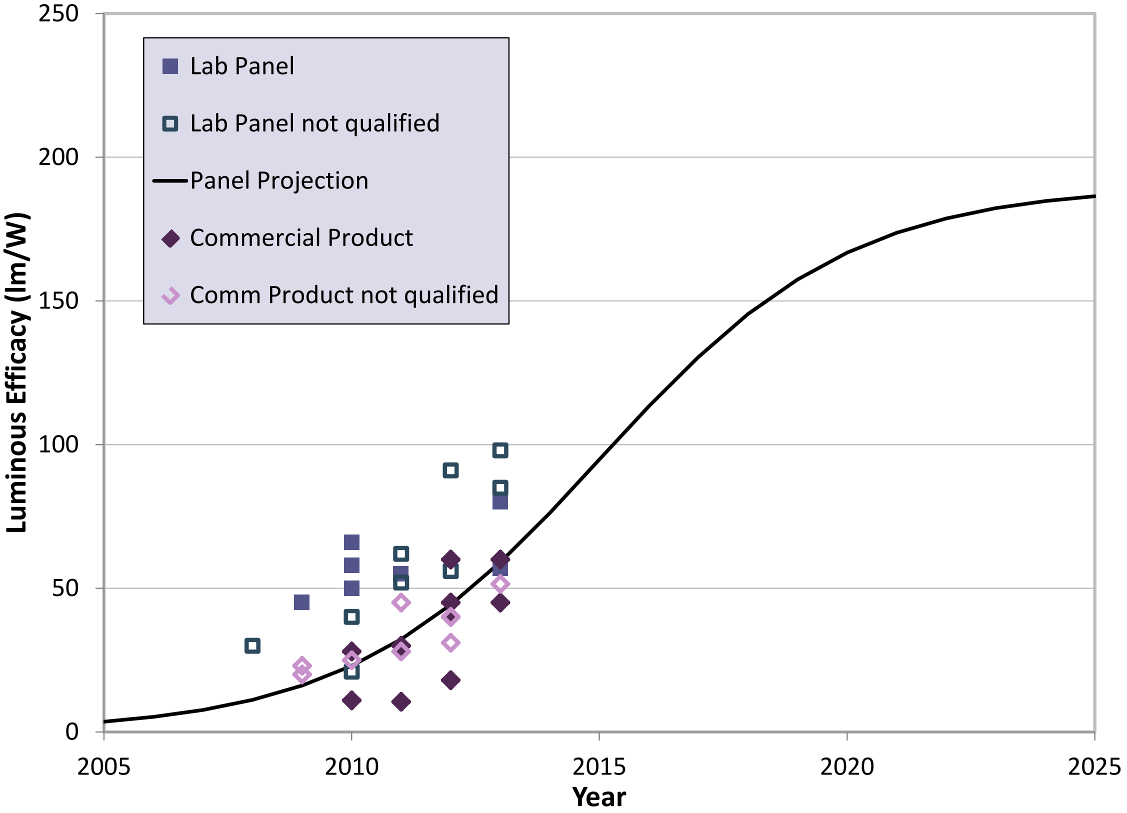

FIGURE 4.2 WHITE-LIGHT OLED PANEL EFFICACY PROJECTIONS

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 PROGRESS PROJECTIONS FOR OLED COMMERCIAL PANEL EFFICACY (LM/W)**

| Metric | 2013 | 2015 | 2017 | 2020 | Goal |
|---|---|---|---|---|---|
| **LER (lm/W)** | 325 | 330 | 335 | 340 | 360 |
| **Internal Quantum Efficiency** | 75% | 85% | 90% | 90% | 90% |
| **Electrical Efficiency** | 80% | 80% | 80% | 82% | 84% |
| **Extraction Efficiency** | 31% | 45% | 54% | 64% | 70% |
| **Panel Efficacy (lm/W)** | 60 | 100 | 130 | 160 | 190 |
| **$L_{70}$ Lumen Maintenance (1,000 hours)** | 15 | 25 | 35 | 40 | 50 |

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

Achieving efficiency gains and lumen depreciation goals will not be sufficient to make commercially viable lighting products. The films must also be producible in large areas at low cost, which may limit materials choices. Improvements to the shelf lifetime of OLED luminaires must also be realized. OLEDs are sensitive to oxygen, moisture, and other pollutants in the operating environment, which 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 goals and milestones have been identified through the R&D Workshop discussions that will mark progress over a ten-year period. These milestones are updated annually, but are not exclusive to the progress graphs shown earlier. Rather, they are highlighted goals that reflect significant gains in SSL technology advancement. Where only one metric is explicitly targeted in the milestone description, it is assumed that there is concurrent progress on the other metrics (e.g., color, lifetime), but the specific metric listed emphasizes the meaningful breakthrough.

