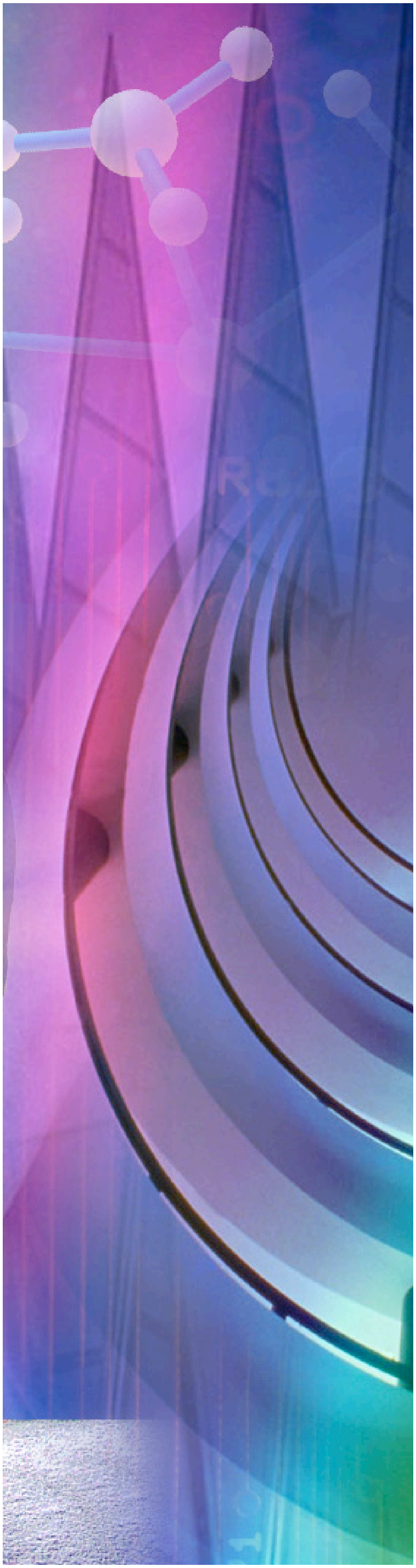

Solid-State Lighting Research and Development:

Multi Year Program Plan

March 2011 (Updated May 2011)

Prepared for:

Lighting Research and Development
Building Technologies Program

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

Solid-State Lighting Research and Development

Prepared for:

Lighting Research and Development
Building Technologies Program
Office of Energy Efficiency and Renewable Energy
U.S. Department of Energy

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March 2011

(Updated May 2011)

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ACKNOWLEDGEMENTS

The Department of Energy would like to acknowledge and thank all the participants for their valuable input and guidance provided to develop Section 5.0 of the Multi-Year Program Plan (MYPP). The DOE would like to thank those individuals who participated in the solid-state lighting roundtables of November 2010 in Washington, D.C:

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Dennis Bradley	GE Lumination
Bernd Clauberg	Philips Advance
Wendy Davis	National Institute of Standards and Technology
Nathan Gardner	Philips Lumileds
Michael Hack	Universal Display Company
John Hamer	OLEDWorks LLC
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David Hum	Bridgelux
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COMMENTS

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1.0 Introduction

President Obama's energy and environment agenda calls for deployment of "the Cheapest, Cleanest, Fastest Energy Source – Energy Efficiency."[1] The Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy (EERE) plays a critical role in advancing the President's agenda by helping the United States advance toward an energy efficient future.

> ***"LEDs are an obvious area that we can achieve energy savings and we can also achieve economic benefits – job creation."***
> U.S. Senator Jeff Bingaman
> Chair, Senate Energy Committee

Lighting in the United States is estimated to have consumed nearly 10 quads of primary energy in 2010.[3] A nationwide move toward solid-state lighting (SSL) for general illumination could save a total of 16 quads of primary energy between 2010 and 2030. No other lighting technology offers DOE and the nation so much potential to save energy and enhance the quality of our built environment.

The Energy Policy Act of 2005 (EPACT 2005)[4] and the Energy Independence and Security Act of 2007 (EISA 2007)[5] issued a directive to the Secretary of Energy to carry out a "Next Generation Lighting Initiative" (NGLI) to support the research and development (R&D) of SSL (see Appendix A and Appendix B for relevant legislation). The legislation directs the Secretary of Energy to support research, development, demonstration, and commercial application activities related to advanced SSL technologies. In part, these laws specifically direct the Secretary to:

- Support research and development through competitively awarded grants to researchers, including Industry Alliance participants, National Laboratories, and research institutions.
- Solicit comments to identify SSL research, needs, and progress. Develop roadmaps in consultation with the industry alliance.
- Manage an ongoing development, demonstration, and commercial application program for the NGLIA through competitively selected awards.
- Assist manufacturers of general service lamps in manufacturing lamps that, at a minimum, achieve the wattage requirements imposed by EISA 2007 for general service incandescent lamps.

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[1] The Agenda – Energy and Environment. Last Accessed February 26, 2009. Available at: http://www.whitehouse.gov/agenda/energy_and_environment/.

[2] Fleck, J. "Bingaman Thinks LEDs a Bright Idea." *Albuquerque Journal*. 10 November 2003.

[3] Energy Savings Potential of Solid-State Lighting in General Illumination Applications 2010-2030. Prepared by Navigant Consulting, Inc. for the Department of Energy. Washington D.C. February 2010.

[4] The legislation text for EPACT 2005 is available at - http://www.epa.gov/oust/fedlaws/publ_109-058.pdf

[5] The legislation text for EISA 2007 is available at - http://frwebgate.access.gpo.gov/cgi-bin/getdoc.cgi?dbname=110_cong_public_laws&docid=f:publ140.110

In order to effectively fulfill the directives in EPACT 2005 and EISA 2007, DOE has set forth the following mission statement for the SSL R&D Portfolio:

> *Guided by a Government-industry partnership, the 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.*

The follow sections describe the series of goals that DOE has established that relate to the development of the SSL R&D Program.

1.1 DOE Goals and Solid-State Lighting

The overarching mission of DOE is to ensure America's security and prosperity by addressing its energy, environmental, and nuclear challenges through transformative science and technology solutions. DOE has three goals toward achieving the mission, of which the first two align best with the SSL portfolio[6]:

> *Goal 1: Catalyze the timely, material, and efficient transformation of the nation's energy system and secure U.S. leadership in clean energy technologies.*
>
> *Goal 2: Maintain a vibrant U.S. effort in science and engineering as a cornerstone of our economic prosperity, with clear leadership in strategic areas.*

SSL is an emerging clean energy technology that promises to make a significant impact on solving our nation's energy and environmental challenges. Within DOE there are several efforts focused on advancing SSL technology, products, and the underlying science: the Basic Energy Sciences Program, the Advanced Research Projects Agency – Energy (ARPA-E), and the EERE Building Technologies Program.

The Basic Energy Sciences Program in the Office of Science supports fundamental research to understand, predict, and ultimately control matter and energy at the electronic, atomic, and molecular levels in order to provide the foundations for new energy technologies and to support the DOE missions in energy, environment, and national security. Projects funded under this program often have multiple applications, including SSL.

The ARPA-E mission is to fund projects that are considered high-risk, high-reward efforts with potential for significant energy saving impact. Currently, the agency is funding a high risk project on developing low cost, bulk gallium nitride substrates which could improve light emitting diode (LED) performance. ARPA-E is also supporting the development of advanced, energy efficient power supply technologies that could be applied to SSL.

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[6] More information on Department of Energy strategic mission, vision, and themes available at: http://www.energy.gov/media/DOE_StrategicPlan_Draft.pdf

The Building Technologies Program (BTP) in the Office of Energy Efficiency and Renewable Energy (EERE), under which this MYPP has been developed, funds applied research, product development, and manufacturing R&D to advance the technology of SSL and achieve energy savings. BTP SSL also works to provide the technical foundation, tools, education, and resources for informed product selections and maximum energy savings. Listed below are the goals of EERE, BTP, and the SSL Portfolio.

1.1.1 Office of Energy Efficiency and Renewable Energy

The Office of EERE at the U.S. DOE focuses on researching and accelerating technologies that promote a sustainable energy future. To that end, the strategic goals of EERE are to:

- Dramatically reduce, or even end, dependence on foreign oil;
- Reduce the burden of energy prices on the disadvantaged;
- Increase the viability and deployment of renewable energy technologies;
- Increase the reliability and efficiency of electricity generation, delivery, and use;
- Increase the energy efficiency of buildings and appliances;
- Increase the energy efficiency of industry;
- Spur the creation of a domestic bioindustry; and
- Lead by example through government's own actions.

The EERE mission is to strengthen America's energy security, environmental quality, and economic vitality through public-private partnerships that:

- Enhance energy efficiency and productivity;
- Bring clean, reliable, and affordable energy production and delivery technologies to the marketplace; and
- Make a difference in the everyday lives of Americans by enhancing their energy choices and their quality of life.

1.1.2 Building Technologies Program

The mission of the DOE Building Technologies Program is:

> *Develop and promote efficient and affordable, environmentally friendly, technologies, systems, and practices for our nation's residential and commercial buildings that will foster economic prosperity, lower greenhouse gas emissions, and increase national energy security while providing the energy-related services and performance expected from our buildings*

In support of that mission the DOE Building Technologies Program has established a goal to innovate the development and deployment of energy efficient technologies and practices. To achieve this goal, it has developed the following strategies:

- Develop and implement technology roadmaps that drive market transformations;
- Increase private sector collaboration in developing new technologies;

- Perform more open solicitations and cooperative research agreements;
- Focus on cost reduction and market opportunity, making the product more attractive to the market; and
- Develop innovations in key technology areas such as solid-state lighting, HVAC, working fluids and sensors/controls.

1.1.3 DOE Solid-State Lighting Program

Section 912 of the Energy Policy Act of 2005 directs DOE to *"support research, development, demonstration, and commercial application activities related to advanced solid-state lighting technologies based on white light emitting diodes."* In response, the DOE SSL Program has developed a comprehensive national strategy with three distinct, interrelated thrusts (and accompanying roadmaps): Core Technology Research and Product Development, Manufacturing R&D, and Commercialization Support. SSL R&D Program activities in all three areas support the BT vision of decreased energy demand of U.S. buildings.

The commercialized efficacy goal of DOE SSL R&D is to reach an order of magnitude increase in efficacy over incandescent luminaires and nearly a two-fold improvement over fluorescent luminaires.

The goal of the DOE **SSL Core Technology Research and Product Development** program area is to increase end-use efficiency in buildings by aggressively researching new and evolving lighting technologies. Working in close collaboration with partners, DOE aims to develop technologies that have the potential to significantly reduce energy consumption for lighting. To reach this goal, DOE has developed a portfolio of SSL R&D activities, shaped by input from industry leaders, research institutions, universities, trade associations, and national laboratories.

The goal of the SSL R&D Program is:

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

Advances in the efficiency of SSL will reduce the demand for new power plants and improve the reliability of the grid. This SSL portfolio goal also dovetails directly into the EERE strategic goal to "*increase the energy efficiency of buildings and appliances.*"

This Multi-Year Program Plan (MYPP) guides SSL Core Technology Research and Product Development over the next few years and informs the development of annual SSL R&D funding opportunities. This plan is a living document, updated annually to incorporate new analyses, technological progress and new research priorities, as science evolves.

In 2009, DOE added another segment to its R&D portfolio, a **SSL Manufacturing Initiative**, to accelerate SSL technology adoption through manufacturing improvements that reduce costs and enhance quality. The goals of the SSL Manufacturing Initiative are to:

- *Reduce costs of SSL sources and luminaires;*
- *Improve product consistency while maintaining high quality products; and*
- *Encourage a significant role for domestic U.S. based manufacturing in this industry.*

DOE believes that cooperation in understanding best practices, common equipment needs, process control, and other manufacturing methods and issues is the best path to achieve these goals. DOE and industry partners have developed a SSL Manufacturing R&D Roadmap,[7] outlining the likely evolution of SSL manufacturing, best practices, and opportunities for improvement and collaboration. Like the MYPP, the Roadmap is updated annually with input from industry partners and workshop attendees and guides the development of annual SSL manufacturing R&D solicitations.

To ensure that the DOE investments in Core Technology Research, Product Development, and Manufacturing R&D lead to successful market introduction of high quality, energy efficient SSL products for general illumination, DOE has also developed a Five Year **SSL Commercialization Support Plan**.[8] The plan is shaped by input from a wide array of market side partners – standards setting organizations, energy efficiency groups, utilities, retailers, lighting designers, and others – as well as lessons learned from the past.

The purpose of the Plan is to set out a strategic, five year framework for guiding the DOE commercialization support activities for high performance SSL products for the U.S. general illumination market. The DOE commercialization support activities are strategically designed to create the conditions, specifications, standards, opportunities, and incentives that:

- Lead buyers to high performance SSL products that are most likely to reduce energy use and satisfy users;
- Accelerate commercial adoption of these products; and
- Support appropriate application of these products to maximize energy savings.

Together, these efforts are intended to reduce energy use by businesses and consumers, and to save them money. Like the MYPP and Manufacturing R&D Roadmap, the Commercialization Support Plan is updated regularly, drawing on input gathered from workshops and roundtable attendees, DOE partners, and market reconnaissance on products and issues.

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[7] DOE's SSL R&D Manufacturing Roadmap can be found at: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_manuf-roadmap_july2010.pdf

[8] DOE's Five-Year SSL Commercialization Support Plan can be found at http://www1.eere.energy.gov/buildings/ssl/pdfs/ssl_5year-plan_09-13.pdf

1.2 Significant SSL R&D Program Accomplishments to Date

1.2.1 Recent SSL R&D Program Highlights

February 2011 – DOE SSL R&D Workshop

The eighth annual DOE SSL R&D Workshop was held February 1st to the 3rd, 2011, in San Diego, CA. With 350 attendees and three days of formal and informal discussion, the workshop provided a unique opportunity to share updates and to network with stakeholders from industry, academia, research institutions, and government. Both speakers and attendees offered insights on key issues impeding SSL technology advances, and ideas to move past the current limits of SSL efficacy and performance. Attendees also provided input to guide updates to the SSL MYPP.

Energy Savings Estimates of Light Emitting Diodes in Niche Lighting Applications

In January 2011, DOE released an analysis which investigates the energy use for twelve different markets where LEDs are competing or are poised to compete with traditional light sources (e.g., incandescent and fluorescent). Estimates of the energy saved due to current levels of LED market penetration, as well as estimates of potential energy savings if these markets switched completely to top performing LEDs 'overnight,' are given. In addition, non-energy saving benefits of LEDs in each market are discussed. Annual energy savings from SSL in 2010 from the twelve markets analyzed was approximately 3.9 terawatt-hours, equivalent to the electricity needed to power more than a quarter million average U.S. households. The complete report is available for download on the DOE SSL website at www.ssl.energy.gov/tech_reports.html.

Number of Products Registered with Lighting Facts® Surpasses 2,300

Continuing to grow rapidly, Lighting Facts is a voluntary pledge and labeling program to ensure accurate and consistent reporting of product performance claims. LED lighting manufacturers pledge to use the Lighting Facts label on their product packaging and materials, while retailers, distributors, lighting professionals, utilities, and energy efficiency organizations pledge to look for and use products bearing this label. There are now more than 2,300 products registered with Lighting Facts, and over 200 manufacturers have signed on as Lighting Facts partners, along with 180 retailers and distributors and over 200 lighting professionals. Registered products are listed on the products page of the Lighting Facts website along with their Lighting Facts label data. The Lighting Facts label presents independently verified LM-79 performance data in an easy-to-understand way in order to facilitate accurate product comparison. It currently covers light output, power consumption, efficacy, correlated color temperature (CCT), and color rendering index (CRI). For more information, see www.lightingfacts.com.

Lighting for Tomorrow Announces 2010 Competition Winners

Winners of the eighth annual Lighting for Tomorrow competition were announced in September 2010 at the American Lighting Association (ALA) Annual Conference in Las Vegas. Organized by the ALA, the Consortium for Energy Efficiency (CEE), and DOE, the competition aims to increase market acceptance and awareness of energy efficient lighting by recognizing the best designed energy efficient lighting products on the market. This year, the competition was expanded beyond SSL fixtures to include LED replacement lamps as well as lighting control devices compatible with such energy efficient technologies as LED and fluorescent. Fifty companies submitted a total of 107 products. Five SSL fixtures were selected as winners—Kichler's Lighting Design Pro LED Broad Roof LED Path & Spread Light and Pro Design ProLED Modular and Disc System; Edge Lighting's Scope LED Pendant and Scope LED Monorail/Track Light; and Philips Lighting's EnduraLED™ A19 replacement lamp. More information on all the winning entries is available at www.lightingfortomorrow.org.

L Prize℠ Evaluates First Entry, Welcomes New Partners

Sponsored by DOE, the L Prize competition challenges industry to develop LED replacements for two of the most widely used and inefficient types of light bulb—the common 60W bulb and the PAR-38 lamp. In September 2009, the competition received its first entry, a 60W replacement product from Philips Electronics. That entry is currently undergoing a rigorous evaluation process that began with photometric testing and continues with long term lumen maintenance testing and field assessments. The long term testing is conducted for a minimum of 6,000 hours at high temperatures and will continue through at least early 2011. The field assessments, completed in September 2010, were conducted in a wide range of applications and settings by 14 L Prize Partners at more than 30 sites across the continent. In addition, four new partners have signed up to be L Prize Partners, bringing the total number to 31 and counting. The L Prize Technical Review Committee, a key element of the evaluation process, has been formed and is reviewing all reports, results, findings, and documentation for the Philips entry. For more information, visit www.lightingprize.org.

DOE Hosts Fifth Annual DOE SSL Market Introduction Workshop

In July 2010, more than 300 lighting leaders—including industry, government, efficiency organizations, utilities, municipalities, designers, specifiers, retailers, and distributors—gathered in Philadelphia, Pennsylvania, to share the latest insights, updates, and strategies for the successful market introduction of high quality SSL products. The workshop itself was preceded by a series of tutorials for those new to SSL and a webcast on evaluating LED street lighting solutions. The webcast, hosted by DOE's Solid-State Street Lighting Consortium, was attended by over 500 people who participated either in person or online. More information, including pre-conference and workshop highlights and presentations, is available on the SSL website at www.ssl.energy.gov/philadelphia10_highlights.html.

DOE Hosts Workshop: SSL in Higher Education Facilities
In May 2010, DOE hosted a workshop in Portland, Oregon, to facilitate conversations between SSL luminaire manufacturers and end-users, focused on the complex lighting needs of colleges and universities, with an aim toward improving the design of SSL products. Colleges and universities collectively comprise an important market for lighting products, and they use almost every kind of luminaire. A college campus is like a small city, with lighting applications spanning classrooms and offices to theaters, labs, libraries, dining halls, dormitories, museums, chapels, walkways, parking lots, garages, lecture halls, arenas, and outdoor stadiums.

Funded by the American Recovery and Reinvestment Act (ARRA) of 2009, the Portland workshop provided SSL manufacturers an opportunity to go beyond the bottom line to understand the perspectives of those who specify, pay for, install, use, maintain, and dispose of lighting systems for nearly every type of application. Workshop presenters included lighting designers, engineers, and facilities managers. To encourage active participation, the audience was limited to 100 SSL manufacturers. Workshop materials are available at www.ssl.energy.gov/higher_ed_workshop2010_materials.html.

DOE Educates at National Conferences
As part of the ongoing DOE commitment to SSL education, DOE hosted an informational booth and several educational seminars at the LIGHTFAIR® International Trade Show, May 12–14, 2010, in Las Vegas, Nevada. Cosponsored by the Illuminating Engineering Society of North America and the International Association of Lighting Designers, LIGHTFAIR is the world's largest annual architectural and commercial lighting trade show and conference, attracting roughly 500 exhibitors and 20,000 lighting, design, architectural, and engineering professionals.

In the DOE booth, staffers offered a series of free tutorials on a wide range of SSL topics, from "How to Reduce the Risk of Specifying LEDs" to "Recent SSL Installations: The Good, the Bad, and the Ugly" to "Dimming and LEDs: Can this be a Happy Marriage?" In addition, as part of the continuing education offerings prior to the show, DOE Lighting Program Manager Jim Brodrick gave a lunchtime keynote talk at the LIGHTFAIR Institute/LIGHTFAIR Daylighting Institute. More information on SSL activities at LIGHTFAIR is available at www.ssl.energy.gov/news_detail.html?news_id=16008.

In FY2010, DOE SSL increased its educational activities with a broad based effort to reach out to a wide variety of audiences, each with its own level of understanding regarding LED education. In response to the growing number of invitations, DOE representatives have presented at multiple conferences across the country, with unique messages tailored for specific knowledge levels and expertise. As part of this effort, DOE SSL partnered with Jack Curran of LED Transformations to provide a number of workshops and seminars on behalf of DOE, including a half day workshop at GovEnergy in August. Attended by more than 100 Federal facility managers, designers, and manufacturers, the workshop provided a comprehensive introduction to LED technology, appropriate applications, and questions to consider when evaluating LED products.

DOE Publishes Recommendations for Testing and Reporting LED Luminaire

In May 2010, DOE published a new guide, *LED Luminaire Lifetime: Recommendations for Testing and Reporting*, developed by a working group created by DOE and the Next Generation Lighting Industry Alliance (NGLIA). The working group is under the guidance of the DOE SSL Quality Advocates program and is composed of a diverse group of experts in reliability, lighting, and LED technology. These recommendations are an important first step toward consistent, industry wide understanding of LED luminaire lifetime and will assist standards organizations in their work. The guide is a follow-up to an earlier publication, *Reporting LED Luminaire Product Performance*, which laid the groundwork for the Lighting Facts label. A PDF copy of the recommendations is available at http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/led_luminaire-lifetime-guide.pdf. A new, updated edition of this guide is planned for release later this year.