The LED package and luminaire milestones in Table 4.4 were revised in 2010 to reflect recent progress. Fiscal year (FY) 2010 and FY 2015 milestones reflect efficacy and/or price targets for LED packages with lumen maintenance values of 50,000 hours. The FY 2012 milestone focused on the development of higher-efficiency luminaires. The SSL community successfully demonstrated the FY 2012 LED goal of a high-efficiency luminaire with an output of 1,000 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 FY 2015, it is expected that costs for LED packages will fall to around $2/klm while retaining the high efficacy of over 100 lm/W and 50,000 hours lumen maintenance. By 2017 (three years ahead of the original schedule), DOE expects the focus to shift toward realization of a commodity-grade luminaire product with output exceeding 3,500 lumens and price below $100, while maintaining reasonable efficacy. By 2020, DOE anticipates the introduction of cost-effective smart lighting in the form of troffers with integrated controls and a price below $85. At this price point, LED sources will represent a significant improvement in price, performance, and total cost of light compared to conventional lamp and luminaire systems.

The LED package and luminaire milestones represent well-defined phases in developing low-cost, high-performance SSL luminaires. 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 luminaires. 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 | Milestones |
|---|---|
| **FY10** | Package: >140 lm/W (cool-white); >90 lm/W (warm-white); <$13/klm (cool-white) |
| **FY12** | Luminaire: 100 lm/W; ~1,000 lumens; 3500K; 80 CRI; 50,000 hours |
| **FY15** | Package: ~$2/klm (cool-white); ~$2.2/klm (warm-white) |
| **FY17** | Luminaire: >3,500 lumens (neutral-white); <$100; >150 lm/W |
| **FY20** | Luminaire: 200 lm/W<br>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. The thrust of this phase of development is to realize substantial price reductions for high-efficiency OLED panels and luminaires while simultaneously improving the efficacy, color quality, and lumen maintenance. The availability of high-performance panels at affordable prices will make commercialization of OLED luminaires more attainable. Though not highlighted as a milestone, the approach to luminaire development will also affect the adoption of this lighting technology. Differentiation of the technology—whether in thinness, flexibility, transparency, light distribution, color quality, or other means—is essential.

The milestones for panels and luminaires have differences in price and efficacy, but color specifications and lumen maintenance goals should be similar. It is expected that, for each milestone, all performance specifications are reached simultaneously in the same device. Thus, when a price is tied to a milestone, the performance goal for that device may be slackened to allow for the cost-performance trade-off. For all years, milestones assume a minimum panel size of 50 cm$^2$ and CCT in the range of 2580K to 3710K.

Milestones for OLED product prices have been heavily debated and difficult to predict. Current prices are at a minimum \$500 and \$1,400 for panels and luminaires, respectively. The price difference stems from the additional costs incurred by luminaires in the power supply, mechanical structure, and any added secondary optics or thermal management. The OLED luminaire efficacy is expected to be just 10 to 20 percent less than panel efficacy due to losses in the power supply and possible optical losses that must be accounted for in luminaires.

The FY 2010 OLED Milestone of a laboratory panel with efficacy greater than 60 lm/W has been achieved and commercial panels are currently available with efficacies at and above this level. The FY 2012 OLED Milestone called for a laboratory panel with an efficacy greater than 70 lm/W, CRI greater than 85, and lumen maintenance ($L_{70}$) over 10,000 hours. These targets have been achieved by LG Chem and others. However, this milestone also assumed a panel of large enough area and luminous emittance to obtain 200 lumen output. This output for a single panel has not yet been realized while meeting all other performance requirements.

The FY 2015 milestone focuses on cost reduction. The goal is a commercial panel priced at \$200/klm with an efficacy of 80 lm/W, $L_{70}$ of 25,000 hours, and CRI greater than 90. LG Chem, Philips, and Panasonic are targeting efficacies of 120 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$^2$ [64] [65] [66]. However, the pricing is still highly uncertain. Meeting the FY 2015 milestone would more than halve the price of OLEDs while also achieving high efficacy and lumen maintenance.

OLED developers are close to reaching the desired targets for lumen maintenance and color quality. However, further attention is needed for 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 panel price goal of \$200/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 luminaire price goal of \$80/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 | Milestones |
|---|---|
| **FY10** | Panel: >60 lm/W |
| **FY12** | Laboratory Panel: 200 lm/panel; >70 lm/W; >10,000 hours |
| **FY15** | Commercial Panel: <\$200/klm (price); >80 lm/W; 25,000 hours; CRI>90 |
| **FY17** | Commercial Panel: \$100/klm<br>Luminaire: 100 lm/W; CRI >90 |
| **FY20** | High-Performance Panel: 160 lm/W<br>Luminaire: price <\$80/klm; 100 lm/W, 40,000 hours |

Note: Panel size >50 cm$^2$; CCT < 2580-3710K

## 4.3 Critical Priorities and Tasks

At the R&D Workshop in Tampa, Florida, DOE hosted a discussion of priority R&D tasks and invited input from attendees regarding the most critical SSL R&D priorities.

For the LED community, R&D task discussion focused on a handful of topics preselected by DOE as most likely priorities. The preselected LED R&D topics were the following:

- Emitter Materials Research
- Down-Converters
- Light Quality Research
- Substrate Development
- System Reliability and Lifetime
- Novel LED Luminaire Systems
- Electronic Subsystems Research

Attendees were given the opportunity to discuss additional topics but elected to stick with the pre-selected topics. Discussion occurred at “topic tables” and the table groups provided a short presentation to all of the LED stakeholders at the R&D Workshop.

The OLED community revisited the entire task list (see Section 5.3) and chose the following tasks for discussion:

- Stable White Devices
- Light Extraction
- Panel Reliability
- Panel Manufacturing Technology
- Low-Cost Electrodes
- Substrates
- Power Supply Units
- Electrical Connections

There was not enough time at the R&D Workshop to receive input on all the recommended OLED task areas or to further prioritize within this list; therefore, a follow-up conference call with several of the most active R&D Workshop participants was held in March 2014 to elucidate the key issues. It was determined that Stable White Devices are a key issue; Light Extraction remains a priority task for both Core Technology and Product Development; Panel Reliability and Panel Manufacturing Technology are better suited as Manufacturing project tasks; and due to the need for market-ready products, a Product Development OLED Luminaire task encompassing work on power supply units and electrical connections should be added.

The tasks listed in Table 4.6 have thus been identified as the most critical R&D priority tasks. 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; however, that does not diminish their importance in overcoming key barriers to success. Industry researchers are encouraged to address as many of the priority tasks as possible. In fact, all of the R&D task areas deserve continued R&D attention. The limited number of priority R&D tasks reflects the practical reality that DOE must leverage limited R&D funding to achieve the most meaningful advancements possible.

**TABLE 4.6 PRIORITY R&D TASKS**

| | Core Technology Research | Product Development |
|---|---|---|
| **LED** | A.1.2 Emitter Materials Research<br>A.1.3 Down-Converters<br>A.8.1 Light Quality Research | B.6.3 System Reliability and Lifetime<br>B.6.4 Novel LED Luminaire Systems |
| **OLED** | C.1.2 Stable White Devices<br>C.6.3 Novel Light Extraction and Utilization | D.6.3 Panel Light Extraction<br>D 4.2 OLED Luminaire |

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.

**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 | 2580-3710K<br>(ANSI 2700, 3000, 3500K) | >80 |
| | Neutral | 3711-4745K<br>(ANSI 4000, 4500K) | >70 |
| | Cool | 4746-7040K<br>(ANSI 5000, 5700, 6500K) | >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.

### 4.4.1 LED Core Technology Research Tasks

Core technology research remains central to the DOE SSL Program. Most of the performance metrics and goals have not changed. An efficient green emitter remains elusive, although phosphor-converted greenish-white LEDs have been used together with monochromatic red to help close 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 and mitigating 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 | 2013 Status | 2020 Targets |
|---|---|---|
| IQE @ 35 A/cm$^2$ | 88% (Blue)<br>38% (Green)<br>75% (Red)<br>13% (Amber) | 95% (Blue)<br>54% (Green)<br>87% (Red)<br>32% (Amber) |
| External Quantum Efficiency (EQE) @ 35 A/cm$^2$ | 75%(Blue)<br>32% (Green)<br>54% (Red)<br>10% (Amber) | 86% (Blue)<br>46% (Green)<br>65% (Red)<br>24% (Amber) |
| Power conversion efficiency[17] @ 35 A/cm$^2$ | 55% (Blue)<br>22% (Green)<br>44% (Red)<br>8% (Amber) | 80% (Blue)<br>35% (Green)<br>55% (Red)<br>20% (Amber) |
| 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)<br>85% (Green)<br>50% (Red)<br>25% (Amber)[18] | 98% (Blue, Green)<br>75% (Red, Amber) |

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

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

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

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 and longevity. Non-rare earth metal and nontoxic down-converters are encouraged.

| Metrics | 2013 Status | 2020 Targets |
|---|---|---|
| Quantum yield (25°C) across the visible spectrum | 95% (Green)<br>90% (Red) | 99% (Green)<br>95% (Red) |
| Thermal stability – Relative quantum yield at 150°C vs. 25°C | 90% | 95% |
| Average conversion efficiency[19] (pc-LED) | 70% | 74% |
| Spectral FWHM | 100 nm (Red) | <30 nm for all colors |
| Color shift over time (pc-LED) | Δu’v’ <0.007 @ 6,000 hours | Δu’v’ <0.002 over life |
| Spectral efficiency relative to a maximum LER ~395 lm/W | 81% | 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 R&D Workshop. Participants noted the importance of gaining industry agreement on metrics for describing color rendering, and 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 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.

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[19] 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.