DOE Hosts Second Annual DOE SSL Manufacturing R&D Workshop

In April 2010, more than 250 industry leaders from all steps of the supply chain—including chip makers, luminaire manufacturers, material and equipment suppliers, packagers, luminaire testers, and makers of testing equipment—gathered in San Jose, California, to share insights, ideas, and updates related to manufacturing R&D. This workshop is a key part of an initiative launched by DOE in 2009 to enhance the quality and lower the cost of SSL products through improvements in manufacturing equipment and processes and to foster a significant manufacturing role in the U.S. This year, attendees explored a wide range of related topics and focused on reexamining and updating the SSL Manufacturing R&D Roadmap. More information, including workshop highlights and presentations, is available on the SSL website at www.ssl.energy.gov/san_jose10_highlights.html.

DOE Launches Municipal Consortium on LED Street Lights

To leverage the efforts of multiple cities pursuing evaluations of LED street lighting products, DOE launched a Municipal Solid-State Street Lighting Consortium in April 2010. The goal is to build a repository of valuable field experience and data that will significantly accelerate the learning curve for buying and implementing high quality, energy efficient LED street lights. DOE selected Seattle City Light to lead the national effort to collect, analyze, and share information and lessons learned related to LED street lighting demonstrations. As the body of knowledge accrues, experience and best practices will be disseminated through national and regional meetings, webcasts, web-based discussion forums, and other means. Since its launch, the Consortium hosted a kickoff webcast in May and a second webcast prior to the Market Introduction Workshop in July. In September, the Consortium held its first annual meeting and joined with the City of Los Angeles to host its first southwest regional workshop.

Membership is open to municipalities, utilities, and energy efficiency organizations, with participation at various levels from other interested parties with investments in LED street lighting. The DOE Municipal Lighting Consortium efforts are funded under the 2009 ARRA. For more information, see www.ssl.energy.gov/consortium.html.

First-Year Results Under the SSL Manufacturing R&D Initiative
The SSL Manufacturing R&D Initiative (launched in FY2009) has two primary goals: to enhance product consistency and quality and to accelerate cost reductions through manufacturing improvements. A third objective is to encourage domestic U.S. based manufacturing of SSL products. In FY2010, DOE selected the first round of projects under the initial funding opportunity (see the R&D Highlights section of this report for more details). These first eight manufacturing R&D projects are funded under the Recovery Act. In June, DOE issued a second funding opportunity for manufacturing R&D projects; these project selections will take place in FY2011.

Next Generation Luminaires™ Announces LED Design Competition Winners
Winners of the second annual Next Generation Luminaires™ awards were announced in February 2010 at the Strategies in Light Conference in Santa Clara, California. Sponsored by DOE, IES, and IALD, the competition recognizes excellence in the design of energy efficient LED commercial luminaires. A total of 126 entries were judged from 60 lighting companies. Of the entries, 47 were selected for recognition, with four of these products designated as Best in Class: Style Styk wall washing fixture from SPILIGHTING Inc.; VizorLED parking garage lighting from Wide-Lite; CURVE task lighting fixture from Finelite, Inc.; and Evolve™ LED R150 roadway luminaire lighting from GE Lighting Solutions. In addition, 43 products were recognized for excellence in a variety of indoor and outdoor categories. More information on all the winning entries is available at www.ngldc.org.

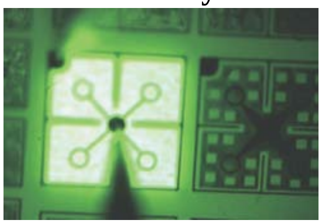
1.2.2 Recent Research Highlights

Considerable progress has been made in the advancement of SSL technology since DOE initiated its support for SSL R&D in 2000. 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 for projects funded since March 2010.

The University of North Texas Develops Record-Breaking OLED Materials

The University of North Texas, in conjunction with the University of Texas at Dallas, achieved record OLED performances using novel platinum based phosphorescent emitters. These include improvements in OLED efficacies by as much as 65% as compared to baseline devices (from 43 lm/W to 71 lm/W for turquoise blue OLED devices), and demonstrating high efficiency (70 lm/W without out-coupling; 100% IQE) doping free warm white OLEDs (DFW-WOLEDs) with unparalleled color stability (< 0.1% change in CCT) using only one or two phosphors. Using these emitters to replace the more commonly used iridium based emitters with ones based on more abundant elements in OLED devices, simpler device architectures (including efficient DFW-WOLEDs containing only two or three thermally evaporated organic materials) and lower material and/or device fabrication costs may be achieved while also providing improvements in stability, efficacy, brightness and color quality of white OLEDs. (March 2011)

Rensselaer Polytechnic Institute (RPI) Advances Efficiency of Non-Polar LEDs

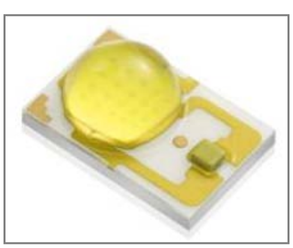


RPI has demonstrated non-polar green emitting LEDs with good efficiency and reduced 'droop.' Typically, LEDs used for SSL are grown in a polar crystalline orientation, often thought to be the cause of efficiency 'droop' at high current densities. LEDs grown in a non-polar orientation are theorized to have very little droop, but so far have not demonstrated high efficiency. RPI has demonstrated non-polar green LEDs emitting at 510 nm with a peak IQE of 12%. Conventional polar LEDs emitting at this wavelength have IQE around 40%, but demonstrate significantly reduced IQE at higher operating current (droop).The RPI result demonstrates that, with further work, non-polar green LEDs can expect to have IQE comparable to that of conventional polar LEDs and minimal droop. Currently, the low efficiency and droop of green LEDs limits the performance of Red/Green/Blue (RGB) SSL systems. RGB approaches have the potential to be significantly more efficient, with enhanced color quality and tunability, than phosphor converted white light systems that currently dominate the LED-based lighting market.(January 2011)

Sandia National Laboratory Develops Deep Level Optical Spectroscopy (DLOS) Technique to Identify Efficiency Killing Defects in LEDs

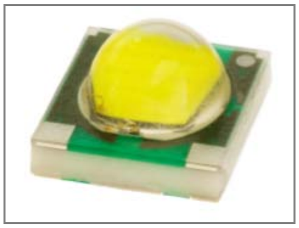
Sandia National Laboratory has developed a technique, unique in the world, to identify defect concentrations and energy levels in LEDs used for SSL. The technique enables the systematic understanding and minimization of defects in LED structures, which will result in the development of more efficient LEDs and LED-based light sources. The DLOS technique can also be used to determine the generation of defects over time and to better understand the physical mechanisms that lead to performance degradation over the life of the LED. This technique will aid future studies of how defects fundamentally impact important LED challenges such as efficiency droop, blue versus green efficiency, and potential implications for LED reliability. (March 2011)

Philips Lumileds Bests DOE FY2010 Performance Target



Philips Lumileds has indicated that their LUXEON Rebel cool white LED will soon be able to achieve an efficacy of 139 lm/W. The top bin LED, developed with a single InGaN die and phosphor conversion, shows high performance characteristics: up to 138 lm at 350 mA, with a forward voltage of 2.83 V. The CCT of the device is 5,385K and the CRI is 70. The performance gain partially results from improvements in chip level electrical injection efficiency and optical extraction efficiency, developed with funding from DOE. (August 2010)

Cree LEDs Deliver 121 lm/W



Cree's high power white LEDs can now deliver 121 lm/W at 35 A/cm^2 current density. Laboratory results for Cree's latest generation of devices based on their EZBright® LED chip platform have demonstrated an output of 267 lumens at a drive current of 700 mA and an operating voltage of 3.14 V. These devices generate white light with CCT of 6,850K and CRI of 72. The commercial version will be released as the XLamp XP-G product. The EZBright® LED chip platform was developed in part with funding from DOE. (August 2010)

New Class of Quantum Dots Makes the Leap from SBIR Project to Small Business Market Success

Renaissance Lighting, a Virginia based start-up acquired by Acuity Brands Lighting in August 2010, showcased an innovative commercially available downlight at the May 2010 LIGHTFAIR, applying a new phosphor-converted LED (pc-LED) technology with superior lumen efficacy and color rendering and offering warm color temperatures with spectrally tunable output. This promising product introduction has roots in a Small Business Innovation Research (SBIR) funded project initiated by Nanomaterials & Nanofabrication Laboratories in 2007, which improved the light extraction efficiency of pc-LEDs by incorporating high quantum efficiency doped nanocrystal quantum dots (D-dots™) into high index TiO_2 using sol-gel techniques. The D-dots, manufactured in Arkansas, have been incorporated by NNCrystal into high quality colloidal nanocrystals called Qshift Lucid. Renaissance Lighting combined Qshift technology with its patented Constructive Occlusion® optical technology to produce a tunable optic emitter providing 1,600 lumens, an output 30% greater than that achieved by comparable phosphor solutions, without the use of rare earth elements. (May 2010)

Universal Display Corporation (UDC) and Other Industry Leaders Team Up to Demonstrate High Efficiency OLED Ceiling Luminaire

UDC, along with project partners Armstrong World Industries and the Universities of Michigan and Southern California, have successfully demonstrated two phosphorescent OLED (PHOLED™) luminaire systems—the first of their kind in the U.S. This achievement marks a critical step in the development of practical OLED lighting in a complete luminaire system, including decorative housing, power supply, mounting, and maintenance provisions. Each luminaire has overall dimensions of approximately 15 by 60 cm and comprises four 15 by 15 cm phosphorescent OLED lamps. With a combined power supply and lamp efficacy of 51 lm/W, the prototype luminaire is about twice as efficient as the market leading halogen based systems. In addition, the OLED lighting system snaps into Armstrong's TechZone™ Ceiling System, which is commercially available in the U.S. (August 2010)

UDC Achieves World Records in OLED Performance

A pair of OLED projects funded under Phase II of DOE's Small Business Innovation Research (SBIR) program have resulted in world record OLED performance achievements. In the first project, UDC and University of Michigan researchers successfully assembled a stacked phosphorescent OLED (SOLED). Using an industry accepted standard lifetime measuring method L70, they recorded the longest lifetime yet for an all phosphorescent white light SOLED pixel: 37,500 hours at an initial luminance of 2,000 cd/m^2. In the second project, UDC achieved a 15 cm^2 phosphorescent OLED lighting panel with a measured efficacy of 66 lm/W at a luminance of 1,000 cd/m^2 by utilizing a novel fluid lens extraction technique. This key milestone is believed to mark a world record achievement of efficacy for a large area OLED device. (August 2010)

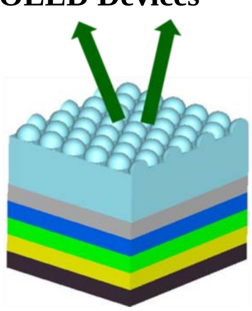
OSRAM SYLVANIA Demonstrates Downlight Luminaire with Light Output of 1,439 Lumens

OSRAM SYLVANIA researchers have demonstrated a downlight luminaire that achieves 1,439 lumens at an efficacy of 82 lm/W in steady-state operation. The white light is generated by an array of blue LEDs covered by a phosphor-coated glass disk. These results exceed the project goals of achieving 1,300 lumens and 70 lm/W at a CCT of 3,500K and CRI of 80. Improvements in LED chips, phosphors, optics, electronics, and thermal management at OSRAM all contributed to the higher than projected luminaire performance. (September 2010)

OSRAM SYLVANIA Demonstrates Small LED Light Source with 80 lm/W Efficacy

OSRAM SYLVANIA researchers are working to overcome the challenges of small form factor and high lumen output required to create a successful LED replacement for conventional halogen reflector lamps. Midway through the two year project, the team has demonstrated a small LED light source that achieves 350 lumens at an efficacy of 80 lm/W. The ultimate goal is 500 lumens with an efficacy of 100 lm/W. (August 2010)

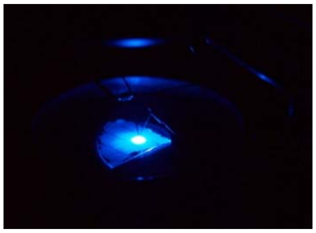
University of Florida and Lehigh University Improve Extraction Efficiency in OLED Devices



Because of the mismatch of index of refraction between organic materials, glass substrate, and air, the efficiency of OLEDs is significantly limited by total internal reflection. To address this, researchers at the University of Florida and Lehigh University are developing a thin film microlens array. Preliminary results demonstrate an increase in of about 60%. With further optimization, it is expected that the efficiency enhancement can exceed 100%. The new process uses rapid convective deposition of a suspension, which is low cost and can be scaled for large area manufacturing. While other techniques can achieve similar results, they are either too costly or have limited scalability. (August 2010)

Georgia Institute of Technology Demonstrates Improved LED Electron Blocking Layer

Georgia Institute of Technology has demonstrated a new InAlN electron blocking layer



within a GaN based LED structure. With no adverse effects on the LED active layers, the new electron blocking layer reduced efficiency droop by 14% compared to traditional AlGaN blocking layers when the LED was driven at higher current densities. Efficiency droop at high current density operation is an ongoing technical challenge within LED research. Understanding the underlying physical mechanisms of droop could lead to more efficient and lower cost LEDs. (August 2010)

Lightscape Materials, Inc. Improves the Efficiency of Phosphors for Use in LEDs

Red and green phosphors are typically integrated with blue LEDs to create efficient white emitting LEDs with good color rendering. However, phosphor efficiency degrades as the LED heats up during normal operation, a phenomenon known as phosphor thermal quenching. Thermal quenching reduces light output from LEDs and can cause a color shift. Working to overcome this limitation, researchers at Lightscape Materials have developed high efficiency red and green phosphors with thermal quenching of less than 10% at 150°C operation—less than half of the thermal quenching that occurs with conventional phosphor materials. These new phosphors may lead to white LEDs with better efficiency maintenance at higher temperatures and light output levels as well as improved color stability of the emitted light. (August 2010)

2.0 Lighting Market and Energy Use

The Energy Information Administration (EIA) estimates total U.S. primary electricity consumption to be 40 quadrillion BTU (quads) in 2010.[9] DOE estimates that lighting technologies across all sectors (residential, commercial, industrial, and outdoor) were responsible for nearly 10 quads of primary electricity in 2010.[10] In residential and commercial buildings, lighting is the second largest end-use of energy. DOE estimates that lighting constituted approximately 14% of residential building electricity consumption and 22% of commercial building electricity consumption in 2010. [11] New lighting technologies, especially solid-state sources, offer one of the greatest opportunities for electricity savings within the building sector and nationally. This chapter briefly summarizes the current state of the lighting market and the energy savings potential of SSL in various applications.

2.1 Lighting Market

The global market for lighting is estimated to be approximately $110 billion, of which the U.S. market share is estimate to be approximately 25%, or $27 billion. The market has shown a gradual trend towards energy savings over the course of the last decade. Figure 2.1 compares the 2001 commercial and residential breakdown of total lamp installations by technology type for the U.S. with similar data obtained for the state of California in 2006 and 2008.[12] Although California is not a perfect representation of the national trend, the data still serves to demonstrate a distinct transition from incandescent lamps to compact fluorescent lamps (CFLs) and fluorescent lighting.

In the residential sector, incandescent lamps have suffered a loss of market share as CFLs have gained popularity. When CFLs were initially introduced to the market, there was much resistance from residential consumers because of their high initial cost and performance issues, such as slow turn-on time, poor color quality, and problems with dimmability. However, this resistance to adopt the technology is starting to dissipate due to significant performance and efficiency improvements, recognition of energy and cost savings, and utility subsidies. CFLs are now a major player in the market, accounting for over 25% of all residential lamp sales in 2009.[13] As seen in Figure 2.1, though incandescent lighting still dominates the installed base, comprising approximately 60% of all lamps, the share of CFLs installed in homes has markedly increased from approximately 2% in 2001 to 22% in 2008. This trend is expected to continue with the implementation of EISA 2007 general service incandescent lamp standards. These

[9] Annual Energy Outlook 2011 Early Release. U.S. Energy Information Administration. Available at: http://www.eia.doe.gov/oiaf/aeo/index.html

[10] Energy Savings Potential of Solid-State Lighting in General Illumination Applications 2010-2030. Prepared by Navigant Consulting, Inc. for the Department of Energy. Washington D.C. February 2010.

[11] 2010 Building Energy Data Book, U.S. Department of Energy, Office of Planning, Budget and Analysis, Energy Efficiency and Renewable Energy. Prepared by D&R International, Ltd., October 2009

[12] The residential installed stock is based on the number of sockets; however, it is assumed that the ratio of sockets-to-lamps is 1.

[13] "CFL Market Share Rises During Second Quarter", Association of Electrical and Medical Imaging Equipment Manufacturers, August 2009

maximum wattage standards will begin to go into effect in 2012, and effectively require the efficacy of general service incandescent lamps to increase approximately 25%. Halogen incandescent lamps that meet these standards are currently commercially available. In addition, EISA 2007 also states that by 2020, the efficacies of general service lamps must be at least 45 lm/W. Currently, the only technologies capable of meeting these second tier efficacy standards are fluorescent, high-intensity discharge (HID) and LED.

While in the commercial sector there has been a similar movement from incandescent sources toward fluorescent sources, there has also been a distinct trend from lower efficiency magnetic T12 linear fluorescent systems toward higher efficiency T8 and T5 electronic systems. For example in 2001, T12 lamps constituted approximately 43% of the linear fluorescent installed base; in 2006, based on a California study, T12 lamps constituted only 12%. More recently, there has also been a trend toward an increased use of low wattage metal halide lamps as replacements for higher wattage halogen lamps in applications such as track and down lighting.

It is also important to note that although incandescent lighting sources dominate lamp installations, this does not necessarily reflect the types of light that are used most frequently. Incandescent lamps are mainly used in residential applications, and over the course of a day tend to be in use much less compared to commercial fluorescent lamps. Therefore, in terms of lumen-hours per year, fluorescent lighting represents the greatest lighting demand even though the majority of installations are incandescent.

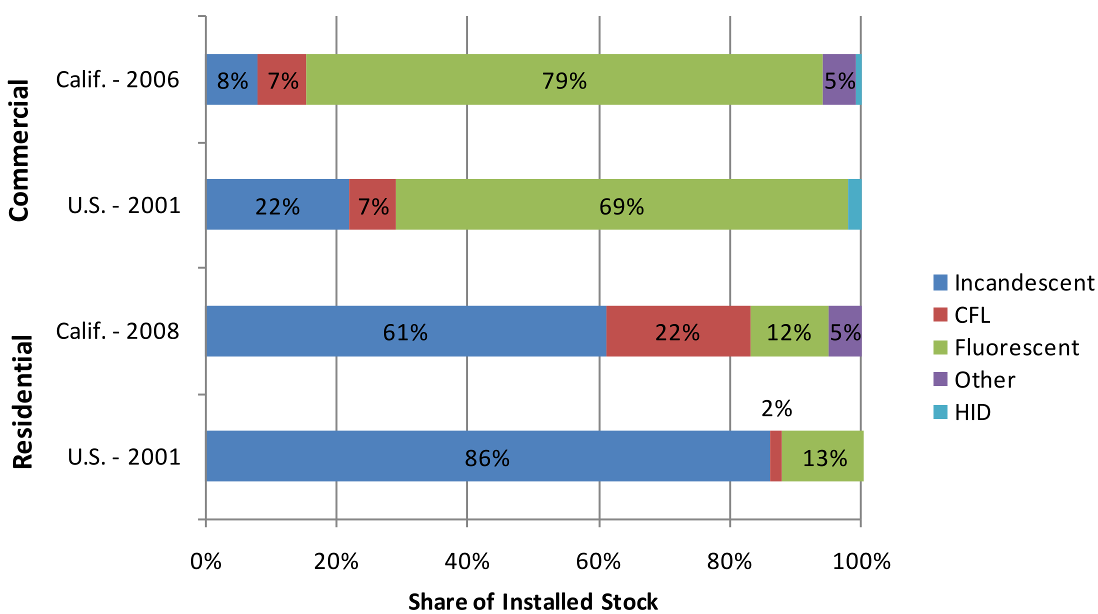


Figure 2.1: Estimate of the U.S. Installed Stock of Lamps (based on California data)
Sources: Residential – Final Evaluation Report: Upstream Lighting Program, CPUC
Commercial – California Commercial End-Use Survey, CEC

HID lamps such as mercury vapor, high-pressure sodium and metal halide have been the most common lighting technologies in use for outdoor area lighting. Today, yellow/orange high-pressure sodium lamps are still very common across a variety of outdoor lighting applications including roadway and parking lot. However, more recently, metal halide lamps have become the light source of choice for outdoor applications where color rendering is of importance. For example in 2001, the outdoor sector was comprised of 17% mercury vapor, 47% high pressure sodium, and 6% metal halide lamps; however, a recent study on several outdoor applications indicates that metal halide now comprise over 26% of lamps installed in the outdoor sector.[14] All conventional HID lamps, however, are also beginning to face significant competition from LED-based lamps. And in 2007 Raleigh, North Carolina became the first of a dozen U.S. cities to begin testing and replacing their conventional street and area lighting with LED fixtures. Currently, it is estimated that LED-based lamps account for roughly 1.5% of the total U.S. installed roadway, parking, area and flood outdoor lighting applications.