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 Funding Opportunity Announcement (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)** | **2013 Status** | **2020 Target(s)** |
| Additional or improved color metric | Current color metrics (CRI, CQS[20], CCT, CMF[21]) 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 task that addresses luminaire design emphasizes novelty: How can we better approach the issue of light sources with an improved system architecture? What nontraditional luminaire designs might take best advantage of the unique attributes of LEDs?

There were continued and extensive discussions on the importance of a better understanding of system reliability and lifetime, the subject of task B.6.3, 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; however, it may be advantageous for the consortium to define that work and for DOE to contract specific parts of it outside the FOA process.

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[20] Color Quality Scale
[21] Color Matching Function

| 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** | **2013 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 to all possible energy-saving lighting products, 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, materials utilization and re-use, 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** | **2013 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 R&D Workshop in January 2014, there was an emphasis on getting more OLED products on the market. Introducing products is important for developing consumer familiarity with OLED technology and for promoting consumer consideration of OLED products for lighting applications. Further, developing a market for OLEDs allows for revenue to be generated to offset R&D costs. Concern was expressed that the progression of OLED lighting technology from laboratory experiments to commercial products has been too slow and costly. Any tasks oriented towards reducing costs or developing marketable luminaires were generally supported. In particular, there was overwhelming support for developments in light extraction technologies, as advances in this area have the potential to yield tremendous performance gains in terms of greater efficacy, light output, and lifetime, as well as cost reductions. It was also noted that this need is unique to OLED lighting and the community cannot expect to leverage technology from OLED displays.

Other routes to cost reductions include improving panel reliability and reducing manufacturing costs by improving panel manufacturing technology. There was considerable discussion around the need for panel reliability, as this has a great impact on product cost as well as market acceptance, because if yield is not high enough, first products exhibiting early failure will dissatisfy consumers and further hinder adoption. CFLs were cited as a case history. Thus, it is important to understand underlying failure mechanisms as well as to find ways to manufacture panels and luminaires to improve panel yield. Routes to higher yields can be attained through product development efforts (e.g., adding smoothing layers such as a thick hole injection layer to eliminate electrical shorting through the OLED device) or through manufacturing efforts (e.g., developing coating processes that allow for more uniform layers). It was determined that the most urgent efforts for Panel Reliability and Panel Manufacturing Technology are related to manufacturing issues. Thus, it was determined that these two tasks are best described as Manufacturing tasks rather than Core Technology or Product Development tasks. Manufacturing tasks are prioritized annually at the DOE Manufacturing R&D Workshop and described in the Manufacturing Roadmap.

In addition to supporting the push for market-competitive products, it was noted that Core Technology R&D needs immediate attention in order to achieve the long-term SSL goals. Of critical concern is the remaining 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. Though investigated by large materials developers supporting the OLED display industry, there are many approaches to this problem beyond all-phosphorescent systems and traditional structures. Novel exploration in this area with new materials and structures could help support a needed breakthrough.

### 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 emitter systems. Novel blue emitter systems or different materials systems or architectures that overcome these issues are needed.

### C.1.2 Stable White Devices

**Description:** Develop novel materials and structures that can help create a highly efficient, stable white device. The device should have good color, long lifetime, and high efficiency, even at high brightness. The approach may include the development of highly efficient blue emitter materials and hosts or may comprise a device architecture leading to longer lifetime. Any proposed solutions should keep cost, complexity, and feasibility of scale-up in mind. Materials/structures should be demonstrated in OLED devices that are characterized to ascertain the performance as compared to the metrics below. Novel materials/structures should demonstrate a significant improvement in stability, while maintaining or improving other metrics.

| Metrics | 2013 Status | 2020 Targets |
|---|---|---|
| Lumen maintenance ($L_{70}$) from 10,000 lm/$m^2$ | 15,000 hours | 50,000 hours |
| Efficacy without extraction enhancement (lm/W) | 35 lm/W | 50 lm/W |
| CRI | 85 | >90 |

Task C.6.3, novel light extraction approaches, was selected for the investigation of unique, unexplored 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. The light extraction efficiency (EQE/IQE) of a conventional white OLED on standard indium tin oxide /borosilicate glass substrate typically lies between 20 and 25 percent. While scalable improvements demonstrating extraction efficiency of up to 40 percent have been demonstrated, the long-term goal is to achieve techniques allowing for light extraction efficiency of 70 percent or more. Proposed solutions may explore methods of shaping the beam distribution of OLED devices in addition to enhancing light extraction. A Lambertian light emission profile is not an ideal beam pattern in many applications, and techniques that can alter this profile may enable increased utilization of emitted light. This task seeks novel approaches that can be demonstrated in conjunction with a high-performance OLED that can lead to a scalable, low-cost improvement in extraction efficiency.

### C.6.3 Novel Light Extraction and Utilization

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

| Metrics | 2013 Status | 2020 Targets |
|---|---|---|
| Extraction efficiency (EQE/IQE) | 40% | 70% |

### 4.5.2 OLED Product Development Tasks

Task D.4.2 focuses on the development of OLED luminaires. It was agreed that OLED technology would benefit from the availability of more OLED lighting products on the market. Regardless of the application, luminaires that present an attractive cost-benefit comparison and generate market demand are needed. By increasing the number of OLED lighting products available, more consumers will be educated about this technology, allowing for interest to generate for future lighting purchases. OLED lighting sales will generate revenue for OLED companies to continue and expand their efforts.

### D.4.2 OLED Luminaire

**Description:** Develop general illumination OLED luminaire systems and components that provide a pathway toward greater market adoption. Proposed luminaires should be primarily based on OLED light sources and should have a unique set of features that justifies marketability and product demand. Example characteristics include, but are not limited to: high performance (efficacy, long lifetime, and color quality); low cost; color tunability; modularity; unique form factor (thin, flexible); efficient power supplies; and improved electrical connections. Proposals should provide quantitative targets for distinctive performance in addition to addressing the metrics below. Potential customer appeal as well as market size and penetration should be supported with a cost-benefit comparison and a competitive analysis that takes into consideration competitive products based on other lighting technologies.

| Metrics | 2013 Status | 2020 Targets |
|---|---|---|
| Efficacy | 50 lm/W | 100 lm/W |
| Lumen Maintenance ($L_{70}$) | 15,000 hours | 50,000 hours |

Task D.6.3, like C.6.3, is prioritized because 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. In this product development task, integration of the proposed light extraction solution with state-of-the-art, large-area white OLEDs is key. The approach should be compatible with standard OLED manufacturing techniques and provide a cost-effective solution. Impact on device yield, lifetime, cost, and manufacturability should be assessed and extraction efficiency (EQE/IQE) targets (rather than comparative device improvements) should be quantified. The R&D Workshop attendees recommended that attention should be focused on attaining a solution that can be brought to market within three to four years.

| **D.6.3 Panel Light Extraction** | | |
|---|---|---|
| **Description:** Demonstrate manufacturable approaches to improve light extraction efficiency for OLED panels. The approach should retain the thin profile and state-of-the-art performance of OLED panels (e.g., extraction layers should not lead to voltage increases, reduction in device efficacy, and angular dependence of color). Further, panel yield, lifetime, performance, and cost should not be compromised by the proposed technology. Solutions could involve modifications within the OLED stack, within or adjacent to the electrodes, and/or external to the device. The approach should be demonstrated with high-performance, large-area OLED devices (greater than 25 cm$^2$) and must be amenable to low-cost manufacture. | | |
| **Metrics** | **2013 Status** | **2020 Targets** |
| Extraction efficiency (EQE/IQE) | 40% | 70% |
| Incremental cost | | <\$10/m$^2$ |
| Angular variation in color | | $\Delta u'v' < 0.002$ |

## 4.6 Current SSL Project Portfolio[22]

DOE received \$25.8 million from Congress for SSL R&D in the 2014 fiscal year (FY 2014, which began in October 2013) and has requested \$25.8 million in funding for FY 2015. These levels are consistent with congressional appropriations from previous years, which have hovered around \$25 million each year. In FY 2009 an additional, one-time funding of \$50 million was provided through the American Recovery and Reinvestment Act of 2009, to be used to accelerate the SSL R&D Program and jump-start the manufacturing R&D initiative.

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[22] Figures and charts in this section may not sum to stated cumulative values due independent rounding.

The active DOE SSL R&D Portfolio as of April 2014, shown in Figure 4.3, includes 12 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 $36.2 million in government and industry investment.