Though there has been a clear migration toward energy efficient lighting technologies over the past decade, the lighting market faces several challenges in further shifting to even higher efficiency technologies, such as SSL. In some cases, people are unaware of newer, more efficient lighting technologies or they are opposed to the technology's appearance and inherent characteristics. In other cases, the higher first cost will deter the consumer in spite of a lower total cost of ownership. In some instances the people who decide which lighting system to purchase (typically building contractors or landlords) are rarely those who pay the electricity of the building (building owners or renters). Because of these split incentives, building contractors, and thus lighting manufacturers, focus on low first-cost lighting instead of more expensive energy efficient lighting products with lower lifecycle costs. Therefore, the federal government can effectively take a leading role in supporting investments in energy efficient lighting.

2.2 Applications for Solid-State Lighting

LED-based lighting forms a small, but rapidly growing segment of the lighting market, and technical advances have enabled LEDs to make significant strides toward cost competitiveness for several sizable applications in outdoor and interior lighting. LED technology is capturing these new applications because it cost effectively offers higher quality light than less efficient conventional light sources such as incandescent, halogen incandescent, and compact fluorescent. At the 2009 Solar Decathlon cosponsored by DOE,[15] many of the universities' solar homes featured LED-based lighting products. Figure 2.2 shows photographs from this event of integrated LED lighting products that the university teams chose to incorporate into their designs.

In addition, DOE cosponsors two design competitions called "Next Generation Luminaires" and "Lighting for Tomorrow" to encourage the use of SSL products in a variety of applications in the residential and commercial sectors.[16] The Next Generation

[14] Includes roadway, parking, and area and flood lighting. Please refer to the report "Energy Savings Estimates of Light Emitting Diodes in Niche Lighting Applications," which can be found at: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/nichefinalreport_october2008.pdf.
[15] For more information on this event, see http://www.solardecathlon.org/.
[16] Details about the "Next Generation Luminaires" competition is available at: http://www.ngldc.org/. Details about "Lighting for Tomorrow" competition is available at: http://www.lightingfortomorrow.org/

Luminaires™ Solid State Lighting Design Competition seeks to encourage technical innovation and recognize and promote excellence in the design of energy efficient LED commercial lighting luminaires. Next Generation Luminaires encourages manufacturers to develop innovative commercial luminaires that are energy efficient and provide high lighting quality and consistency, glare control, lumen maintenance, and luminaire appearance needed to meet specification lighting requirements. In addition, Lighting for Tomorrow launched its 2011 competition on January 20, 2011 with a focus on lighting control devices and SSL fixtures and replacement lamps for the residential sector.

Exterior hanging light

Exterior porch light

Track light

Interior recessed can

Figure 2.2: LED Technologies Employed during 2009 Solar Decathlon

In addition to numerous interior lighting applications and small outdoor applications, LED-based street lamps are currently competing favorably with HID lamps in street, roadway, parking and larger outdoor area lighting applications. Several cities including Raleigh, NC, Austin, TX, and Ann Arbor, MI, have installed LED-based roadway and area lights to save on energy and maintenance costs.[17] The DOE SSL GATEWAY program has demonstrated installations of outdoor SSL systems in several other areas across the country.[18]

2.3 SSL Growth and Projected Energy Savings

Most of LED sales growth to date has come from high-brightness (HB) LEDs. Globally, sales of HB LEDs were $10.8 billion in 2010, and are estimated to grow to $18.9 billion in 2015.[19] Of the HB LED revenues, approximately $890 million, or 8%, was attributable to lighting applications with the remaining 92% representing mobile displays, automotive lighting, signs and displays, signals, and other small indicator lighting applications. Strategies Unlimited estimates that the global market for LEDs for lighting applications will increase to $4.5 billion by 2015.

[17] Details about the LED city program are available at: http://www.ledcity.org/.
[18] DOE's Solid-State Lighting GATEWAY program is at: http://www1.eere.energy.gov/buildings/ssl/gatewaydemos.html
[19] Business Wire, 2010 Worldwide High-Brightness Market Grew By 93 Percent According to Strategies Unlimited, http://www.businesswire.com/news/home/20110223005343/en/2010-Worldwide-High-Brightness-LED-Market-Grew-93

A 2011 study[20] analyzed the energy savings potential of LEDs in seven market segments that included outdoor and indoor general illumination.[21] Figure 2.3 summarizes the on-site electricity savings of the seven applications, as well as the total. Also displayed is the energy savings equivalent in terms of household electricity consumption. As shown, LEDs are achieving significant energy savings for several applications.

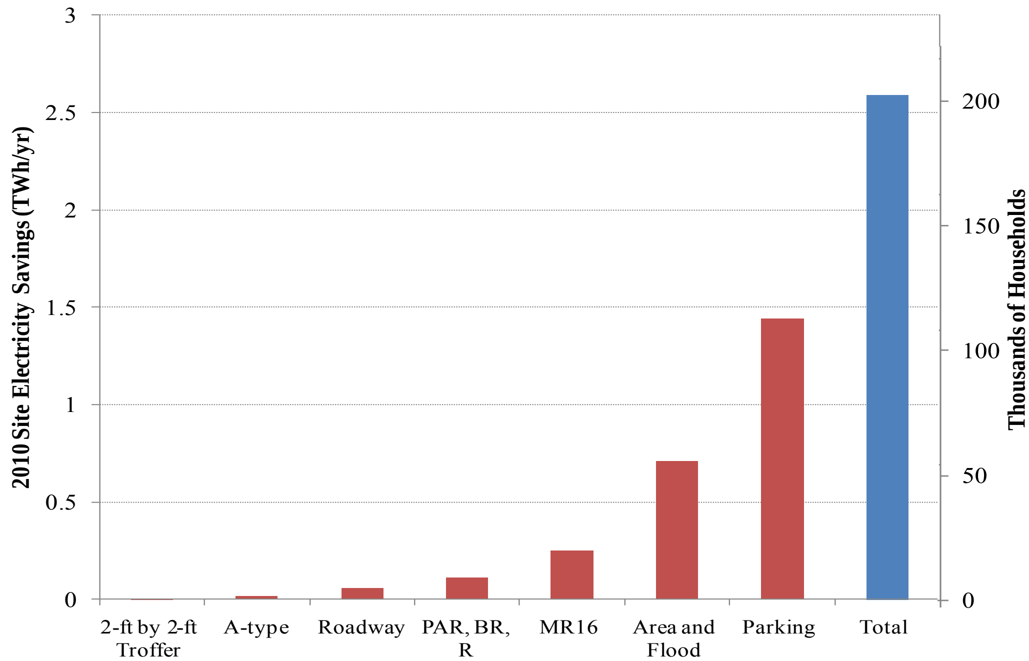


Figure 2.3: 2010 Electricity Saving from the Selected Niche Applications
Source: *Energy Savings Estimates of Light Emitting Diodes in Niche Lighting Applications*. Prepared by Navigant Consulting, Inc. for the Department of Energy. Washington D.C. January 2011.

Figure 2.3 shows that in 2010, the penetration of LEDs in the seven general illumination and outdoor applications analyzed in this report resulted in a total realized electricity savings of 2.6 TWh per year, which is equivalent to the electricity needed to power over two hundred thousand average U.S. households. It also shows that the electricity savings attributable to LEDs in 2010 were dominated by outdoor parking lighting, where LEDs have achieved an estimated 4.3% market penetration. This application represents about 56% of the total energy savings from the use of LEDs in 2010. After parking lighting,[22] the market application with the second greatest energy savings in 2010 was area and

[20] To review the complete analysis, please refer to the report "Energy Savings Estimates of Light Emitting Diodes in Niche Lighting Applications," which can be found at: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/nichefinalreport_october2008.pdf.
[21] In the 2011 "Energy Savings Estimates of Light Emitting Diodes in Niche Lighting Applications" report, outdoor lighting includes roadway, parking, area and flood and residential outdoor lighting. General illumination considered PAR, BR and ER lamps, MR16, 2-ft by 2-ft troffers and A-type replacement lamps.
[22] Parking lighting only includes off-street parking and has been divided into covered parking garage lighting and parking lot lighting.

flood lighting,[23] which contributed to 27% of the total site electricity savings in 2010 and has an LED penetration of about 0.72%. LED MR16, PAR, BR and R, as well as roadway lamps, also demonstrated significant energy savings, in total representing 16% of the total 2010 savings. Other sectors such as 2-ft by 2-ft troffer fixtures and A-type replacement lamps have low levels of LED penetration, and thus contribute less than one percent to the 2010 savings, though energy savings in white light applications such as these are expected to increase in coming years.

A 2010 study[24] examined the national energy savings that could be realized through the market penetration of energy efficient SSL in general illumination applications if the technology achieves DOE forecasted price and performance objectives. Projections were made for three conventional technology improvement scenarios, which forecast efficacy, price, and other performance parameters for three different rates of technology improvement.[25] These energy savings projections indicate that while SSL products have relatively low penetration in the general illumination market now, the energy savings is expected to reach 2.05 quads a year starting in 2030, or a 25% reduction in lighting energy use. That represents enough electricity to illuminate more than 95 million homes in the U.S. today.

[23] Within the lighting industry, area and flood lighting often includes both parking and roadway lighting, however, this analysis quantifies these applications separately. In this analysis area and flood lighting are defined as lights that illuminate various outdoor areas such as landscapes, walkways, and common spaces.

[24] Energy Savings Potential of Solid-State Lighting in General Illumination Applications 2010-2030. Prepared by Navigant Consulting, Inc. for the Department of Energy. Washington D.C. February 2010.

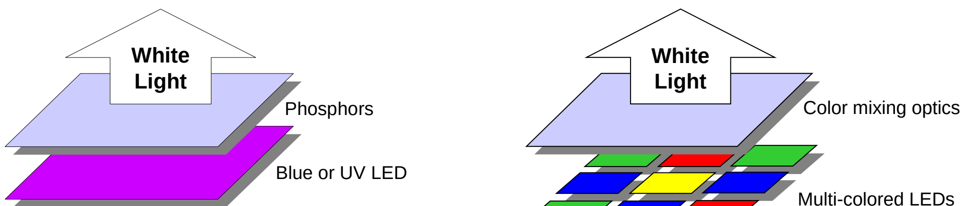
[25] For more information on these technology improvement scenarios, please see the DOE report at: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_energy-savings-report_10-30.pdf

3.0 SSL Technology Status

This chapter outlines the current status of LED and OLED technology, as well as a comparison of established incumbent lighting technologies, including incandescent, fluorescent and HID. Also provided is an overview of the typical initial and lifetime costs associated with SSL and incumbent commercially available replacement lamps.

3.1 Light-Emitting Diodes

LEDs are discrete semiconductor devices with a narrow-band optical emission that can be manufactured to emit in the ultraviolet (UV), visible or infrared regions of the spectrum. To generate white light for general illumination applications, multiple colors must be controllably mixed. White light LEDs components and luminaires are typically based on one of three approaches: (a) phosphor-conversion, (b) discrete color-mixed, and (c) a hybrid consisting of phosphor converted (white) and monochromatic packages (or different LEDs in a single package). Figure 3.1 shows two of these approaches to white light production.



(a) Phosphor-Converted LED **(b) Color-Mixed LED**

Figure 3.1: General Types of White Light LED Packages

The phosphor-converted (pc) LEDs create white light by blending a portion of the blue light emitted directly from the LED die with light emission down-converted by a phosphor located either within the LED package or spaced from the LED light source (remote phosphor). Discrete color-mixed packages, on the other hand, blend together the light output from discrete LED sources with different emission wavelengths, creating white light.

In the pc-LED approach, an LED die emits blue light, generally around 450 to 460nm. Some of this light is emitted directly, and some of it is down-converted by a phosphor from the 450 to 460nm wavelength (blue) to longer wavelengths (e.g., green, yellow, red) to produce white light. Some manufacturers have successfully lowered the CCT and increased the CRI by adding a second phosphor to the package. These warm white packages are currently available with an efficacy of 87 lm/W and a CCT of 3000 K at a current density of 35 A/cm^2.

One of the challenges confronting manufacturers of pc-LED devices is the difficulty of maintaining consistent white light due to natural variations in the LED pump (blue) wavelength and in the deposition of the phosphors. The white light produced by pc-LEDs is susceptible to variations in LED optical power, peak emission wavelength, and operating temperature. Additionally, variations in phosphor thickness and thermal quenching of the phosphor at different operating conditions can lead to color shift, and phosphor stability can affect color over lifetime. Thus, noticeable variations in color appearance can occur from one pc-LED to another as well as lead to color shift over time, a potentially serious problem for many lighting applications. Both Philips Lumileds and Cree have recently announced much improved color accuracy.[26] This has been accomplished through improvements in color uniformity of the LED chips and improvements in the color matching of the phosphors to the LED chip emission wavelength.

Stokes' loss, the energy difference between the LED pump wavelength and the phosphor emission wavelength, is a fundamental loss mechanism in the phosphor conversion process limiting the efficiency of pc- LEDs. In addition, some phosphors have relatively low quantum efficiencies. Most phosphors lead to optical scattering losses and phosphor emission spectra are generally very broad which can reduce the spectral efficiency by producing light outside the visible spectrum. This in turn reduces the maximum potential efficacy of the LED.

For these reasons, discrete color-mixed LEDs are thought to promise the highest theoretical efficacy for SSL. Color mixing combines emissions from two or more LED dies to generate white light. Color mixing can also include a hybrid approach, wherein white pc-LEDs are used along with colored LEDs to achieve higher spectral efficiency improved color quality, and higher efficacy. Hybrid designs require new phosphor formulations to maximize efficiency and still result in some Stokes loss. Both approaches require controls for maintaining color stability as the different LEDs respond differently to temperature variations and ageing, and a means of blending the discrete colors may be necessary. Some excellent examples of hybrid LED designs are on the market today with very good color performance, and analysis has shown that with direct color-mixing a high luminous efficacy of radiation can be achieved for good color quality white light.

However, the efficiency of the color-mixed approach is currently limited by the low efficiency of green and amber emitting LEDs, and may require an optical design to effectively and efficiently mix the light output from the multiple color LEDs. This approach can also require more complicated control circuitry to maintain the white color point. The different color LEDs respond differently to variations in temperature and current density, and degrade at different rates over their lifetime. The control circuitry is necessary to compensate for these effects and can reduce the efficiency of the system.

Another important attribute of LEDs is that they show a slow but significant depreciation of lumen output over time. However, the character of this depreciation varies widely with specific package designs, and depends on several mechanisms intrinsic to the LED chip, the phosphor material, lens material, and other assembly related package issues. Consequently, lumen depreciation of a given LED design is very difficult to project over

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[26] Cree press release can be found at http://www.cree.com/press/press_detail.asp?i=1288616204417, and the Philips Lumileds press release can be found at http://www.philipslumileds.com/uploads/news/id136/PR148.pdf

long periods of time. The Illuminating Engineering Society of North America (IESNA) standard LM-80[27] describes an accepted method for measurement of the change in light output over time for an LED package, but does not provide a method for extrapolating the change to longer time periods than measured. IES TM-21, which is soon to be released, does provide a method of estimating a time for a specific amount, typically 30% of lumen depreciation. Also, lumen depreciation is only one aspect of lifetime. Other failure mechanisms exist, including such things as connection or adhesion failures or optical lens failure, which may be caused by manufacturing defects, inadequate materials control, or moisture penetration. When incorporated into a luminaire, many additional failure mechanisms may further reduce product life. These issues are more fully discussed in the DOE/NGLIA document, *LED LUMINAIRE LIFETIME: Recommendations for Testing and Reporting*.[28]

3.2 Organic Light-Emitting Diodes

OLEDs are thin-film multilayer devices based on organic molecules. As with inorganic LEDs, the objective is to convert energy from electrical current flowing between two electrodes into visible light resulting in light emitting into the external environment. The major distinction between inorganic and organic LEDs for the application of lighting is the form factor. OLEDs produce light at relatively low intensity spread over large areas, while LEDs are more compact sources.

In most OLEDs the current flows through organic materials confined between planar electrodes with a separation that is typically only about 100 nm. Multiple layers are required to assure balanced transport of electrons and holes and the production of light with the desired color qualities. Most devices use red, green and blue emitters that can be arranged in several configurations to produce white light, as illustrated in Figure 3.2.

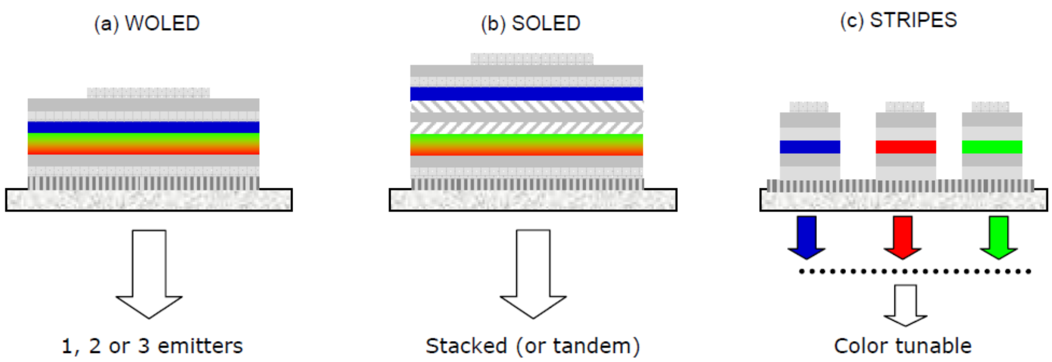

Figure 3.2: Three Arrangements on Red, Green, and Blue Emission Layers
Source: UDC

In order for the light to escape from the device, at least one of the electrodes must be transparent. Because of the high sensitivity of organic materials and cathode metals to oxygen and water, the structure must be encapsulated using a non-porous substrate, cover

[27]The LM-80 standard can be found at http://www.ies.org/store/site/search.cfm?search=lm-80
[28] http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/led_luminaire-lifetime-guide.pdf

and edge seals. However, due to the index of refraction mismatches between the organic layers, transparent electrode, substrate and air, further light extraction surfaces must be added to reduce wave guiding of light in these layers. Finally, in all but the smallest devices, a current spreading structure must be provided to ensure uniform transmission of current from the edge of the device across the whole panel.

OLED technology for general illumination applications is in a critical stage of development. OLEDs have been very successful as display in handheld devices and show great promise for flat-panel televisions. Many challenges still remain in the adaptation of the technology to lighting applications, and in the reduction of the production cost to levels appropriate for general illumination. Despite continued development of this technology, OLED lighting panels have only been available as lighting design kits or in prototype luminaires with modest performance at very high prices for niche applications.

Several aspects of OLED technology development have become clearer in the past year.

- Polymeric emitters have not yet demonstrated the efficacy necessary for general illumination applications;
- It is possible to adapt small molecule emitters to processing in solution, with only small penalties in efficacy and lifetime, so that printing techniques can be used in material deposition and patterning;
- The major obstacle to achieving efficacy targets is the trapping of light inside the OLED device. Some of the techniques suggested to enhance light extraction can be implemented on small laboratory devices, but may not be suitable for high volume production of large panels;
- Phosphorescent red and green materials have demonstrated excellent lifetime and efficiency. The use of blue phosphorescent emitters would be desirable, but adequate lifetime has not yet been achieved. Some groups are investigating efficient hybrid systems in which fluorescent blue emitters are combined with phosphorescent red and green emitters. The energy that is initially trapped in triplet states of the blue emitters can be transferred to the red and green emitting molecules;
- It seems very unlikely that transparent conductors can be developed with sheet resistances low enough to allow effective transport of current across a large panel using only a thin homogeneous sheet. Alternative architectures such as tandem OLED structures or additional current spreading mechanisms, such as wire grids, must be used. The use of a current spreading approach can allow for more flexibility for choice of the transparent conducting material;
- Encapsulation remains a concern, even for devices fabricated on rigid substrates. Although multilayer barrier coatings have been developed that provide adequate protection for OLEDs on flexible substrates, it has yet to be demonstrated that defect free coatings can be fabricated at acceptable costs for lighting applications;
- Prototype panels have demonstrated performance levels acceptable for general illumination applications. Commercial production of these panels is anticipated within the next year, but the low manufacturing volumes and consequent high cost will still deter widespread adoption; and

- The introductory manufacturing stage will rely heavily on equipment and production processes that have been developed for display applications, which are currently designed for small panels and produce relatively little light. Thus early OLED luminaires are likely to use tiled panels or chandelier like fixtures.

One special focus of current OLED lighting research is the development of materials and structures that are appropriate for large area panels. Pixel sized OLED devices have achieved efficacies as high as 124 lm/W, whereas the best commercially available OLED panels have efficacies of only 28 lm/W. It is projected that the performance gap between LED lamps and OLEDs with respect to the basic metrics, such as efficiency, lifetime, color quality and cost/kilolumen will be reduced significantly by 2020. Details of the anticipated savings in production costs will be provided in the 2011 update to the SSL Manufacturing Roadmap.

3.3 Worldwide R&D in SSL Technology

LED-based SSL technology has its roots in the initial demonstration of a high performance blue LED-based using GaN by Nichia in 1993. More specifically, a few years later, the same group demonstrated a white LED through combining the blue LED with a YAG phosphor. This set the scene for SSL. Subsequent to these announcements there was an explosion of R&D activity worldwide culminating in the commercial availability of white HB LEDs from Nichia (Japan), Toyoda Gosei (Japan), Philips Lumileds (U.S.), Cree (U.S.), and OSRAM (Europe). These companies continue to be major players in this market, but patent cross licensing has opened up the market to other players and has broadened the R&D base. A 2009 analysis of worldwide patent activity[29] recognized growing R&D activity in Asia, partly in Korea because of Samsung's role, and partly in Taiwan and mainland China. LED manufacturing is now a global business and the supporting R&D activities are also located globally.