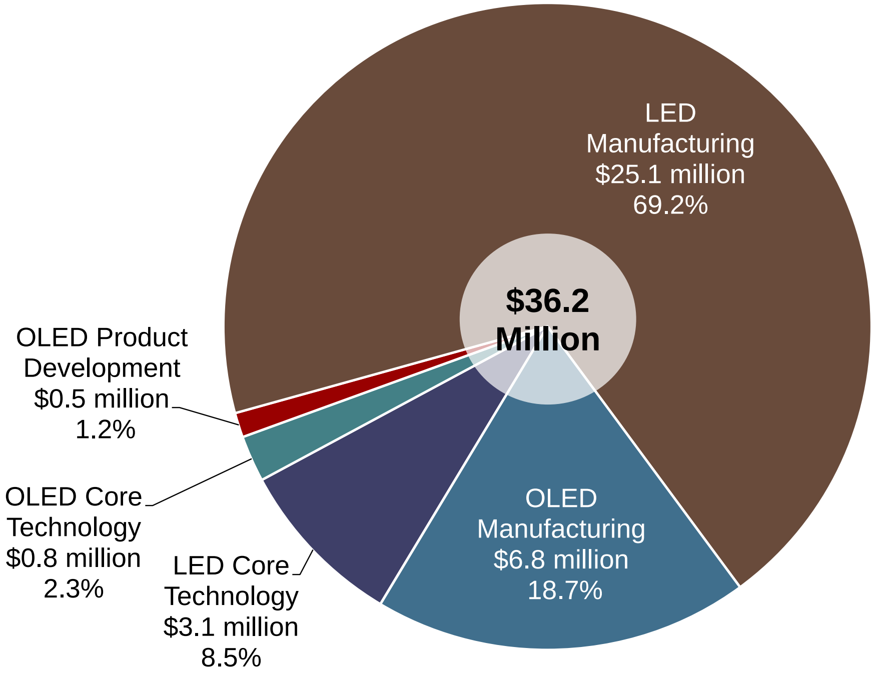

**FIGURE 4.3 DOE SSL TOTAL PORTFOLIO SUMMARY, APRIL 2014**

Figure 4.4 provides a graphical breakdown of the funding for the current SSL project portfolio as of April 2014. DOE is currently providing $19.9 million in funding for the projects, and the remaining $16.3 million is cost-shared by project awardees. Of the 12 projects active in the SSL R&D portfolio, seven focus on LED and five focus on OLED technology.