R&D activity in Europe is generally coordinated through industry consortia such as the European Photonics Industry Consortium (EPIC)[30] and voluntary cross-border associations such as Photonics21.[31] Much of the government funding is channeled through European Union collaborative R&D projects. In the area of LED-based SSL technology there are a number of projects currently underway including SSL4EU, SMASH, SINOPLE, RAINBOW, ECOSTREETLIGHT and THERMOGRIND. These projects have a combined project cost of approximately $43 million with project funding of $31 million from the EU, and are typically three years in duration. The two largest programs (SSL4EU and SMASH) are fronted by OSRAM. In addition, IMEC (Belgium) launched an industrial affiliation program (IIAP) in 2009 that focuses on the development of GaN-on-Si process and equipment technologies for manufacturing LEDs and next generation power electronics components on eight inch Si wafers. This multi-partner GaN R&D program includes Micron Technology, Applied Materials and Ultratech.

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[29] "SSL technology development and commercialization in the global context", Kenneth L. Simons and Susan Walsh Sanderson, EERE Programmatic Lighting Support program, award 570.01.05.007.

[30] www.epic-assoc.com

[31] www.photonics21.org. Note that their Strategic Research Agenda (SRA) "Lighting the way ahead" was published in January 2010.

In Taiwan, the primary source of R&D funding is the business sector, at around 70%, followed by the government, at around 30%. The main research institute for LED R&D is the Industrial Technology Research Institute (ITRI) which recently announced it was setting up a LED research center with Oxford Instruments, and has embarked on a three year project to develop cheaper, longer lasting LED backlights. Total investment in the LED industry was thought to top $600 million in 2010, the largest amount worldwide. Much of this will be for manufacturing equipment and infrastructure with key companies including Epistar, Everlight, TSMC, Excellence Opto, Unity Opto, etc. For example, TSMC is scheduled to complete the $170 million first phase engineering work for its LED R&D and manufacturing center by year-end and to begin mass production in the first quarter of 2011 with technology licensed from Philips. TSMC is reported to be planning to establish a vertically integrated activity covering epitaxy, packaging and module manufacture, and to release its own brand of LED lighting sources and light engines.[32]

The private sector is a key player in Korean R&D activities, contributing around 74% of R&D funding in 2007. The major contributors to Korean R&D activity are Korean global companies in high tech industries, such as Samsung electronics, LG electronics, Hynix and Hyundai Automobile. In Korea the white LED activity has been driven primarily 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 are now well established at these and other companies such as Seoul Semiconductor, and that expertise is expected to be turned increasingly toward the production of lighting class LEDs as the demand for LED televisions begins to saturate and oversupply begins to erode prices.

China has identified LED manufacturing as an important strategic market and has provided significant financial incentives for companies to locate in China, including tax incentives, equipment subsidies, and funding for R&D. In particular the government has provided approximately $1.6 billion in subsidies for the purchase of MOCVD equipment (up to $1.8 million per machine). Consequently, China's installed base of such equipment has risen from 135 in 2009 to around 300 at the end of 2010, and an anticipated 900 by 2012 and 1500 by 2015. A total of thirteen industrial science parks have been established throughout the country for SSL R&D and manufacturing. Patent activity in China has increased significantly in the past few years with 28,912 LED related patents at the end of 2009, including 59% on applications and 13% on packaging.[33]

Up until recently, R&D in OLED technologies has focused on display applications. The initial research in the 1980's was performed in the U.S. and Europe, following the pioneering work on small molecule emitters by Eastman Kodak and on light emitting polymers at Cambridge University and Cambridge Display Technologies. The most significant discovery of the 1990's was that of phosphorescent emitters at the University of Southern California and Princeton University, subsequently developed by UDC.

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[32] Mutek International Co, http://www.mutek.com/news/industry-news/44-taiwan-led-investment-top.html
[33] "China SSL Technology and Industry Development Strategies" Yuan-Fu, CSA Consulting, Jan 2011

Since 2000, the manufacturing of OLED displays has been pursued almost exclusively by Asian companies and the production has been supported by a broad range of R&D activities. The IP from Eastman Kodak was sold to LG Chemical (Korea) and that of Cambridge Display Technologies to Sumitomo Chemical (Japan).

Research specific to lighting has been promoted through several government programs in Asia, Europe and the U.S. Several multinational projects have been supported through the European Union. The goal of the initial four year initiative (2004 to 2008) OLLA was a white OLED with efficacy of 50 lm/W and lifetime of 10,000 hours. This was followed by three projects in the period from 2008 to 2011. The targets for OLED100 include efficacy of 100lm/W, lifetime of 10,000 hours and manufacturing costs of €100/m^2 on substrates of 1 m^2. Project COMBOLED is focused upon printing techniques and transparent devices, while Fast2light is exploring roll-to-roll production on flexible substrates. Total funding has been approximately $75 million, distributed over many countries.

Among the several national consortia in Europe, the programs coordinated by the German Federal Ministry for Education and Research (BMBF) are the strongest, with total investment exceeding $200 million. The initial OPAL and Rollex projects (2006 to 2009) led to four new programs. The goal of TOPAS 2012 is to produce a 1,000 lumen device based upon phosphorescent emitters. Light In-Line (LIli) is focused upon processes and equipment to reduce manufacturing costs, whilst NEMO and S-Light are exploring a broad range of new materials. The Rollex project has also been extended to include lighting applications.

OLED lighting research in Asia has been stimulated by government supported consortia in Taiwan, Korea and Japan. For example, in 2003 the New Energy and Industrial Technology Development Organization of Japan (NEDO) sponsored the formation of the Research Institute for Organic Electronics in Yamagata, with the following roadmap shown in Figure 3.3.

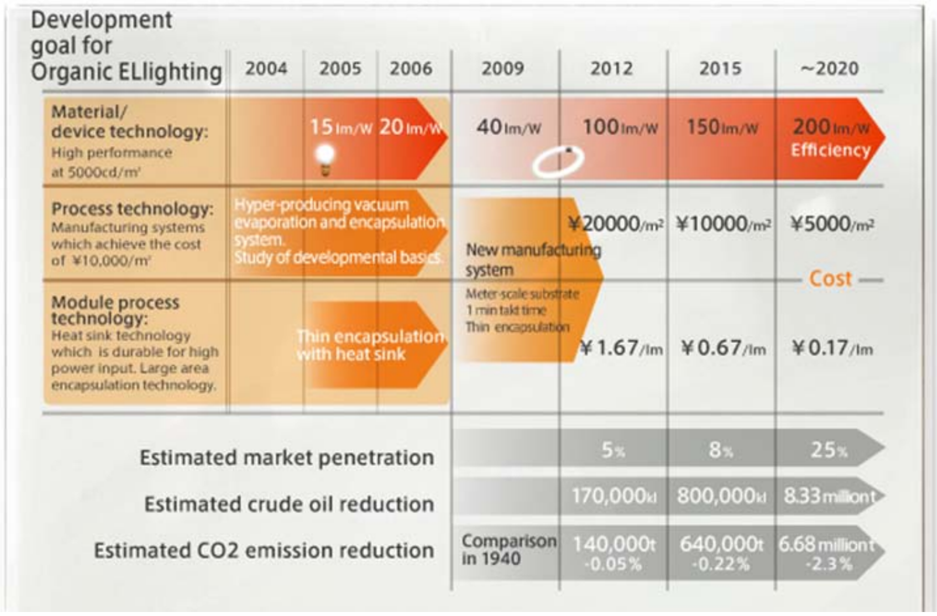

Figure 3.3: Roadmap for the OLED Lighting Project funded by NEDO
Source: Research Institute for Organic Electronics

Although many universities in Asia are now conducting research in OLED lighting, the largest efforts are in major companies who are pursuing material and equipment development as well as device design and manufacturing processes. Market competition is anticipated between companies in Korea and Taiwan that are trying to leverage their dominance of OLED display production into lighting products, as well as Japanese companies that are currently focusing on lighting applications.

3.4 Comparison to Incumbent Technologies

Though replacement lamps currently only represent a small portion of the SSL market, due to the large installed base of medium screw base sockets, they are often targeted as the largest near term market opportunity for SSL. This section provides some comparisons of LED-based replacement lamps with various incumbent lamp technologies. LED-based replacement lamp technology has shown commercial products with more than twice the efficacy of some of today's most efficacious white light sources. Figure 3.4, developed from historical lighting catalogues and the SSL projections discussed in Chapter 5.0, depicts this potential.

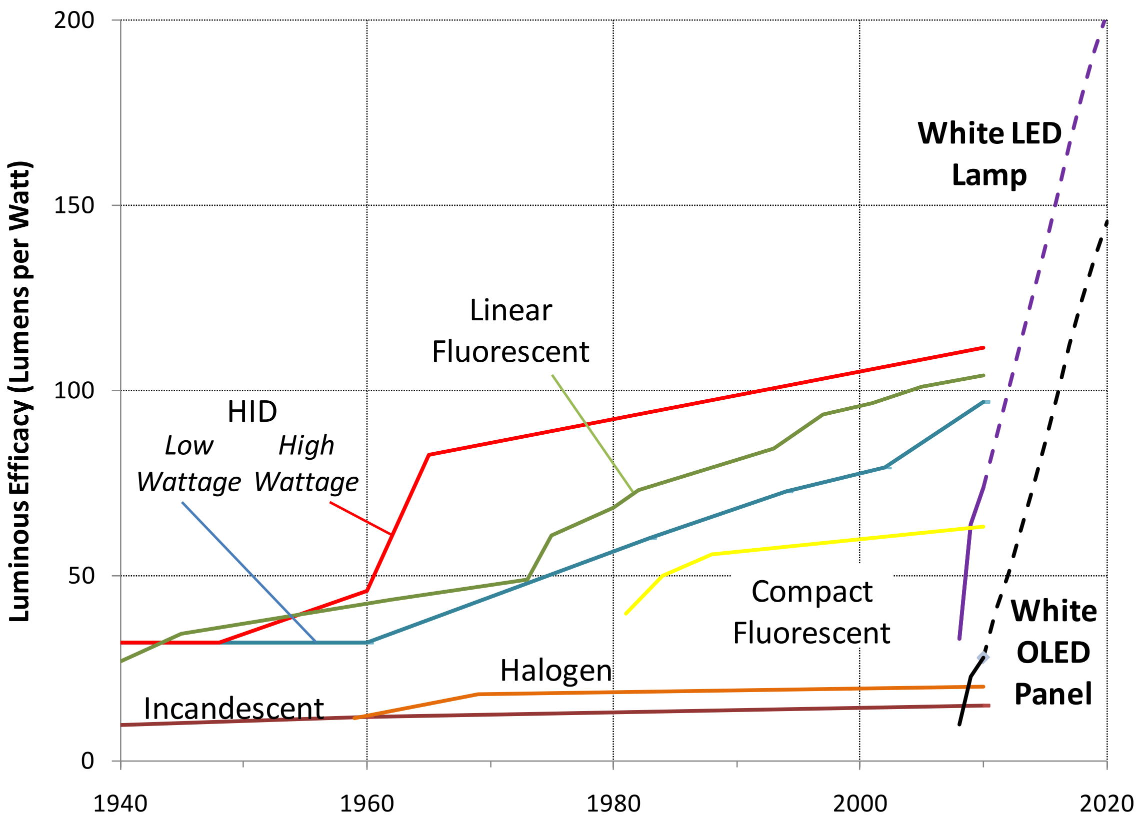

Figure 3.4: Historical and Predicted Efficacy of Light Sources[34]
Source: Navigant Consulting, Inc - Updated Lumileds' chart with data from product catalogues and press releases
Note: Efficacies for HID, fluorescent, and LED sources include driver or ballast losses.

The traditional three light sources – incandescent, fluorescent (which includes CFLs and linear fluorescent) and HID – have evolved to their present performance levels over the last 70 years. As LED and OLED research progresses, conventional energy efficient lighting technologies continue to improve in efficacy and cost through the efforts of the major manufacturers, further raising the bar for market penetration of SSL. This section outlines the research directions for conventional and SSL technologies and the potential for higher efficacy lamps from this research.

Current incandescent and halogen incandescent light sources range in efficacy from 3 to 20 lm/W.[35] Research is being conducted on higher efficiency halogen incandescent light

[34] LED Luminaire and OLED panel projections based on Chapter 5.0. SSL data points have not been tested by independent sources. Luminous efficacies depicted are for lamps with lumen output similar to following technologies:
60 Watt incandescent lamp;
75 Watt halogen lamp;
100 Watt HID lamp (low Wattage);
400 Watt HID lamp (high Wattage);
15 Watt CFL; and
4-foot MBP 32 Watt T8 lamp.
[35] U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy. Final Report: U.S.

sources and has the potential to incrementally raise the efficacy of these lamps. Basic and applied research and product development are being conducted on advanced infrared reflectors and selective radiators that tailor the spectrum of incandescent emissions to maximize emission in the visible spectrum. Some researchers claim that halogen incandescent sources may be able to achieve efficacies greater than 45 lm/W.[36] These efficacies are thought to be achievable through combinations of burner design, IR coating design and deposition process and, in some instances, filament temperature increase. The latter can be accompanied by reductions in operating lifetime.

Efficacies for fluorescent lamps range from 25 to 118 lm/W, depending on length, wattage, and color temperature. However, this efficacy does not account for ballast losses, resulting in overall system efficacies for fluorescent systems as high as 108 lm/W (see Table 3.1). Recent improvements in linear fluorescent system efficacy have included a movement toward higher efficiency ballasts and T5 lamps. Other means to improve efficacy of fluorescent lamps include reducing the voltage drop at the electrodes, and use of a greater composition of higher efficacy rare earth phosphors.

HID lamps (including mercury vapor, metal halide, and sodium vapor lamps) are the most efficacious lamps currently on the market, with efficacies ranging from 25 to 150 lm/W, while efficacies for HID systems can be as high as 111 lm/W (see Table 3.1). However, the highest efficacies (found in sodium vapor sources) are often achieved at the expense of color quality. Ceramic metal halide lamps, some of which achieve color rendering comparable to incandescent and fluorescent sources, have achieved efficacies as high as 120 lm/W and laboratory results have reported efficacies exceeding 150 lm/W.[37] Further improvements in ceramic metal halide lamps are also expected through the use of electronic ballasts, improved driver efficiency and breakthroughs in microwave technology.[38]

Commercial LED-based light sources have the potential to surpass the efficacy of the most efficient conventional light sources, and in 2010 achieved efficacies of 93 and 130 lm/W for commercially available warm and cool white LED packages.[39] Laboratory results have shown values as high as 208 lm/W (see Figure 5.4). In addition, ongoing R&D in a variety of areas, as outlined in this report, is expected to raise the efficacy of commercial warm and cool white LED packages to approximately 266 lm/W by 2020. Current LED performance and this potential sets LED-based SSL apart as, the most efficacious and promising lighting technology.

Lighting Market Characterization, Volume I: National Lighting Inventory and Energy Consumption Estimate. 2002. Washington, D.C. Available at: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/lmc_vol1_final.pdf

[36] Deposition Sciences Incorporated, 2010.

[37] K. Stockwald, et al., *Significant Efficacy Enhancement of Low Wattage Metal Halide HID Lamp Systems by Acoustically Induced Convection Configuration*, ICOPS 2008, Karlsruhe, Germany, June 2008.

[38] NEMA, *The Strengths and Potentials of Metal Halide Lighting Systems*, Rosslyn, Virginia. 2010.

[39] Philips Lumileds, 2010. CREE, 2010. Product Catalogs.

LED replacement lamp products (as shown in Figure 3.4 and Table 3.1) generally offer efficacies that are lower than the LED package efficacy, due to losses in the luminaire and power supply. Commercially available LED lamps currently reach efficacies as high as 64 lm/W. An LED-based lamp refers to an integrated assembly comprised of LED packages (components) or LED arrays (modules), LED driver, ANSI standard base and other optical, thermal, mechanical and electrical components (see Section 5.1.1. for further definitions). LED replacement lamps are compared throughout the report due to their popularity and the likelihood that these products will be the largest near term market opportunity for LED lighting technology. LED lamps, since they include the electronic driver, should be compared to HID and linear fluorescent systems. However, LED luminaire products with optimized form factors are able to better utilize the inherent benefits of LED technology, and can produce efficacies that are significantly greater.

While the performance of commercially available OLED panels has not yet met lumen output or cost targets, panels are available with efficacies up to 28 lm/W. Some laboratory OLED panels are surpassing efficacies of conventional technologies such as incandescent, halogen, and compact fluorescent lighting. The best laboratory efficacy for an OLED panel is currently around 66 lm/W.

As indicated above SSL offers extraordinary potential, and offer efficacies far greater than traditional incumbent lighting sources. However, there are still factors that need to be improved in order to further accelerate adoption. In order to successfully compete with the most incumbent lighting technologies, lower first costs of LED and OLED products are necessary (see Section 3.5 for description of SSL and incumbent lighting technology costs). In addition, the efficiency of SSL products needs to continue to improve in order to fully compete with highly efficacious fluorescent and HID lamps. Ongoing research is still required to fully realize the potential of this technology for creating efficient white light.

Table 3.1 presents the performance of 2010 SSL products on the market[40] in comparison to some of the most efficient conventional technologies. Additional performance attributes (such as lifetime and CRI) have been provided for context, and are not meant to represent the optimum levels of performance. As can be seen below, some of the SSL products available today have efficacies exceeding conventional light sources.

[40] It should be noted that LED laboratory prototypes reach much higher efficacies than those listed in Table 3.1.

Table 3.1: SSL Performance Compared to Conventional Lighting Technologies in 2010

Product Type	Luminous Efficacy	Luminous Output	Wattage	CCT	CRI	Lifetime
LED White Package (Cool)	130 lm/W	130 lm	1 W	5650 K	70	50k hours
LED White Package (Warm)	93 lm/W	205 lm	2.2 W	3500 K	80	50k hours
LED A19 Lamp (Warm White)[41]	64 lm/W	800 lm	12.5 W	2700 K	80	25k hours
LED PAR38 Lamp (Warm White)[42]	52.5 lm/W	1050 lm	20 W	3000 K	80	25k hours
OLED Panel[43]	28 lm/W	50 lm	2W	2700-6500 K	80	8k hours
HID (High Watt) Lamp and Ballast	120 lm/W 111 lm/W	37800 lm	315W 341W	3000 K	90	20k hours
Linear Fluorescent Lamp and Ballast	118 lm/W 108 lm/W	3050 lm 6100 lm	26W 56W	4100 K	85	25k hours
HID (Low Watt) Lamp and Ballast	104 lm/W 97 lm/W	7300 lm	70W 75W	3000 K	90	12k hours
CFL	63 lm/W	950 lm	15W	2700 K	82	12k hours
Halogen	20 lm/W	970 lm	48 W	2750 K	N/A	4k hours
Incandescent	15 lm/W	900 lm	60W	3300 K	100	1k hours

Notes: For LED packages (defined in Section 5.1.1) - drive current density = 35 A/cm^2, T_j=25°C., batwing distribution, lifetime measured at 70% lumen maintenance. Sodium lamps are not included in this table. Source: GE 2010, Cree 2010, Philips Lighting 2010, OSRAM Sylvania 2010 product catalogs, LED lamp based on Lighting Facts product registrations.

3.5 Cost of Light Sources

The prices of light sources are typically compared on a price per kilolumen basis. The first costs for principal replacement lamps indicate the degree of the challenge facing SSL in the marketplace in 2010:

41 Based on Lighting Facts Label data for Osram SylvaniaUltra LED12A19/DIM/F/927
42 Based on Lighting Facts Label data for GE Energy Smart LED20P38S/FL
43 Verbatim, 2011 color tunable panel.

Incandescent Lamp (A19 60W high efficiency)	$0.5	per kilolumen
Compact Fluorescent Lamp (13W)	$2	per kilolumen
Compact Fluorescent Lamp (13W dimmable)	$10	per kilolumen
Fluorescent Lamp and Ballast System (F32T8)	$4	per kilolumen[44]
LED Lamp (A19 60W dimmable)	$50	per kilolumen[45]
OLED Panel[43,46]	$2,560	per kilolumen[47]

On a normalized light output basis (dollars per kilolumen), LED lamps remain around 100 times the cost of the incandescent light bulb and around five times the cost of an equivalent dimmable CFL,[48] but the price of LED lamps is expected to continue to fall rapidly and the performance is expected to continue to improve. As a consequence, LED light sources are projected to become increasingly competitive on a first cost basis.

The first OLED products are only now becoming commercially available, and as the table above shows these products are not yet cost competitive. However, these products serve to introduce the new light source to the market and prices are expected to decrease rapidly, similar to LEDs.

While the first cost of a lamp is an important parameter, it is the lifecycle cost that ultimately determines the overall economic benefit. The GATEWAY demonstration projects represent an excellent source of lifecycle cost analyses for a variety of LED lamp installations[49] in actual operating environments. These economic analyses use the National Institute of Standards and Technology's Building Life-Cycle Cost (BLCC) software, which calculates the lifecycle costs for energy conservation projects that have significant upfront costs, but save energy over the long term. A good recent example is the assessment of LED retrofit lamps for the San Francisco Intercontinental Hotel. This study concerned the replacement of 287 existing 20 W premium halogen MR16 lamps and 40 W PAR30 lamps with LED equivalents rated at 6 W and 11 W respectively. On a first cost basis the LED lamps were between five and seven times more expensive than the halogen lamps. However an analysis of the capital, maintenance, and energy costs of the retrofit projected over a three year period concluded that the payback period was as short as 1.1 years. As the first cost of the LED lamps reduces, so will the payback period.

Not all lighting applications will experience this level of payback, but this example serves to illustrate the importance of considering lifecycle costs when evaluating the overall

[44] Assumes 13 W self-ballasted compact fluorescent lamp, 2-lamp 32 W T8 linear fluorescent lamp-and-ballast system, and 60 W A19 incandescent lamp with 2010 prices.
[45] Philips EnduraLED A19 with a typical selling price of $39.97.
[46] "LED lamp" and "OLED panel" are defined in Sections 5.1.1 and 5.4.1.
[47] Lumiotec prototype at highest power level
[48] Because LEDs can be more directional than conventional technologies, comparing them on a lumen per lumen basis based on the lamp may not be entirely accurate. For example, if a CFL and LED lamp emitted the same lumens, there could be more light from the LED luminaire reaching a specific surface than the light from the CFL luminaire.
[49] GATEWAY reports are available at http://www1.eere.energy.gov/buildings/ssl/gatewaydemos_results.html

economic feasibility of a lighting installation. As the price of LED sources comes down, more and more applications will experience viable payback periods.

3.5.1 LED Lamp Prices

Lamp and luminaire prices can vary widely depending upon the application, decorative enhancements, and control features. To validate the progress on price reductions for LED-based lighting, a comparison of replacement lamps is both practical and appropriate. Figure 3.5 shows a comparison of an integrated white light LED replacement lamp to a 13 W compact fluorescent lamp, and to the revised MYPP targets. The price estimates represent the average retail purchase price. During 2010 we have seen a significant number of good quality replacement lamps emerge, often appearing on the shelves at big box retail stores. Prices for such products have decreased rapidly, with a typical retail price of $20 for a 400 lumen (40 W equivalent) warm white A19 replacement lamp and around $40 for an 800 lumen (60 W equivalent) product. As a consequence, normalized prices in 2010 have dropped to around $50/klm, some two years ahead of the original schedule. In recognition of these more rapid cost reductions, the MYPP targets have been updated as illustrated in Figure 3.5.

Directional PAR and MR16 style lamps have also become more competitive during 2010 with prices in the $20 to $30 range for a 6 to 7 W MR16 lamp (250-350 lumens) and in the $40 to $60 range for a 17 to 18 W PAR38 lamp (750-850 lumens). Downlights have also benefited from significant price reductions with products now available in the $50 range ($87/klm). It is important to keep in mind that energy savings, replacement cost, and labor costs factor into a lamp’s overall cost of ownership. LEDs are already cost competitive on that basis with incandescent products in certain applications as described in Section 3.5.

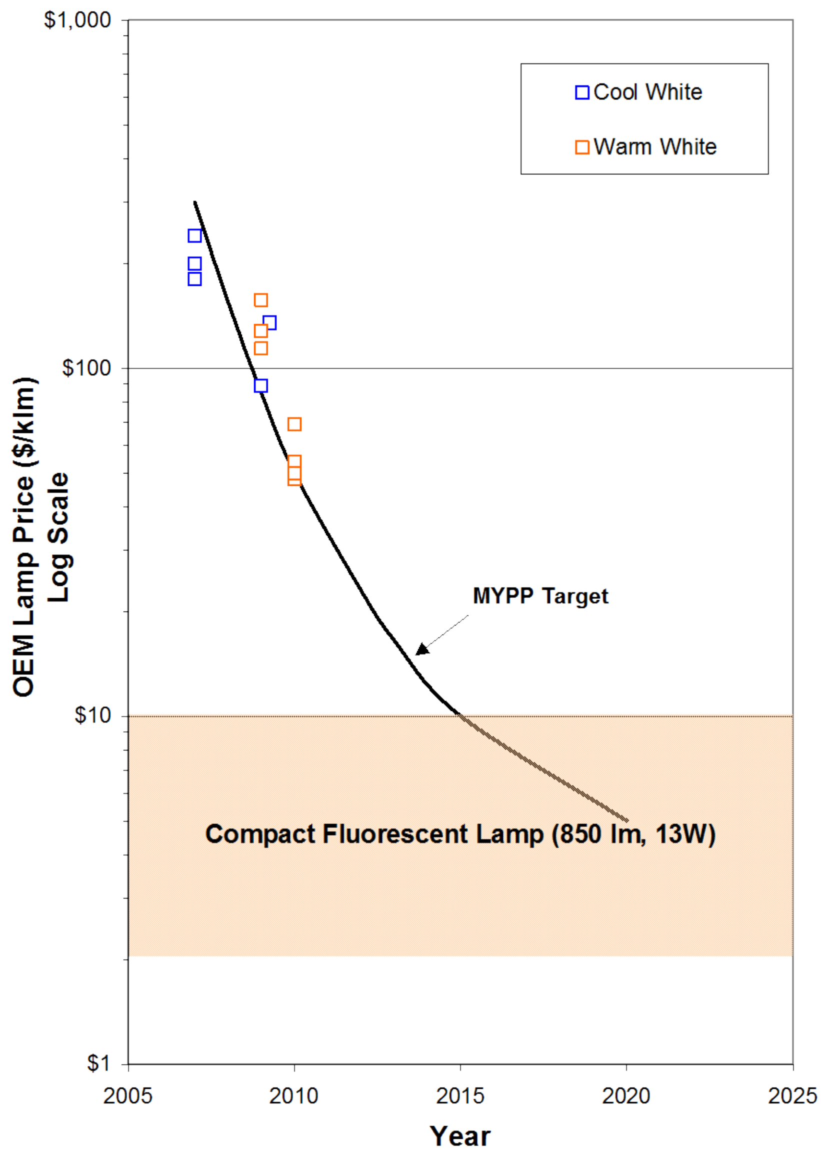

Figure 3.5: White Light Integrated LED Lamp Price Projection (Logarithmic Scale)
Note: Assumes current prices for compact fluorescent price range (13 W self-ballasted compact fluorescent; non-dimmable at bottom, and dimmable at top).

3.5.2 LED Package Prices

The following price estimates represent typical retail prices for packaged LEDs purchased in quantities of 1000 from major commercial distributors such as Digi-Key, AVNET, Newport, and Future Electronics. Each LED manufacturer produces a number of variants for each package design covering a range of color temperatures and lumen output. The selected data represents devices in the highest efficacy bins, which fall within specified ranges of color temperature and CRI. In all cases the price is expressed in units of $/klm and has been determined at a fixed current density of 35 A/cm^2 at 25°C.

Prices have continued to fall in 2010, and performance has continued to improve. This behavior is illustrated in Figure 3.6. Note that there is a lot of scatter in the data so ellipses have been superimposed on the chart for each major time period in order to identify the mean and standard deviation of each distribution. For warm white LEDs we have seen significant improvements in both efficacy and price, with both parameters running ahead of the original 2010 MYPP projections. In particular, the normalized price ($/klm) was nearly a factor of two lower than our original goal. The differential in the retail price between cool and warm white LED packages has essentially disappeared, and the normalized $/klm price for warm LED packages has therefore been updated to reflect this parity. For cool white LEDs the overall price efficacy performance closely matched the 2010 MYPP projections, although the highest efficacy devices were still able to command higher prices. The normalized price projection for cool white LED packages remains unchanged.

The MYPP efficacy projections for warm and cool white LED packages has been revised in 2011 to reflect progress. The revised efficacy projections represents the fitted efficacies shown in Figure 5.4 and is superimposed on the price-efficacy chart below.

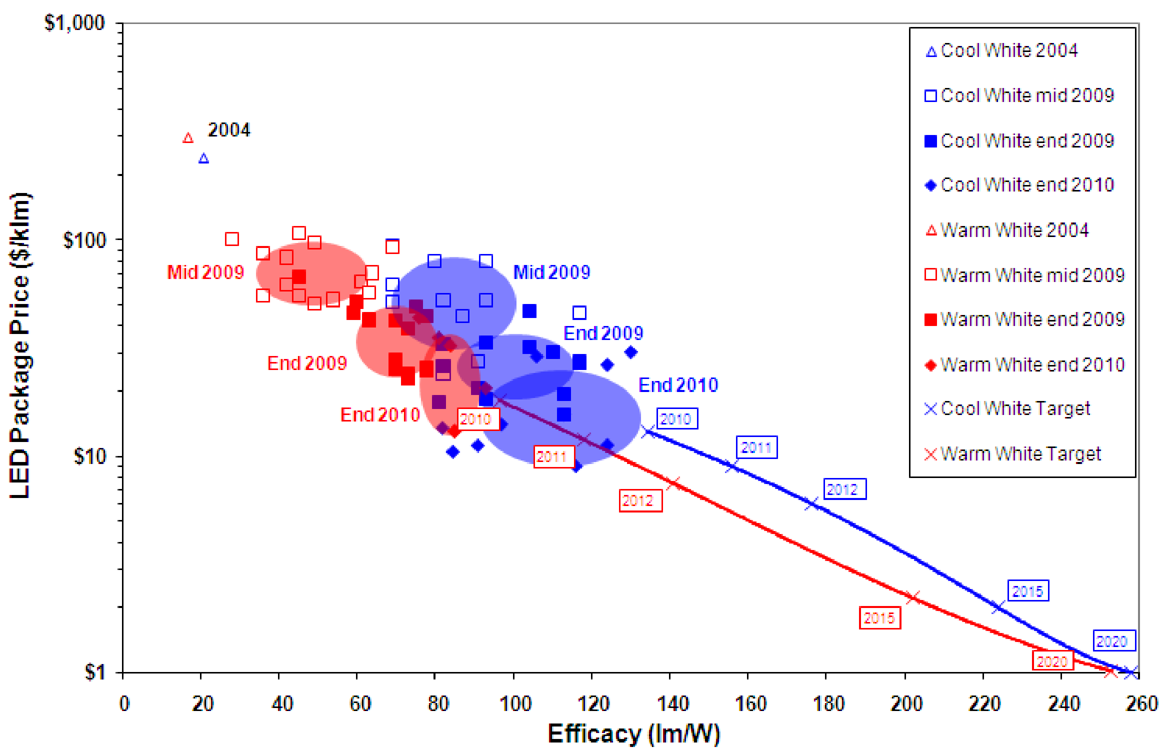

Figure 3.6: Price-Efficacy tradeoff for LED Packages at 35 A/cm^2

Note:

1. Cool white packages assume CCT=4746-7040K and CRI=70-80; warm white packages assume CCT=2580-3710K and CRI=80-90.
2. Ellipses represent the approximate mean and standard deviation of each distribution.
3. The revised MYPP projections have been included to demonstrate anticipated future trends.

Table 3.2 summarizes the LED package price and performance projections in tabular form.

Table 3.2: Summary of LED Package Price and Performance Projections

Metric	2010	2012	2015	2020
Cool White Efficacy (lm/W)	134	176	224	258
Cool White Price ($/klm)	13	6	2	1
Warm White Efficacy (lm/W)	96	141	202	253
Warm White Price ($/klm)	18	7.5	2.2	1

Note:

1. Projections for cool white packages assume CCT=4746-7040K and CRI=70-80, while projections for warm white packages assume CCT=2580-3710K and CRI=80-90. All efficacy projections assume that packages are measured at 25°C with a drive current density of 35 A/cm^2.
2. Package life is approximately 50,000 hours assuming 70% lumen maintenance at a drive current density of 35 A/cm^2.

3.5.3 OLED Costs

While samples of OLED lighting products have been available since 2009, commercial offerings have been limited to expensive luminaires for decorative applications and prototyping panel kits. Therefore, only limited price data is available for OLED panels and luminaire cost projections contain a high degree of uncertainty as these are not yet optimized or manufactured in volume. Similarly, lifetime values for OLED panels and luminaires are highly speculative at this point in time due to the lack of OLED general illumination products and uncertainties in protocols for accelerated life testing. The cost of materials and manufacturing equipment scales much more closely with the area of the panels that are produced than the light emitted from the lamps. Raising the brightness of the panels is thus a major factor in cost reduction, so long as the increased brightness does not lead to excessive heat requiring added costs for thermal management or reduced efficacy or lifetime. Further, the brightness increase should not be so great that the panel causes undue glare or has to be shielded from view by a shade or diffuser.

Making the lamps brighter by increasing the drive current generally leads to significant reduction in operating lifetime. Commercially available OLED products claim L70 lifetimes ranging from around three to four thousand hours up to 15,000 hours at an initial luminous emittance of about 3,000 lm/m^2. Further reductions in lifetime caused by operation at high drive current would be unacceptable.

One promising approach to the creation of more light is the use of tandem OLED structures, in which OLEDs are stacked vertically. In such structures, the light generated can be configured to scale with the number of units in the stack while the current density is kept constant. Whatever architecture is chosen, further basic research is needed to enable higher efficacy through materials advancements and improved light extraction techniques. With higher efficacy and brightness, the OLED cost per kilolumen can be dramatically reduced.

4.0 Current Solid-State Lighting Portfolio

This chapter offers a description of the SSL R&D Program's current funding levels with an overview of the projects in the current project portfolio. This project portfolio includes all SSL projects active in the applied R&D funding programs. Further description of how the SSL project portfolio is determined is contained in Chapter 5.0.

4.1 Current SSL Project Portfolio

This section provides an overview of the current projects in the SSL portfolio (as of March 2011). The SSL Project Portfolio is grouped into six topic areas.[50]

Group 1: Inorganic SSL Core Technology Research
Group 2: Inorganic SSL Product Development
Group 3: Inorganic SSL Manufacturing R&D
Group 4: Organic SSL Core Technology Research
Group 5: Organic SSL Product Development
Group 6: Organic SSL Manufacturing R&D

Within each of the six grouped topic areas, the DOE SSL R&D agenda is divided into tasks. At the consultative workshops, participants discuss each of the tasks and provide recommendations for prioritizing R&D activities over the next one to two years. The overall structure of the tasks is outlined in Appendix D. Details on the current funded tasks are presented in the tables and charts in this section, while details on the newly prioritized subtasks are presented in Chapter 5.0. Under each subtask there are a number of metrics to guide specific efforts by researchers in addressing the goals of the task.

4.2 Congressional Appropriation and Current Portfolio[51]

Figure 4.1 presents the congressional appropriation for the SSL portfolio from FY2003 through FY2010 and the FY2011 appropriation request. The funding received for the 2010 fiscal year (FY2010, which began in October 2009) totaled $27 million. In FY2009 an additional, one time, funding of $50 million was provided through the ARRA of 2009 to be used to accelerate the SSL R&D Program and jumpstart the manufacturing R&D initiative. The SSL R&D Program has requested $27 million in funding for FY2011. As of the date of this publication, the 2011 Federal budget is operating under a continuing resolution, while Congress completes negotiations on a final agreement for the remainder of fiscal year 2011.

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[50] The definitions of Core Technology Research, Product Development, and Manufacturing R&D are provided in Appendix C. In short, Core is applied research advancing the communal understanding of a specific subject; Product Development is research directed at a commercially viable SSL material, device, or luminaire; and Manufacturing R&D provides support for improved product quality and consistency and significant cost reduction.
[51] Figures and charts in this section may not sum to stated cumulative values due independent rounding.

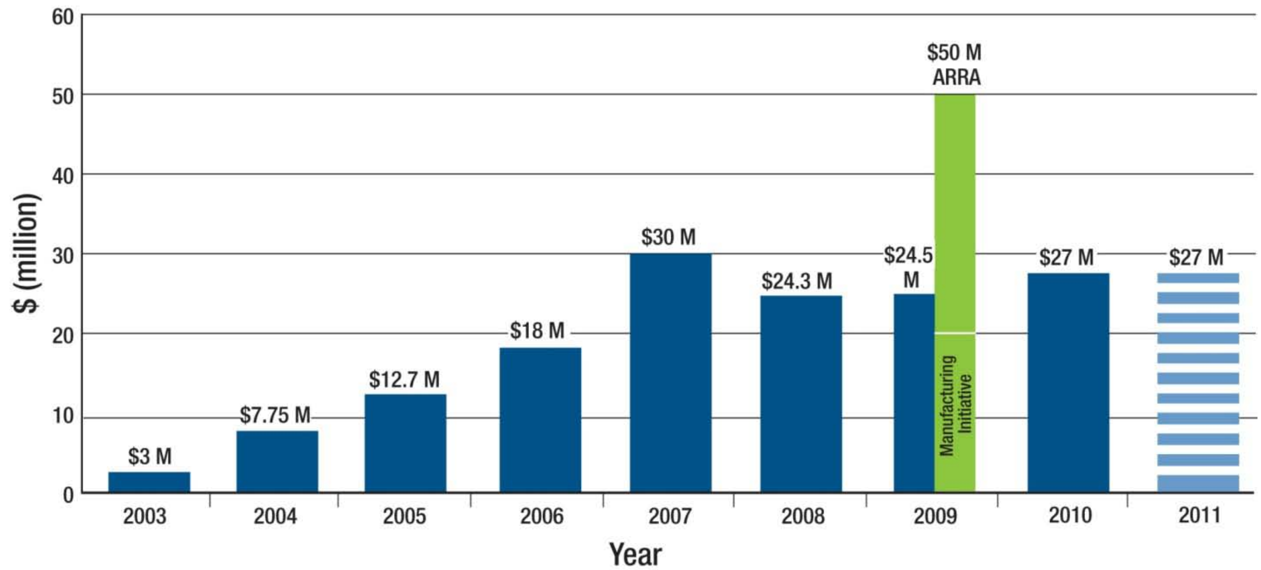


Figure 4.1: Congressional Appropriation for SSL Portfolio, 2003-2011

The active DOE SSL R&D Portfolio as of March 2011 includes 47 projects, which address LED and OLED technologies. Projects balance long-term and short-term activities, as well as large and small business and university participation. The portfolio totals approximately $120.0 million in government and industry investment.

Figure 4.2 provides a graphical breakdown of the funding for the current SSL project portfolio; this value represents funding levels for all active projects as of March 2011. DOE is currently providing $72.4 million in funding for the projects, and the remaining $47.6 million is cost-shared by project awardees. Of the 47 projects active in the SSL R&D portfolio, 28 are focused on LED technology and 19 are focused on OLEDs.

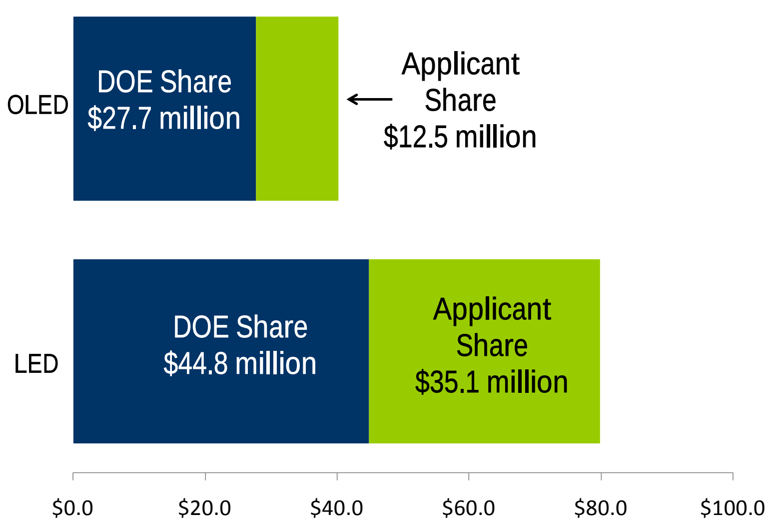


Figure 4.2: Funding of SSL R&D Project Portfolio by Funder, March 2011

Figure 4.3 shows the DOE funding sources and level of support contributing to the SSL project portfolio. The Building Technologies Program in the Office of EERE, along with funding from the 2009 ARRA, provided the majority of the funding; 38 projects receive $116 million (including the cost share portion) in funding from this source, which is managed through the National Energy Technology Laboratory. The SBIR Program in the Office of Science funded the remaining nine projects for a total of $4.1 million.

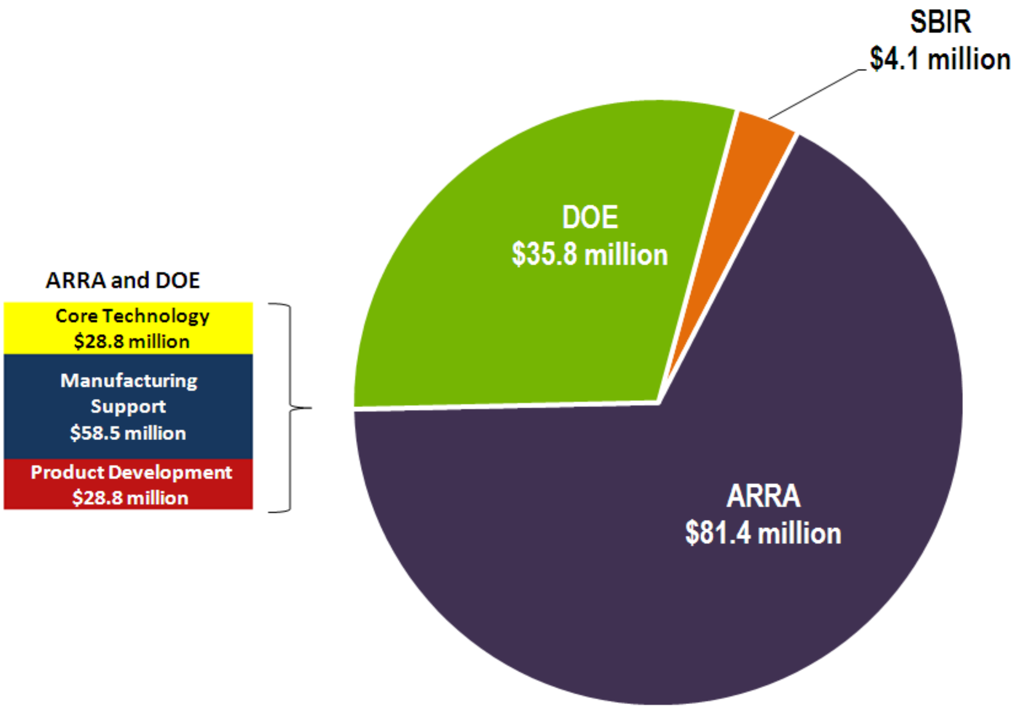


Figure 4.3: Cumulative SSL R&D Portfolio Funding Sources, March 2011

DOE supports SSL R&D in partnership with industry, small business, academia, and national laboratories. Figure 4.4 provides the approximate level of R&D funding contained in the current SSL portfolio among the four general groups of SSL R&D partners. Industry participants receive approximately 64% of portfolio funding, with $76.3 million in R&D activities. Small businesses comprise the next largest category and receive 20%, or $24.1 million, in research funds. Finally, universities and national laboratories comprise 9% and 7% of the R&D portfolio and receive $10.7 million and $8.8 million, respectively.