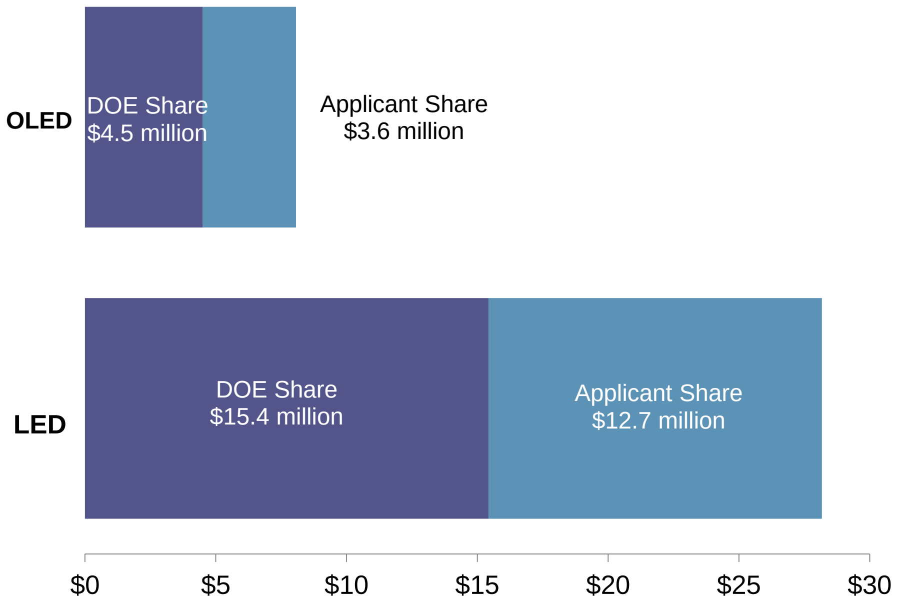

FIGURE 4.4 FUNDING OF SSL R&D PROJECT PORTFOLIO BY FUNDER, APRIL 2014

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

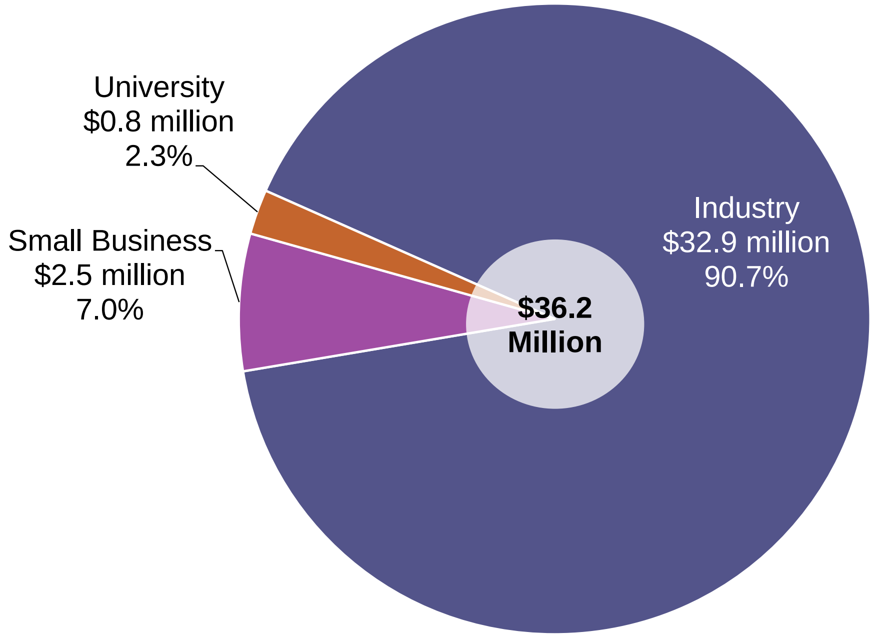

FIGURE 4.5 DOE SSL TOTAL PORTFOLIO SUMMARY BY RECIPIENT GROUP, APRIL 2014

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

TABLE 4.8 SSL R&D PORTFOLIO: CORE TECHNOLOGY RESEARCH PROJECTS, APRIL 2014

| Task | Number of Projects | Funding ($ million) |
|---|---|---|
| **Light-Emitting Diodes** | **2** | **$3.1** |
| Emitter Materials | 1 | $1.0 |
| Optimizing System Reliability | 1 | $2.1 |
| **Organic Light-Emitting Diodes** | **1** | **$0.8** |
| Novel Materials | 1 | $0.8 |
| **Total** | **3** | **$3.9** |

TABLE 4.9 SSL R&D PORTFOLIO: PRODUCT DEVELOPMENT PROJECTS, APRIL 2014

| Task | Number of Projects | Funding ($ million) |
|---|---|---|
| **Light-Emitting Diodes** | **0** | **-** |
| **Organic Light-Emitting Diodes** | **2** | **$0.5** |
| Light Extraction | 1 | $0.2 |
| Substrate | 1 | $0.2 |
| **Total** | **2** | **$0.5** |

TABLE 4.10 SSL R&D PORTFOLIO: CURRENT RESEARCH PROJECTS, APRIL 2014[23]

| | Research Organization | Project Title |
|---|---|---|
| LED | Cree, Inc. | Scalable Light Module for Low-Cost, High-Efficiency LED Luminaires |
| | Cree, Inc. | Low-Cost LED Luminaire for General Illumination |
| | Eaton Corporation | Print-Based Manufacturing of Integrated, Low-Cost, High-Performance SSL Luminaires |
| | KLA-Tencor Corporation | High-Throughput, High-Precision Hot Testing Tool for HBLED Testing |
| | Philips Lumileds | Development and Industrialization of InGaN/GaN LEDs on Patterned Sapphire Substrates for Low-Cost Emitter Architecture |
| | Research Triangle Institute | System Reliability Model for SSL Luminaires |
| | Soraa | Light-Emitting Diodes on Semipolar Bulk GaN Substrate with IQE >80% at 150 A/cm$^2$ and 100°C |
| OLED | Arizona State University | High-Efficiency and Stable White OLED Using a Single Emitter |
| | OLEDWorks, LLC | Innovative, High-Performance Deposition Technology for Low-Cost Manufacturing of OLED Lighting |
| | PPG Industries | Manufacturing Process for OLED Integrated Substrate |
| | MicroContinuum, Inc.* | Roll-to-Roll Production of Low-Cost Integrated OLED Substrate with Improved Transparent Conductor & Enhanced Light Outcoupling |
| | Pixelligent Technologies LLC* | Advanced Light Extraction Material for OLED Lighting |

*Small Business Innovation Research projects.

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

# 5 APPENDICES

## 5.1 Program Organization

The U.S. Department of Energy (DOE) has made a long-term commitment to advance the development and market introduction of energy-efficient white-light sources for general illumination. Solid-State Lighting (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 research and development (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”* [11]. 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 Multi-Year Program Plan 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 Market-based Technology Advancement Multi-Year Plan are published as separate documents at http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_manuf-roadmap_sept2013.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 Announces Collaborative OLED R&D Testing Opportunity | February 2014 | http://www1.eere.energy.gov/buildings/ssl/oled-testing-opportunity.html |
| Next-Generation Luminaires™ Design Competition Announces 2013 Outdoor Winners | February 2014 | www.ngldc.org |
| DOE Hosts Eleventh Annual SSL R&D Workshop | January 2014 | http://www1.eere.energy.gov/buildings/ssl/tampa2014_materials.html |
| "Solid-State Lighting: Early Lessons Learned on the Way to Market" | January 2014 | http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_lessons-learned_2014.pdf |
| "Hammer Testing Findings for Solid-State Lighting Luminaires" | December 2013 | http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/hammer-testing_Dec2013.pdf |
| DOE Hosts Eighth Annual DOE SSL Market Introduction Workshop | November 2013 | http://www1.eere.energy.gov/buildings/ssl/portland2013_highlights.html |
| DOE Hosts Roundtable on OLED Lighting Industry Planning | October 2013 | http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/oled-roundtable-report_oct2013.pdf |
| DOE Updates L Prize PAR38 Competition | July 2013 | http://www.lightingprize.org/news_doe_update.stm |
| DOE Hosts Fifth Annual DOE SSL Manufacturing R&D Workshop | June 2013 | http://www1.eere.energy.gov/buildings/ssl/boston13_highlights.html |
| DOE Informs and Educates at LIGHTFAIR® International 2013 | April 2013 | http://www1.eere.energy.gov/buildings/ssl/news_detail.html?news_id=19174 |
| 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 2013 resulting from DOE-funded projects. More detail is available on DOE's website at: www.ssl.energy.gov/highlights.html.