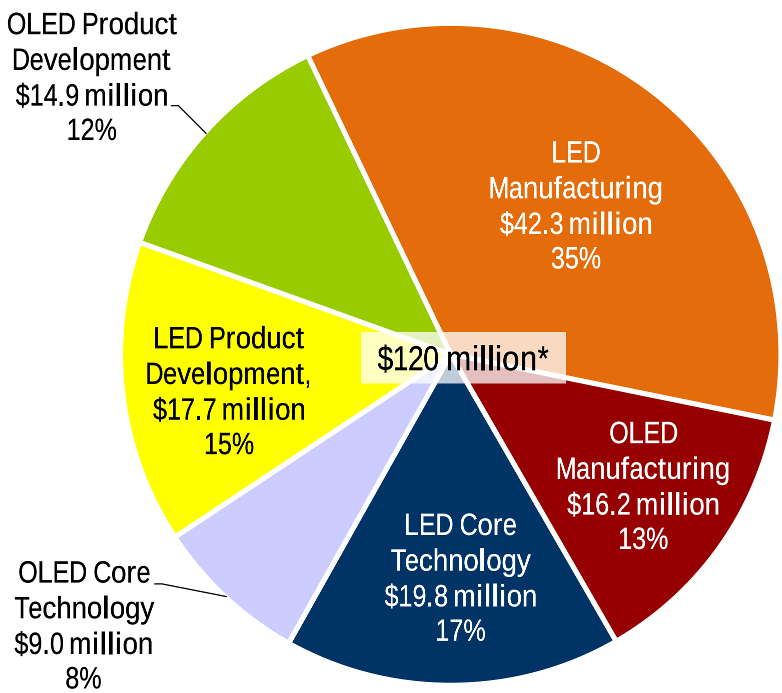


Figure 4.4: DOE SSL Total Portfolio Summary, March 2011

Table 4.1 and Table 4.2 show the total number of SSL R&D Core Technology and Product Development projects and total project funding for each. Table 4.1shows the categories in which there are active projects that DOE funded or has selected for funding, keeping with the evolving priorities, under the Core Technology solicitations. Table 4.2 shows the categories in which there are projects that are currently funded in Product Development. Table 4.3 and Table 4.4 present the full listing of SSL Core Technology and Product Development projects funded by DOE.

Table 4.1: SSL R&D Portfolio: Core Technology, March 2011

	Number of Projects	$ Funding (Million)
Light-Emitting Diodes		
Emitter Materials Research	6	$11.4
Down-converters	3	$5.3
Novel Emitter Materials and Architectures	1	$1.1
Optical Component Materials	1	$2.0
Total LED	**11**	**$19.8**
Organic Light-Emitting Diodes		
Novel Device Architecture	1	$1.1
Novel Materials	4	$5.2
Material Degradation	1	$0.8
Electrode Research	1	$2.0
Total OLED	**7**	**$9.0**
TOTAL	**18**	**$28.8**

Table 4.2: SSL R&D Portfolio: Product Development, March 2011

	Number of Projects	$ Funding (Million)
Light-Emitting Diodes		
Semiconductor Materials	1	$2.3
Phosphors	2	$4.7
Emitter Thermal Control	1	$0.1
Luminaire Thermal Management Techniques	3	$5.7
Electronic Components Research	3	$4.8
Off-Grid Lighting	1	$0.1
Total LED	**11**	**$17.7**
Organic Light-Emitting Diodes		
Practical Implementation of Materials and Device Architectures	2	$6.6
Substrate Materials	2	$2.2
Luminaire Mechanical Design	1	$2.4
Luminaire Thermal Management	1	$0.1
Large Area OLED	1	$2.0
OLED Light Extraction	3	$1.6
Total OLED	**10**	**$14.9**
TOTAL	**21**	**$32.6**

Table 4.3: SSL R&D Portfolio: Current LED Research Projects, March 2011[52]

Research Organization	Project Title
Sandia National Lab	Novel Defect Spectroscopy of InGaN Materials for Improved Green LEDs
Cree, Inc.	SSL Luminaire with Novel Driver Architecture
PhosphorTech	High Extraction Luminescent Materials for Solid State Lighting
Georgia Tech Research Corporation	Fundamental Studies of Higher Efficiency III-N LEDs for High-Efficiency High-Power Solid-State Lighting
Yale University	Multicolor, High Efficiency, Nanotextures LEDs
Osram	Highly Efficient Small Form Factor LED Retrofit Lamp
Philips	High Efficiency Driving Electronics for General Illumination LED Luminaires
Soraa	High Efficiency m-Plane LEDs on Low Defect Density Bulk GaN Substrates
Sandia National Lab	Semi-polar GaN Materials Technology for High IQE Green LEDs
Cree, Inc.	Ultra-Compact High-Efficiency Luminaire for General Illumination
GE	Optimized Phosphors for Warm White LED Light Engines
Lightscape Materials	Nitride- and Oxynitride-Based Phosphors for SSL
Osram	High-Flux Commercial Illumination Solution with Intelligent Controls
Lumileds	130 Lm/W, 1000 Lm Warm White LED for Illumination
Rensselaer Polytechnic Institute	High Efficacy Green LEDs by Polarization Controlled Metalorganic Vapor Phase Epitaxy
U.S. ARMY Research Laboratory	Exploiting Negative Polarization Charge at n-InGaN/p-GaN Heterointerfaces to Achieve High Power Green LEDs without Efficiency Droop
Eastman Kodak	High Efficiency Colloidal Quantum Dot Phosphors
UCSD	Phosphors for Near UV-Emitting LEDs for Efficacious Generation of White Light
White Optics	Low-Cost, Highly Lambertian Reflector Composite for Improved LED Fixture Efficiency and Lifetime
Sandia National Lab	Novel Defect Spectroscopy of InGaN Materials for Improved Green LEDs

[52] See Appendix E for a list of patents awarded through DOE funded projects.

Table 4.4: SSL R&D Portfolio: Current OLED Research Projects, March 2011

Research Organization	Project Title
PNNL	Charge Balance in Blue Electrophosphorescent Devices
UDC	High Efficacy Integrated Under-Cabinet Phosphorescent OLED Lighting Systems
Dupont Displays, Inc.	Solution-Processed Small-Molecule OLED Luminaire for Interior Illumination
PPG	Low-Cost Integrated Substrate for OLED Lighting
PNNL	Development of Stable Materials for High-Efficiency Blue OLEDs through Rational Design.
University of Florida	Top-Emitting White OLEDs with Ultrahigh Light Extraction Efficiency
University of Florida	High Efficiency Organic Light Emitting Devices for Lighting
University of Rochester	Development and Utilization of Host Materials for White Phosphorescent OLEDs
Lawrence Berkley National Laboratory	Investigation of Long-Term OLED Device Stability via Transmission Electron Microscopy Imaging of Cross-Sectioned OLED Devices
Cambrios	Solution-Processable Transparent Conductive Hole Injection Electrode for Organic Light-Emitting Diode (OLED) SSL
GE	High Quantum Efficiency OLED Lighting Systems

5.0 Technology Research and Development Plan

The U.S. DOE supports domestic research, development, demonstration, and commercialization activities related to SSL to fulfill its objective of advancing energy efficient technologies. The DOE SSL R&D Portfolio focuses on meeting specific technological goals, as outlined in this document and also in the companion *Solid-State Lighting Research and Development: Manufacturing Roadmap,*[53] that will ultimately result in the development and accelerated adoption of commercial products that are significantly more energy efficient than conventional light sources.

A part of the DOE SSL R&D Program mission, working through a government-industry partnership, is to facilitate new markets for high efficiency general illumination products that will enhance the quality of the illuminated environment as well as save energy. SSL sources are now available for the general illumination market, replacing some of today's lighting technologies in specific applications. Strategies Unlimited estimates the LED lighting market grew from about $5.6 billion in 2009 to about $10.8 billion in 2010, representing a growth rate of 93%.[54] The DOE SSL R&D activities work to ensure that low cost, high quality, energy efficient lighting products are available and U.S. companies remain competitive in the new landscape of next generation lighting technology.

This chapter describes the objectives and work plan for future Core Technology and Product Development activities under the SSL R&D Program for the next few years, and some specific targets for 2020. A separate Manufacturing Roadmap provides similar guidance for manufacturing related R&D.[55] Advancements in the state of SSL technology have resulted in changes to the DOE SSL R&D plan over time and future revisions will continue to reflect the status of technology. The process of updating the content of this chapter for FY2011 began with a series of roundtable sessions convened in Washington, D.C. in November 2010. The industry experts invited to these sessions presented short talks on current topics of interest for LED and OLED technologies and then discussed the most critical R&D tasks based on the current status of the technology. The outcome of this meeting was a preliminary prioritization of the R&D tasks, which were presented at the DOE SSL R&D workshop in San Diego, California at the beginning of February 2011. The workshop gave representatives of various sectors of the lighting industry an opportunity to review and comment on the proposed high priority R&D tasks for 2011. After subsequent review, and considering inputs received at the workshop, DOE has defined the task priorities for 2011 as listed in Sections 5.2 (LEDs) and 5.4 (OLEDs).

5.1 Light Emitting-Diodes

Significant progress has been made in the development of LED-based SSL over the past

[53] The *SSL Research and Development: Manufacturing Roadmap,* can be found at http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_manuf-roadmap_july2010.pdf
[54] Business Wire, 2010 Worldwide High-Brightness Market Grew By 93 Percent According to Strategies Unlimited, http://www.businesswire.com/news/home/20110223005343/en/2010-Worldwide-High-Brightness-LED-Market-Grew-93
[55]

year, and many efficient replacement lamp and luminaire products have reached the market. Several of these products have established significant sales volumes. For example, Lighting Science Group, a U.S. manufacturer, produced over one million LED replacement lamps during 2010. Innovations in LED package design and manufacturing have continued to drive down LED package costs while offering increased lumen output, higher efficacy, and improved color consistency. Improvements in LED package efficacy and reductions in cost remain in line with the targets and milestones set by the SSL MYPP.

LED luminaires are now typically more efficient than incandescent sources and most CFL luminaires, although they still lag slightly behind linear fluorescent luminaires. As the efficiency has improved, the primary development focus has shifted from rapidly increasing efficacy to assuring that other lighting performance parameters such as color quality, color consistency, light distribution, and reliability are adequate for market acceptance. Increasing efficacy still remains a key goal and an important charter of the SSL Program. Continued innovation will lead to the development of LED-based lighting products with efficacies that can match or exceed linear fluorescent products and also retain excellent lighting performance in the other key parameters.

5.1.1 Components of LED Luminaires

The subsequent sections of this MYPP describe LED white light 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.

As SSL has evolved, a number of product configurations have appeared in the market. Two essential levels of product can be identified based on whether or not the product includes a driver (defined in the list below), and a number of terms can be defined for each level. Please note that these definitions have been updated from prior editions of the MYPP to reflect the agreed definitions in IES Standard RP-16[56] Addendum b, as updated and released in 2009.

Component level (no power source or driver)

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

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

additional thermal, mechanical, and electrical interfaces that are intended to connect to the load side of a LED driver. Power source and ANSI standard base are not incorporated into the device. The device cannot be connected directly to the branch circuit.

Subassemblies and systems (including a driver)

- LED Lamp refers to an assembly with an ANSI standardized base designed for connection to an LED luminaire. There are two general categories of LED lamps:
    - Integrated LED Lamp refers to an integrated assembly comprised of LED packages (components) or LED arrays (modules), LED driver, ANSI standard base and other optical, thermal, mechanical and electrical components. The device is intended to connect directly to the branch circuit through a corresponding ANSI standard lamp-holder (socket).
    - Non-Integrated LED Lamp refers to an assembly comprised of an LED array (module) or LED packages (components) 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.

- LED Light Engine consists of an integrated assembly comprised of LED packages (components) or LED arrays (modules), LED 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.
- LED Driver refers to a device comprised of a power source and LED control circuitry designed to receive input from the branch circuit and operate a LED package (component), an LED array (module) or an LED lamp.
    - Power Supply refers to an electronic device capable of providing and controlling current, voltage, or power within design limits.
    - LED 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 a LED package (component) or an LED array (module). LED control circuitry does not include a power source.

- LED Luminaire refers to a complete lighting unit consisting of LED-based light emitting elements 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.

Figure 5.1, below, illustrates a few of these definitions.

Figure 5.1: Photos of LED Components, Lamp and Luminaire
Sources: Cree (LED), Journée (Package), Philips (Light Engine and Lamp), The Lighting Quotient (Luminaire – Cove Light)

5.1.2 LED Efficiency Metrics

To highlight specific opportunities for efficiency improvements, the various elements of power efficiency, both electrical and optical, can be identified within the LED package and for the luminaire as a whole. In addition, the efficiency of converting optical radiated power into useful light is derived from the optical responsiveness of the human eye. This source of inefficiency (the *spectral* or *optical* efficacy of the light) is the difference between an optimal spectrum for a given CCT and CRI (or color quality scale) and the spectrum of the light generated by the LED package or luminaire.

The *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*. The LED 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. This technology plan forecasts both LED package efficacy and luminaire efficacy improvements. It is important to keep in mind that it is the luminaire performance that ultimately determines the actual energy savings.

Opportunities for improvement of the LED package include: reducing the operating voltage of the device (electrical efficiency); improving the efficiency of conversion of electrons into photons (IQE); maximizing the extraction of those photons from the material (extraction efficiency); and tailoring the spectrum of the radiated light to increase the eye response. Tailoring of the spectrum to the eye response is constrained by the need to provide light of appropriate color quality.

The following sections compare efficiencies achieved in 2010 for individual luminaire and LED packages to the 2020 SSL R&D Program goals. These consensus goals were developed and updated at the LED Roundtable meetings and were further refined by contributions from the R&D Workshop. It is important to realize that there may be significantly different allocations of loss for any specific design, which may still result in an efficient luminaire. The following allocation of 2010 efficiency values and 2020 targets serves as a guide for identifying the opportunities for improvement. This example allocation of efficiency is not intended to preclude novel developments, which may employ a different allocation of losses but results in superior luminaire performance.

As described in Section 3.1, white light LED luminaires are typically based on one of three approaches:

a) pc-LEDs;
b) color-mixed LEDs; and
c) a hybrid consisting of a mix of pc-LEDs and monochromatic packages.

Definitions

The following definitions provide some clarification on the efficiency values presented in the figures and for the project objectives over time.

Elements of the LED package power conversion efficiency are:

- *Electrical efficiency* accounts for the efficiency with which electrical charge carriers injected into the LED package find their way to the active region of the LED device. Ohmic (resistive) losses associated with the semiconductor layers and the LED package materials represent the most important loss mechanism. A reduction in electrical efficiency is associated with an increase in the energy (voltage) required to create photons over and above the intrinsic bandgap energy (voltage) of the semiconductor active region;
- *Internal quantum efficiency*, IQE, is the ratio of the photons emitted from the active region of the semiconductor chip to the number of electrons injected into the active region;[57]
- *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;

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

- *External quantum efficiency*, EQE, is the ratio of extracted photons to injected electrons.[58] 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, very low current density, value and that reported as nominal, commonly 35A/cm^2. Luminaires may operate at an even higher current density resulting in additional current droop, defined below. Current droop is considered to be a reduction in the IQE as current density is increased (light extraction efficiency is assumed to be constant), but can be most readily characterized through EQE measurement;
- *Phosphor conversion efficiency* refers to the efficiency with which phosphors convert the wavelength of the absorbed light. The phosphor efficiency includes quantum efficiency of the phosphor and the Stokes loss of the conversion process. This efficiency is relevant only to the pc-LED described in Figure 5.2;
- *Color-mixing/Scattering efficiency* refers to losses incurred while mixing colors in order to create white light (not the spectral efficacy, but just optical losses). This efficiency also 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; and
- *Spectral efficiency* is the ratio of the luminous efficacy of radiation (LER) of the actual spectrum to the maximum possible LER (LER_{max}), as determined by the modeling of an optimized spectrum with appropriate color quality. The actual spectrum may be limited by the response of the phosphor, or when optimal wavelengths for a color mixed or hybrid LED are not available.

Additional efficiency losses occur when the LED package and other subsystems are assembled into a luminaire. Some of them are straightforward new sources of loss associate with the luminaire itself. Some, however, are additional losses that occur as a result of operation of the LED package above room temperature or at higher current density than the nominal.

- *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;

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

- *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.[59] 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; and
- *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).

Phosphor-Converted LED

Figure 5.2 summarizes an analysis of the various sources of efficiency loss, as defined above, in a pc-LED package and luminaire. The chart shows, for each loss channel, an estimate of the present efficiency of that channel and also an estimate of the potential headroom for improvement, that is, the difference between today's efficiency and the MYPP 2020 target. Table 5.1 shows the efficiencies (both status and target) as typically reported for packages, i.e. pulsed measurements taken at a 25°C package temperature and at a nominal current density of $35A/cm^2$. Package loss channels are divided between the blue pump diode and the phosphor. Additional luminaire losses include degradation of both LED and phosphor due to higher temperatures and also optical and driver inefficiencies. For cost effectiveness, some luminaire designs use the diodes at a higher current density, which leads to additional loss due to current droop. That high current "penalty" is included in the last line of the chart. However, luminaire losses vary widely depending on application or design.

The LED package efficacy is then the product of the electrical-to-optical conversion efficiency, the spectral efficiency, and LER_{max}, which is about 345 lm/W for this specific example.

[59] 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.

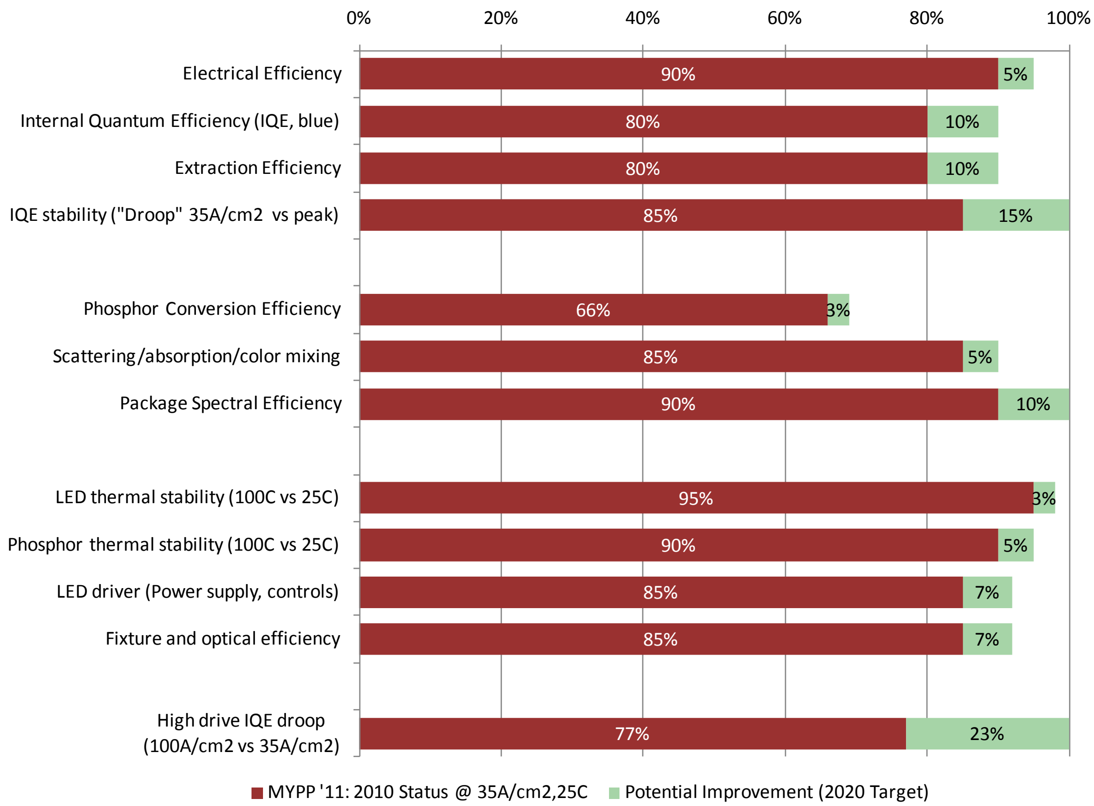


Figure 5.2: pc-LED Package and Luminaire Loss Channels and Efficiencies

Notes:

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

Reducing the sensitivity to current density is a significant opportunity for improved efficacy and cost reduction, but there is room for improvement in many areas.

Combining the estimates for the LED with those of the luminaire, and accounting for spectral efficiency allows an assessment of overall luminaire efficacy under normal operating conditions. For the case of the pc-LED this is summarized in Table 5.1. Although it is uncertain as to whether all of the proposed improvements can actually be realized in a commercial, marketable product, meeting these goals suggests that there is an impressive potential here for an improvement over today's luminaire performance.

Table 5.1: Summary of Warm White pc-LED Luminaire Efficiencies and Efficacies

Metric	2010 Status	2020 Target
Optical Power Conversion Efficiency	49%	77%
Phosphor Conversion/Scattering	56%	62%
Spectral Efficiency	90%	100%
LED Package Efficiency[60]	27%	48%
LED Package Nominal Efficacy (lm/W)	*92*	*165*
Luminaire Efficiency	62%	79%
Luminaire Efficacy (lm/W)	*57*	*130*
High Current Luminaire Efficacy (lm/W)	*44*	*130*

Note: Luminaire efficiency only includes driver, fixture, and thermal effects.

Color-Mixed LED

Figure 5.3 provides a similar analysis to the above for a color-mixed LED luminaire solution. The performance is characterized using four colors red, green, blue and amber. Please note that this analysis has been updated from prior editions of the MYPP to include a fourth color line, which allows for further improvement to the color quality and spectral efficiency. The definitions for the various efficiencies are the same as listed for Figure 5.2. While this is a similar analysis to the pc-LED figure, the lack of commercial product of this type means that the current status is an estimate of what could be done today. As shown in the figure, the lack of efficient green and amber (direct emitting) LEDs limits the capability color-mixed LEDs today.

Because the color-mixed LED does not suffer from Stokes loss, it is theoretically capable of slightly 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 of color-mixed luminaires that must be taken into account, such as additional driver complexity and cost. Other options exist for obtaining different color temperatures or CRI using a hybrid approach. For example, a warm white color can be achieved by mixing white pc-LEDs with monochromatic red or amber LEDs. In fact, high efficacy warm white luminaires employing this hybrid approach are already on the market.

[60] This accounts for a portion of the blue pump not converted by the phosphor.

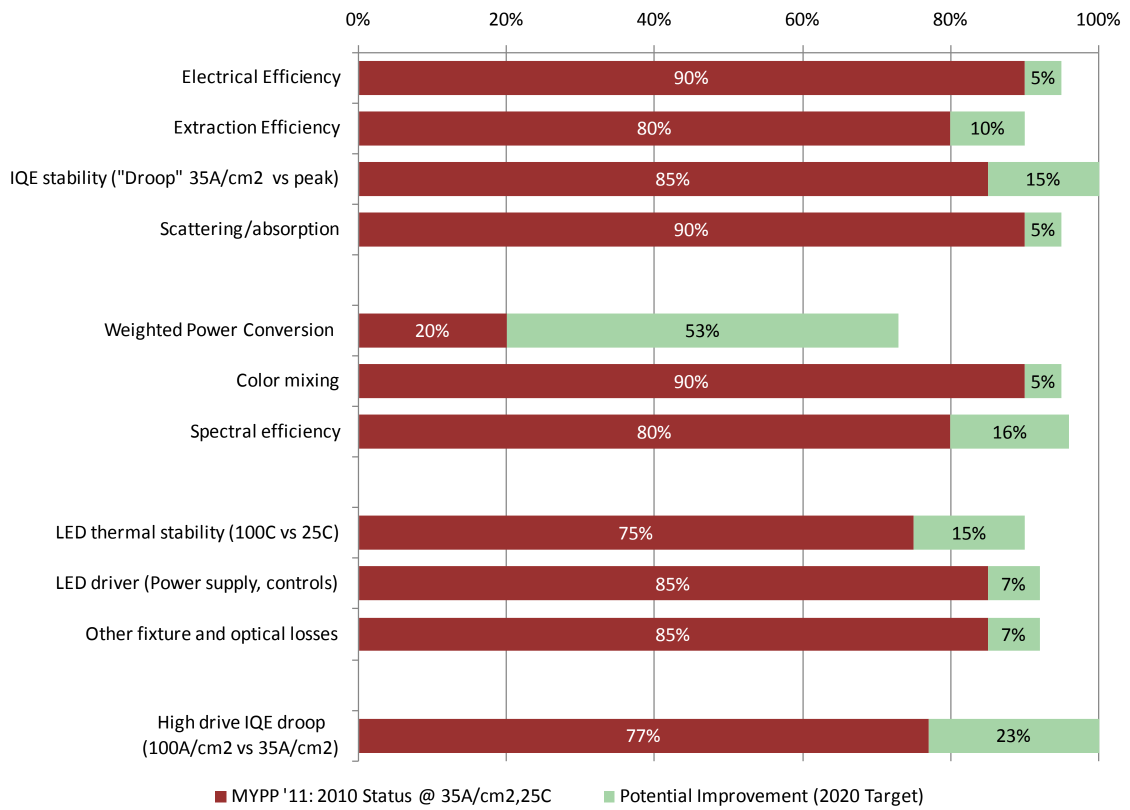


Figure 5.3: Color-mixed LED Package and Luminaire Loss Channels and Efficiencies

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 5.6, later in this chapter.
4. The efficiency allocation shown in this figure is only one example of how the luminaire efficiency target can be met.

Achieving the efficiency targets identified in Figure 5.3 will require more efficient emitters, particularly green and amber LEDs. The ultimate goal is to raise the IQE to 90% across the visible spectrum, bringing the total package conversion efficiency to 67%. As the LEDs become more efficient, there will necessarily be more emphasis on the other luminaire losses in order to maximize overall efficiency.

Table 5.2, below, provides an overall summary of the efficiency and resulting efficacy for a color mixed LED. Present performance is only estimated, but is strongly affected by the low efficiency of green LEDs and by the lack of efficient LEDs at optimal wavelengths for maximum spectral efficiency. On the other hand, the potential is quite a bit higher than for the pc-LED: 202 lm/W for the luminaire.

Table 5.2: Summary of Warm White Color-Mixed LED Luminaire Efficiencies and Efficacies

Metric	2010 Status	2020 Target
Optical Power Conversion Efficiency	18%	69%
Spectral Efficiency	80%	96%
LED Package Efficiency	14%	67%
LED Package Nominal Efficacy	*57*	*266*
Luminaire Efficiency	54%	76%
Luminaire Efficacy	*31*	*202*
High Temperature Efficacy	*24*	*202*

Note: Luminaire efficiency only includes driver, fixture, and thermal effects.

5.1.3 LED Package Performance Targets

The ultimate objectives of the SSL Program relate to luminaire efficacy and cost, so objectives for luminaire performance are also included along with device performance objectives. Innovative fixtures for LEDs can limit the luminaire impact on the efficacy of the LED. For example, package efficiencies (and operating lifetime) reported at 25°C and 35 A/cm^2 can be degraded by 30% or more when operated at full temperature and higher operating currents in a luminaire. The simultaneous accommodation of aesthetic and marketing considerations along with the preservation of the energy saving advantages of SSL is an ongoing challenge for the commercialization of this technology.

The performance of white light LED packages depends on both the CCT of the package and, to a lesser extent, the CRI. Some changes have been made in this report with regard to the designation of color temperature ranges as cool, neutral and warm. These changes have been made to reflect newly defined ANSI binning ranges[61] and to correct earlier inconsistencies. CRI ranges have also been revised for similar reasons. While every case cannot be examined, efficacy projections have been shown for two choices: one for cooler CCT (4746 K to 7040 K) with CRI=70-80, and the other for warmer CCT (2580 K to 3710 K) with CRI = 80-90.

Single LED package efficacies over 200 lm/W have recently been reported in press releases, while commercial products also continue to improve. So a fair question to ask is, just what are the limits?

A starting point is the theoretical maximum efficacies of an SSL product given perfect conversion of electricity to light. This depends on the Luminous Efficacy of Radiation, or LER, which is the useful light in lumens obtained from a given spectrum. Work by NIST has shown that LED emission spectra with good color quality can be modeled that yield LERs in the range of 350 to 450 lm/$W_{optical}$. If we call these theoretical bests LER_{max}, then LER/LER_{max} is the spectral efficiency of a given source.

Table 5.3 shows LER_{max} for a range of choices for CCT and CRI, and the resulting package efficacy for assumed overall package conversion efficiencies of 67%, the

[61] ANSI C78.377-2008

estimated potential maximum conversion efficiency. These figures assume a moderate (approximately 20nm) FWHM of the LED emission in a RGBA configuration. Under these conditions, the analysis suggests that warm white LEDs could have higher efficacies than cooler ones. This will not be the case with pc-LEDs, where broad spectra emit a considerable amount of the long wavelength energy in regions of low eye response and outside of the visible spectrum, and Stokes loss fundamentally limits efficiency. As noted in the footnotes to the tables and charts above, the targets assume a CCT of 3000 K and a CRI of 85, which results in an efficacy target for 67% conversion of about 266 lm/W. This is considered to be a reasonable program goal.

Table 5.3: Estimated efficacies as a function of CCT and CRI (R_a)[62]

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

Figure 5.4 shows revised package efficacy improvement forecasts over time. There are several items to note regarding the figure:

- Though each CRI/CCT permutation may result in a slightly difference theoretical maximum package efficacy, a common 266 lm/W practical limit has been chosen for both cool and warm white;
- Data points are indicated as either qualified, i.e. within the parameters defined for the various curves, or not-qualified, meaning one or more parameters is either outside the indicated limits, or is unknown; and
- In an attempt to clear up past confusion, this chart is intended to show results for a single package product or lab demonstration, but that package *could include more than one LED*, and more than one color. So, RGB solutions or hybrid R-W solutions, for example, might be shown, as long as they are packaged together. In fact, it may require such solutions to reach the higher levels of efficacy shown in this chart.

Press releases for lab results are often unclear about all of the parameters, making a true comparison difficult. They are almost always designed with a cool white CCT or close to it. Current densities may not be reported, and colors may be rather far off the black body curve. Nonetheless, they still provide a useful preview of actual products appearing a few years later.

Products generally are easier to characterize, although there are fewer fully qualified data points for cool white than for warm. Hopefully this will change going forward. It is probably worth noting that, having filtered what data we do have, the warm and cool

[62] Empirical approximation from: Tsao, Jeffrey Y., et. al., Solid State Lighting: An Integrated Human Factors, Technology and Economic Perspective, Proc. IEEE, August 2009.

curves appear to be tracking more closely than we had thought in the past, further supporting the idea that the ultimate limits may not be all that far apart. Several workshop participants and other stakeholders have noted that many products are not as close to the black body curve as one might prefer even though they may be within one of the ANSI-defined color bins. Some CALiPER testing has revealed products so far off the black body value as to call into question whether the product is producing truly white light. It has also been observed that colors above the black body curve (yellowish) are less acceptable in the marketplace than colors slightly below (pinkish). It may be worth additionally qualifying data on the basis of Duv, representing the departure of u', v' values from the black body line, but that will require more complete reporting by the industry than has generally been provided in past years.

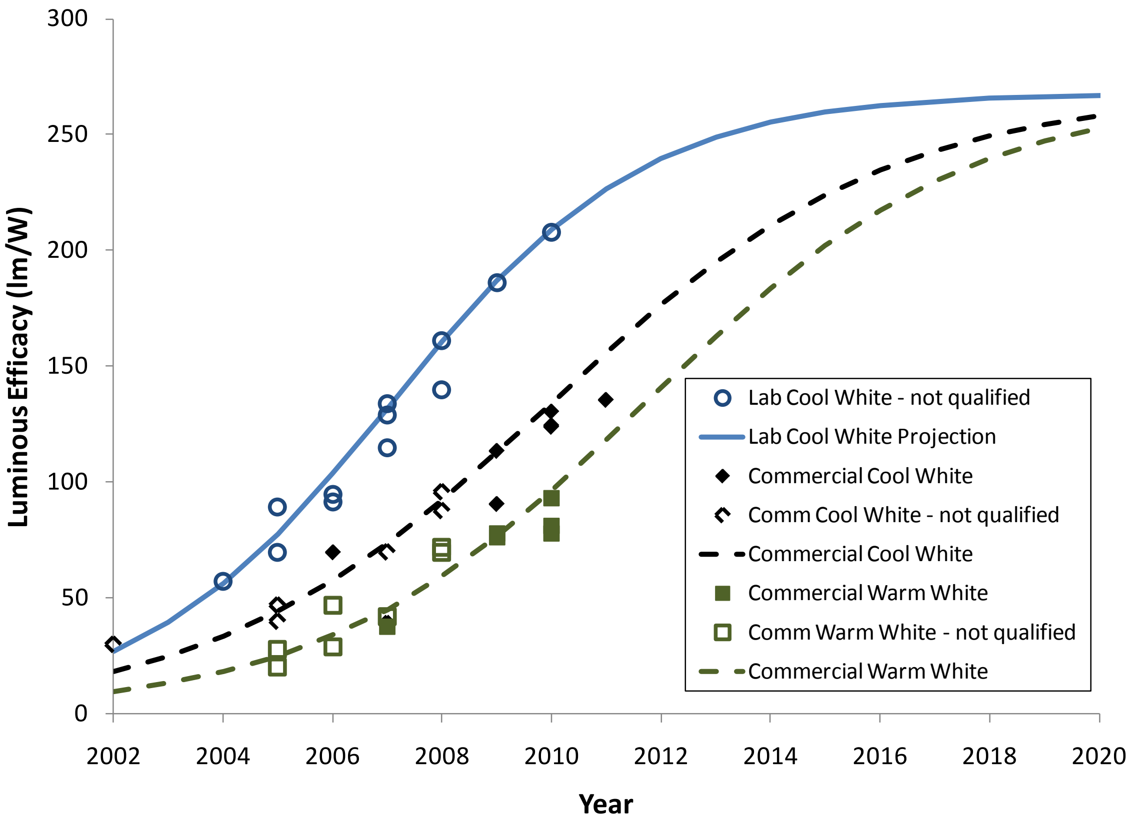


Figure 5.4: White Light LED Package Efficacy Targets[63], Laboratory and Commercial

Notes:

1. Cool White: CRI 70-80; CCT 4746-7040 K
2. Warm White: CRI 80-90; CCT 2580-3710 K
3. Current density: 35A/cm^2
4. These results are at 25°C package temperature, not steady state operating temperature. Thermal sensitivity will reduce efficacies by 24% or so in normal operation, depending on luminaire thermal management.

Based on progress over the last five years using data that can be qualified according to the criteria, the projections indicate that while improvements in warm white have been

[63] Projections are a simple logistical function fit to the qualified data points using a common asymptote of 266 lm/W (3800K/CRI=85 in table 5.3).

somewhat slower than for cool, our expectation is that this gap will close over time, as shown. The lab results may be reaching their limits fairly soon. Table 5.4 summarizes the LED package performance projections. The 2010 statuses in the table represent the fitted efficacies presented in Figure 5.4.

Table 5.4: Summary of LED Package Performance Projections

Metric	2010	2012	2015	2020
Cool White Efficacy (lm/W)	134	176	224	258
Warm White Efficacy (lm/W)	96	141	202	253

Note: Projections for cool white packages assume CCT=4746-7040K and CRI=70-80, while projections for warm white packages assume CCT=2580-3710K and CRI=80-90. All efficacy projections assume that packages are measured at 25°C with a drive current density of 35 A/cm^2.

The maximum LED package life, as commonly defined by 70% lumen maintenance, has increased steadily over the past few years and several manufacturers claim that lumen maintenance is currently at its target of an average of 50,000 hours (for specific products this should be verified by LM-80 test results). Also, lumen maintenance, while thought to dominate the useful life of an LED package, does not account for other failure mechanisms such as manufacturing defects.

Lifetime of a luminaire may be shorter, sometimes much shorter, than an LED package 70% lumen maintenance metric. There are many other potential failure mechanisms. Additional components and subsystems such as the drivers or optical reflectors can fail independently of the LED. There may also be assembly defects or optics that can lead to a failure. Poor luminaire design can shorten the life of an LED package dramatically through overheating. Drivers may also limit the lifetime of an LED package, hastening lumen depreciation, by overstressing the LED. In the case of professional systems, a failure rate of perhaps 10% of product is probably the maximum acceptable value. Usually, these factors lead to a shorter useful life than that indicated by lumen maintenance.

Especially for luminaires, where full product testing is very expensive, methods for characterizing lifetime, especially as changes in materials or processes are introduced, would greatly benefit from accelerated aging tests which so far have not been established for LED technologies. This is an important area of work, and there is an identified task for it (research task B.6.3) described in Section 0.

5.1.4 LED Luminaire Performance Targets

As stated in Section 5.1.2, the LED package is only one component of an LED luminaire. To understand the true performance metrics of a SSL source, the efficiency of the driver the optical efficiency of the fixture, and the thermal impact of the assembly on the performance of the packaged LED must be considered. Provided below in Table 5.5 are luminaire performance projections to complement the package and lamp performance projections.

Table 5.4 and Table 5.5 assume a linear progression over time from the current 2010 fixture and driver efficiency performance levels to eventual fixture and driver efficiency 2020 program targets as given in Section 5.1.1. Estimating the factors that affect the performance of an LED luminaire, it appears that a warm white luminaire in 2010 was capable of achieving 57 lm/W (which is corroborated by the performance of a few SSL products on the market). By 2020 warm white luminaire efficacies should reach a capability of 202 lm/W.

Table 5.5: Summary of LED Luminaire Performance Targets (at operating temperatures)

Metric	2010	2012	2015	2020
Package Efficacy – Commercial Warm White (lm/W, 25°C)	92	141	202	266
Thermal Efficiency	86%	86%	88%	90%
Efficiency of Driver	85%	86%	89%	92%
Efficiency of Fixture	85%	86%	89%	92%
Resultant luminaire efficiency	62%	64%	69%	76%
Luminaire Efficacy – Commercial Warm White (lm/W)	57	91	139	202
High Current Luminaire Efficacy – Commercial Warm White (lm/W)	44	74	123	202

Notes:

1. Efficacy projections for warm white luminaires assume CCT=2580-3710K and CRI=80-90.
2. All projections assume a drive current density of 35 A/cm^2, reasonable package life and operating temperature.
3. Luminaire efficacies are obtained by multiplying the resultant luminaire efficiency by the package efficacy values.

5.1.5 Barriers to adoption of LED-based lighting

The following lists some of the technical, cost, and market barriers to LEDs. Overcoming these barriers is essential to the success of the SSL R&D Program.

1. Cost: The initial cost of LED-based general illumination sources is too high, in comparison with conventional lighting technologies, (see Sections 3.4 and 3.5). Since the lighting market has historically been strongly affected by first cost, lifetime benefits notwithstanding, lower cost LED package and luminaire materials are needed, as well as low-cost, high-volume, reliable manufacturing methods. In 2009, DOE initiated a SSL Manufacturing R&D

program to address these issues. The DOE Manufacturing R&D Roadmap and a description of the program can be found at the DOE SSL website.

2. Luminous Efficacy: As the primary measure of DOE's goal of improved energy efficiency, the luminous efficacy (lm/W) of LEDs can still improve. Although the luminous efficacy of LED luminaires has surpassed that of the incandescent and compact fluorescent lamps, improvement is still needed to compete with other conventional lighting solutions and to maximize the energy savings from this technology. The efficacy of commercial LEDs is not yet near its fundamental limit and still has considerable room for improvement. Further improvements in LED efficacy can lead to even greater energy savings and can impact the cost of SSL sources, which can accelerate adoption of efficient LED products. For example, minimizing the amount of droop that occurs at high drive currents for LEDs can allow for the efficient use of fewer LEDs dramatically impacting cost. In general, improving the efficacy of the LED impacts the number of LEDs required for the lighting application as well as the thermal handling demands in the LED luminaire.

3. Lifetime: A definition of lifetime that focuses on lumen maintenance is inadequate for luminaires. Lumen maintenance is only one component of the lifetime of a luminaire that may be subject to other failure mechanisms such as color shifts, optics degradation, or even catastrophic failure. How the LED is designed into the luminaire can also have considerable impact on the lifetime of the system, inadequate thermal handling can reduce the LED lifetime and the design of the power supply can also impact the lifetime of the LED. A better understanding of the luminaire system lifetime and reliability is necessary for accelerated adoption of energy saving LED-based light sources.

4. Testing: The reported lumen output and efficacies of LED products in the market do not always match laboratory tests of performance. While standardized testing protocols for performance metrics have been developed for light output, color, and efficacy there are still many products that do not match the stated performance claims. DOE has supported the development of the Lighting Facts label to standardize performance reporting. Still, an important barrier for luminaire integrators appears to be the difference in stated LED device specifications versus the actual LED performance at continuous operation in a luminaire. LED manufacturers have begun to address this problem by providing 'hot' performance data on the LEDs. Furthermore, accelerated reliability testing methods for systems and materials would greatly reduce costs and time-to-market. Such tests, capable of providing accurate projections of life, do not currently exist. Uncertainty in both device and luminaire lifetimes creates risk for manufacturers and consumers, potentially reducing adoption rates.

5. Manufacturing: Lack of process and component uniformity will be an important issue for LEDs and is a barrier to reduced costs as well as a problem for uniform quality of light.

5.2 LED Critical R&D Priorities

In order to achieve these projected performance advancements presented earlier, progress must be achieved in several research areas. The original R&D task structure and initial priorities were defined at a workshop in San Diego in February 2005. These priorities have been updated in subsequent editions of the MYPP. Because of continuing progress in the technology and better understanding of critical issues, DOE engaged members of the lighting field, from industry representatives to academic researchers, to revisit and substantially revise the task structure for the 2009 MYPP. In updating the 2011 MYPP, DOE first held SSL roundtable sessions in Washington, D.C. in November of 2010 (see Appendix D for the entire task list). The tasks were further discussed and refined at the February 2011 "Transformations in Lighting" workshop in San Diego, CA. Using these recommendations, and after further internal review, DOE defined a set of task priorities for 2011. It should be noted that the priority list includes one new task (B.6.4) but is generally more focused than in prior years to reflect anticipated budget limitations. The task priorities for 2011 are as follows:

For LED Core Technology:

- Subtask A.1.2 (Emitter Materials Research) addresses the need for an improved understanding of the critical materials issues impacting the development of more efficient LEDs. A key focus will be on identifying fundamental physical mechanisms underlying the phenomenon of current droop in high performance blue LEDs. Another focus will be on reducing the thermal sensitivity of LEDs, especially those in the red and amber spectral regions; and
- Subtask A.1.3 (Down Converters) emphasizes improvements in phosphor quantum yield and thermal stability, and targets phosphors compatible with improved conversion efficiency, spectral efficiency, and color quality for warm white LEDs.