| Research Highlight | Date |
|---|---|
| SUNY/Buffalo Developing High-Efficiency Colloidal Quantum Dot Phosphors | July 2013 |
| RTI International Develops SSL Luminaire Reliability Model | July 2013 |
| Philips Lumileds Develops a Low-Cost, High-Power, Warm-White LED Package | June 2013 |
| PPG Industries Develops a Low-Cost Integrated OLED Substrate | June 2013 |
| Soraa Is Optimizing the Use of Non-Polar and Semi-Polar Substrates to Improve Emitter Efficiency Under High-Current Operation | June 2013 |

## 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[24]
Component level (no power source or driver)

- *LED* refers to a p-n junction semiconductor device (also referred to as chip) that emits incoherent ultraviolet (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 American National Standards Institute (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 an LED driver. Power source and ANSI standard base are not incorporated into the device. The device cannot be connected directly to the branch circuit.

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 composed 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).

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

  - *Non-integrated LED Lamp* refers to an assembly composed 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 composed 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 composed 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 band-gap 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.[25]
- *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.
- *External quantum efficiency* (EQE) is the ratio of extracted photons to injected electrons.[26] 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.

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[25] 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).

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

- *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 cm- 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 cm- or hybrid LED are not available.

<u>Subassemblies and systems</u>

- *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.[27] 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 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.)

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[27] 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.

### 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.

### 5.2.3 Summary of LED Applications

| APPLICATION | LIGHTING PRODUCT | DESCRIPTION |
|---|---|---|
| A-type | Lamps | All A-type lamp shapes with a medium-screw base |
| Decorative | Lamps | All bullet, candle, flare, globe, and any other decorative lamp shapes |
| Directional | Lamps and Luminaires | Includes reflector and PAR lamps as well as recessed and surface-mounted downlights and indoor accent, track, and spotlight luminaires |
| Small Directional | Lamps | All MR lamp shapes |
| Linear Fixtures | Lamps and Luminaires | All troffer, panel, suspended, and pendant luminaires, as well as LED linear replacement lamps, are assumed to compete in this application. Does not include those installed in industrial applications. |
| Industrial | Luminaires | All industrial fixtures including low and high bay |
| Parking Garage | Luminaires | Includes fixtures installed in attached, as well as stand-alone, parking garages |
| Area/Roadway | Luminaires | Includes fixtures installed in street, roadway, and parking lot applications, as well as large outdoor area and canopy lighting |
| Building Exterior | Lamps and Luminaires | Includes all lamp fixtures installed in façade, spot, architectural, flood, wall-pack, and step/path applications |
| Other | Lamps and Luminaires | Includes all other special use lighting applications such as tunnel, signage, wall-wash, and cove |

## 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**

### 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 and utilization**

### 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 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 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**
  - 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 nontoxic 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, and 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 (50,000 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. |
| **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.<br>Product: Luminaire/replacement lamp |

**LED Product Development Tasks**

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

| 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** | OLED luminaire | Develop OLED luminaire systems and components that provide a pathway toward greater market adoption. Proposed luminaires should be primarily based on OLED light sources and should have a unique set of features that justifies marketability and product demand. Example characteristics include, but are not limited to: high performance (efficacy, long lifetime, and color quality); low cost; color tunability; modularity; unique form factor (thin, flexible); efficient power supplies; and improved electrical connections. Proposals should provide quantitative targets for distinctive performance in addition to addressing the metrics below. Potential customer appeal as well as market size and penetration should be supported with a cost-benefit comparison and a competitive analysis that takes into consideration competitive products based on other lighting technologies. |
| **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 lumens 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 scalable, low-cost panel package designs that improve environmental resistance and thermal management. New packaging designs should be demonstrated in a high-efficiency OLED panel and exhibit improved lifetime. |

| OLED Product Development Tasks | | |
|---|---|---|
| | **Task** | **Description** |
| **D.6.3** | Panel light extraction | Demonstrate manufacturable approaches to improve light extraction efficiency for OLED panels. The approach should retain the thin profile and state-of-the-art performance of OLED panels (for example, extraction layers should not lead to voltage increases, reduction in device efficacy, and angular dependence of color). Further, panel yield, lifetime, performance, and cost should not be compromised by the proposed technology. Solutions could involve modifications within the OLED stack, within or adjacent to the electrodes, and/or external to the device. The approach should be demonstrated with high-performance, large-area OLED devices (>25 $cm^2$) and must be amenable to low-cost manufacture. |
| **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 2014, 72 SSL patents have been awarded to research projects funded by DOE. Since December 2000, when DOE began funding SSL research projects, a total of 186 patent applications have been submitted, ranging from large businesses (67) and small businesses (65) to universities (45) and national laboratories (9). These patents are listed on DOE's website at: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/patents_factsheet_jan2014.pdf.

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