For LED Product Development:

- Subtask B.1.1 (Substrate Development) investigates the development of alternative substrate solutions that are compatible with the realization of state of the art LED performance, and are compatible with the production of low-cost high-efficacy LED packages that meet target performance and cost goals;
- Subtask B.3.6 (Package Architecture) supports the development of novel LED package and module architectures that can be readily integrated into luminaries, and address issues such as efficacy, thermal management, cost, color, optical distribution, electrical integration, sensing, and reliability;
- Subtask B.6.3 (System Reliability and Lifetime) encourages the collection and analysis of system reliability data for SSL luminaries and components to

determine failure mechanisms, and the use of this data to develop and validate accelerated test methods leading to an openly available and widely usable software tool to model SSL reliability and lifetime; and

- Subtask B.6.4. (Novel Luminaire Systems) targets the development of truly novel luminaire system architectures and form factors that take advantage of the unique properties of LEDs to save energy, and present a pathway to enhanced market adoption.

5.2.1 LED Priority Core Technology Tasks for 2011

The following definitions are used throughout this section for LED emission wavelength and white LED color point:

Table 5.6: LED emission wavelength and color definitions for this section

Color		Wavelength/CCT range	CRI
Blue		440-460 nm	-
Green		520-540 nm	-
Amber		585-595 nm	-
Red		610-620 nm	-
White	Warm	2580-3710 K (ANSI 2700, 3000, 3500 K)	80-90
	Neutral	3711-4745 K (ANSI 4000, 4500 K)	70-80
	Cool	4746-7040 K (ANSI 5000, 5700, 6500 K)	70-80

A1.2 Emitter Materials Research

Description: **(1)** 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. **(2)** Identify and demonstrate means to reduce current droop and thermal sensitivity for all colors through both experimental and theoretical work. **(3)** Develop efficient red (610-620 nm) or amber (580-595 nm) 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.

Metric(s)	2010 Status(s)	2020 Target(s)
IQE @ 35 A/cm^2	80% (Blue) 38% (Green) 75% (Red) 13% (Amber)	90% (Blue, Green, Red, Amber)
EQE @ 35 A/cm^2	64% (Blue) 30% (Green) 60% (Red) 10% (Amber)	81% (Blue, Green, Red, Amber)
Power Conversion Efficiency[64] @ 35 A/cm^2	44% (Blue) 21% (Green) 33% (Red) 7% (Amber)	73% (Blue, Green, Red, Amber)
Relative EQE at 100 A/cm^2 vs. 35 A/cm^2 (Droop)	77%	100%
Thermal Stability – Relative Optical Flux at 100°C vs. 25°C	95% (Blue, Green) 50% (Red) 25% (Amber)[65]	98% (Blue, Green) 75% (Red, Amber)

[64] Optical power out divided by electrical power in.
[65] This status is representative of direct emitters. Amber pc-LEDs can currently achieve thermal stability of up to 83%.

A1.3 Down Converters		
Description: Explore new non-toxic, high-efficiency wavelength conversion materials for improved quantum yield and phosphor conversion efficiency for the purposes of creating warm white LEDs, with a particular emphasis on improving spectral efficiency with high color quality and improved thermal stability.		
Metric(s)	**2010 Status(s)**	**2020 Target(s)**
Quantum Yield (25°C) across the visible spectrum	90%	95%
Thermal Stability across the visible spectrum - Relative Quantum Yield at 150°C vs. 25°C	90%	95%
Avg. Conversion Efficiency[66] (pc-LED)	66%	69%
Spectral Full Width Half Max. (FWHM)	150 nm (Red)	<50 nm (Red)
Color Stability (pc-LED)	Color Shift 0.012 u'v' over life	Color Shift < 0.002 u'v' over life
Spectral Efficiency relative to a maximum LER = 345 lm/W	90%	100%

5.2.2 LED Priority Product Development Tasks for 2011

See Table 5.6 for definitions that are used throughout this section for LED emission wavelength and white LED color point.

[66] 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.

<table>
<tr><th colspan="3">B1.1 Substrate Development</th></tr>
<tr><td colspan="3">Description: Develop alternative substrate solutions that are compatible with the demonstration of low cost high efficacy LED packages. Suitable substrate solutions might include native GaN, GaN-on-Si, GaN templates, etc. Demonstrate state of the art LEDs on these substrates and establish a pathway to target performance and cost.</td></tr>
<tr><th>Metric(s)</th><th>2010 Status(s)</th><th>2020 Target(s)</th></tr>
<tr><td>Price of LED Package
@ target efficacy</td><td>$10-15/klm (cool)
$20-25/klm (warm)</td><td>$1/klm</td></tr>
<tr><td colspan="3">Though the following metrics are examples for a GaN substrate, this task is not meant to be exclusive to GaN substrates.</td></tr>
<tr><td>GaN Substrate Price</td><td>>$2,000 (25-50 mm)</td><td><$500 (>200 mm)</td></tr>
<tr><td>Droop - Relative EQE at $100A/cm^2$ vs. $35A/cm^2$</td><td>77%</td><td>100%</td></tr>
<tr><td>Thermal Stability – Relative Optical Flux at 100ºC vs. 25ºC</td><td>85% (Blue, Green)</td><td>95% (Blue, Green)</td></tr>
<tr><td>GaN Transparency
(absorption coefficient)</td><td>2-10 cm^{-1}</td><td><0.5 cm^{-1}</td></tr>
</table>

B3.6 Package Architecture

Description: Develop novel LED package and module architectures that can be readily integrated into luminaires. Architectures should address some of the following issues: Thermal management, cost, color, optical distribution, electrical integration, sensing, reliability, and ease of integration into the luminaire or replacement lamp while maintaining state of the art package efficiency. The novel packages could employ novel phosphor conversion approaches, RGB+ architectures, system in package, hybrid color, or other approaches to address these issues.

Metric(s)	2010 Status(s)	2020 Target(s)
Change in Chromaticity over time	Duv < 0.012	Duv < 0.0014 over lifetime
Price of LED Package	$10-15/klm (cool) $20-25/klm (warm)	$1/klm
Price of Luminaire or replacement lamp	$50/klm	$5/klm
System Efficiency		
System Price		

B6.3 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. This task includes projects that focus on specific subsystems such as LED package, driver, and optical and mechanical components.		
Metric(s)	**2010 Status(s)**	**2020 Target(s)**
Mean Time to Failure (either catastrophic, lumen maintenance >70%, color shift, loss of controls)	Device Lumen Depreciation data	Tool to predict Luminaire lifetime within 10% accuracy

B6.4 Novel Luminaire Systems		
Description: Develop truly 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. An important element of this task will be the integration of smart controls/sensors for digital controllability, optimized dimming, color tunability, self-commissioning, occupancy sensing, etc. Luminaire designs should be consistent with the use of materials and production methods that minimize any negative environmental impact. Key attributes will include low weight, compact size, directionality, and/or durability.		
Metric(s)	**2010 Status(s)**	**2020 Target(s)**
System Energy Consumption		
Controls		
Environmental Impact		

5.3 LED Interim Product Goals

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

The FY10 LED package goal described in the 2010 MYPP was to produce a cool white LED package with an efficacy of 134 lm/W at 35 A/cm^2, an OEM price of $13/klm, CRI of 70-80, and CCT between 4745 and 7040 K. The corresponding target for a warm white LED package was an efficacy of 88 lm/W, an OEM price of $25/klm, CRI of 80-90, and CCT between 2580 and 3710K. These goals have been almost entirely met. The best commercial cool white LED products have demonstrated efficacies as high as 130 lm/W and selling prices as low as $12/klm (1000-off quantity), although not for the same device. The best warm white products have achieved efficacies as high as 93 lm/W and selling prices as low as $13/klm. As described previously, efficacy goals have been revised and the 2011 targets for cool white and warm white LED packages are now set at 156 and 118 lm/W respectively. The price targets for 2011 are $9/klm for cool white and $12/klm for warm white.

The FY10 goal for a warm white integrated LED lamp was an efficacy of 59 lm/W (assuming a luminaire efficiency of 62%), and an OEM price of $101/klm. During 2010 we observed the introduction of increasing numbers of replacement lamps with rapidly improving performance (as confirmed by independent testing through programs such as CALiPER) and increasingly competitive prices. In particular, a large number of warm white A19 replacement lamps were introduced with retail prices as low as $17.97. The normalized price for such products during 2010 dropped into the $40 to $50/klm range with efficacies in the 50 to 70 lm/W range (CCT=2700-3000K, CRI~85). Consequently lamp performance comfortably meets the efficacy targets and lamp price is a factor of 2 lower than the $/klm target.

The LED package and luminaire milestones in Table 5.6 have been revised to reflect recent progress. FY2010 and FY2015 milestones reflect efficacy and/or price targets for LED packages with lifetimes (lumen maintenance value) of 50,000 hours. The FY2010 performance and cost targets for cool and warm white LED packages were essentially met, as described earlier. DOE expects to see a high efficiency luminaire on the market by 2012 that has an output of 1,000 lumens, efficacy of 100 lm/W, and warm white color temperature. By FY2015, costs should be in the neighborhood of $2/klm for LED packages while also meeting other performance goals. 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 luminaire troffers with integrated controls and a price below $85.

Table 5.7: LED Package and Luminaire Milestones

Milestone	Year	Target
Milestone 1	FY10	LED Package: >140 lm/W cool white; >90 lm/W warm white; <$13/klm (cool white)
Milestone 2	FY12	Luminaire: 100 lm/W; ~1000 lumens; 3500 K; 80 CRI; 50,000 hrs
Milestone 3	FY15	LED package: ~$2/klm (cool white)
Milestone 4	FY17	Luminaire: >3500 lumens (neutral white); <$100; >140 lm/W
Milestone 5	FY20	<$85 Smart Luminaire Troffer

Assumption: Packaged devices measured at 35 A/cm^2.

The LED package and luminaire milestones represent well defined phases in the development of low cost high performance SSL luminaries. The first phase was to develop a reasonably efficient white LED package that is sufficient for the lighting market. This phase was completed a couple of years ago. The second phase, also essentially complete, is to further improve efficiency while decreasing price in order to realize the best possible energy savings. The availability of LED packages with efficacies in the 130+ lm/W range has begun to shift the focus toward the development of more efficient luminaries. This then becomes the thrust of the third phase, which is expected to last until about 2012. 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 expected to continue past 2015 and will be further supported through the R&D Manufacturing Program.

5.4 Organic Light Emitting-Diodes

Figure 5.5: Luminaire with 16 OLED panels
Source: UDC

Progress in the laboratory performance of OLED pixels and panels has confirmed that OLED-based lighting has the potential for higher efficacy than many of the traditional luminaires on the market today. However, although OLED panels from pilot lines in Europe and Japan have become available over the last three years, the performance of commercially available products is significantly below that attained in demo panels produced worldwide. Commercially available panels offer efficacies ranging from approximately 11 to 28 lm/W and half-lives (L50) of around 5,000 to 30,000 hours at initial luminance of 1,000 cd/m^2. Meanwhile, demo panels such as the ceiling light produced by UDC in cooperation with Armstrong Industries under the DOE SSL R&D Program have shown luminaire efficacy of 51 lm/W, color temperature of about 3320K, CRI of 84 and lifetime (L70) of 10,000 hours. A typical ceiling light fixture contains sixteen 6 by 6 inch panels, producing a total of 640 lumens within an area of 1 by 4 feet. Improved versions of these panels are expected to be commercially available by 2012. The panels will be manufactured on the prototype manufacturing line in Canandaigua, NY being developed by UDC and Moser Baer as part of the DOE SSL Manufacturing Initiative.

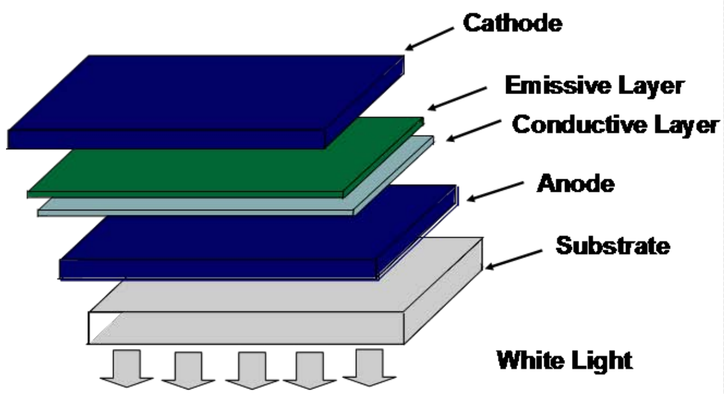
5.4.1 Components of OLED Luminaires

This section of the multiyear plan describes OLED luminaires for general illumination. Understanding each component of a luminaire and its contribution to overall luminaire efficiency highlights the opportunities for energy efficiency improvements and thereby helps to define priorities for DOE's SSL R&D Portfolio.

The core of a typical OLED light source is a stack of thin films with a total thickness of around100 to 200 nm, between two planar electrodes. The application of a voltage across the electrodes results in the transport of electrons and holes that combine in the emissive layers to create visible light. To form a luminaire, mechanisms must be provided to distribute the current uniformly across the electrodes and to protect the active layers from environmental damage.

- OLED 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;

- OLED Panel refers to an OLED with a minimum area of $50cm^2$. In the 2010 MYPP, the OLED Panel was defined to be at least $200cm^2$ in area. To keep terminology consistent with what OLED manufacturers are currently producing as panels, we have reduced the minimum size to $50cm^2$. However, in the long term, it is still believed that for low cost, high light output luminaires, larger area OLED panels will be developed and the DOE projections and priority tasks call for development of panels with a minimum size of $200cm^2$. OLED panels require current conducting structures to ensure uniform emission of light across the panel. They may also incorporate packaging, thermal management, and elements to enhance light extraction. It is expected that the OLED panel will serve as a building block component for OLED luminaires.



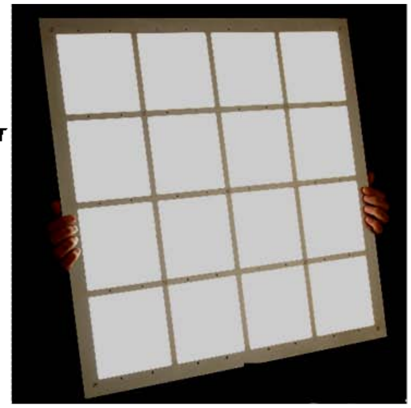


Figure 5.6: Diagram of OLED Device Structure and Photo of OLED Panel
Source: General Electric

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 shown in Figure 5.6. The cathode can then be made from opaque metal and a foil 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% transmission across the visible spectral region). These structures can emit upward from a reflective substrate, such as a reflective metal foil, or can be transparent devices. Figure 5.7 displays a transparent OLED panel employing a transparent substrate and transparent electrodes;

Figure 5.7: Photo of a Transparent OLED Lighting Panel
Source: Novaled

- OLED 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;

Figure 5.8: Prototype luminaires containing many OLED panels
Source : Acuity

- The OLED 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.

5.4.2 OLED Efficiency Metrics

As with LEDs, one can identify various elements of power efficiency including electrical, optical, conversion, and spectral within the OLED panel and luminaire. These components of efficiency can be measured or characterized, and the most critical areas for improvement can be identified.

Opportunities for improvement of the OLED Panel include: reducing electrical losses in the device; improving the efficiency of conversion of electrons into photons (IQE); maximizing the extraction of those photons from the material (extraction efficiency); and tailoring the spectrum of the radiated light to increase the eye response (spectral efficiency). Tailoring of the spectrum to the eye response is constrained by the need to provide light of appropriate color quality (CCT and CRI). Opportunities for improvement of the OLED Luminaire include reducing electrical and optical losses from the power supply, driver, controls, and fixture.

The following sections compare efficiencies achieved by 2010 for individual OLED panels and luminaires to program goals for OLED technologies to be achieved by 2020. These consensus goals were developed by the OLED Roundtable group and further refined through contributions from the R&D Workshop. The allocation of the 2010 efficiency values and the 2020 targets used in the sections to follow, however, serve only as a guide for identifying the opportunities for improvement.

For ease of comparison, OLED efficiencies have typically been reported assuming an OLED pixel, as defined in Section 5.4.1, at a fixed luminous emittance of 3,000 lm/m^2. For cost and performance considerations, luminaire manufacturers have recommended that OLED performance data be reported for larger area devices operating at higher lumen density levels. Thus future performance targets will assume an OLED panel of at least 200 cm^2 with a luminous emittance of 6,000 lm/m^2 for 2012 performance targets and then 10,000 lm/m^2 for performance targets in 2015 and beyond. These values are used as a common reference for the comparison of OLED efficacy and performance levels. It is not the intention of DOE to dictate the brightness, size, or current drive of devices used in practice.

Figure 5.9 shows the efficiency of an OLED panel and compares the typical values for the individual system elements to a set of suggested program targets.[67] The breakdown of loss mechanisms may differ with alternative OLED architectures, but regardless of architecture the drive voltage and out-coupling enhancement show the most room for

[67] The particular values used in this chart correspond to simple devices using phosphorescent emitters for all three colors. Similar overall efficacy levels have been attained using tandem hybrid devices with segmented electrode structures. This leads to higher values of electrical efficiency that offset the lower values of IQE.

improvements. The elements in this chart are described below:

- *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. A reduction in electrical efficiency is associated with an increase in the energy (voltage) required to create photons over and above the optical energy gap;
- *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 active region;
- *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. The LER for some white OLEDs is now around 325 lm/W and the estimated LER_{max} is 375 lm/W;[68]
- *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; and
- *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.

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[68] The use of a lower value of LER_{max} for OLEDs than for LEDs reflects the broader spectrum associated with organic molecules.

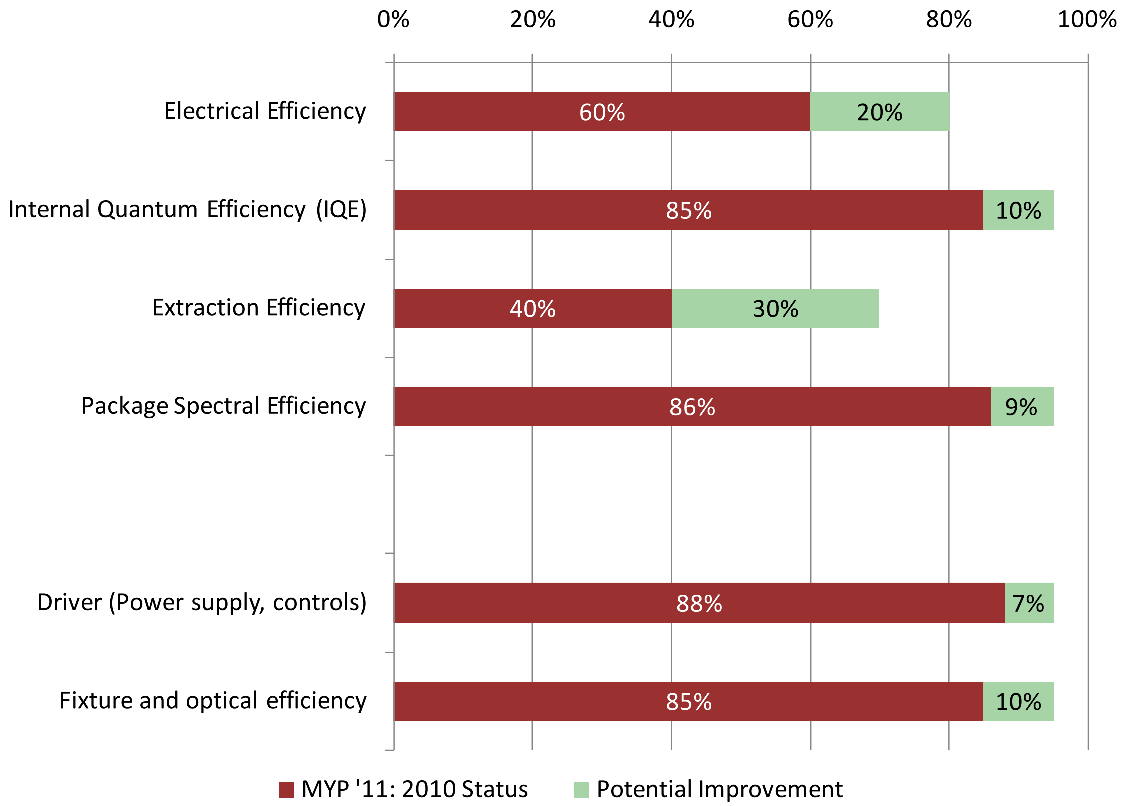

Figure 5.9: OLED Panel and Luminaire Loss Channels and Efficiencies

Note: Assumptions for Target figures: CCT: 2580-3710 CRI> 85, 10,000 lm/m^2, panel area ≥ 200 cm^2

If all the improvements shown in Figure 5.9 are achieved, the efficiency of the OLED panel would rise from the current typical value of 18 to 51%. The corresponding panel efficacy would rise from 66 lm/W to as much as 190 lm/W. The following discussion summarizes opportunities for improvement in the above described loss channels.

Opportunities for gains in electrical efficiency:

Substantial gains in electrical efficiency can be made by lowering the drive voltage from current levels of around 3.5 volts closer to the threshold for photon creation. Using separate red, green and blue emissive layers, each with their own drive voltage, can potentially provide a highly efficient approach. In white OLED devices with a single drive voltage, there will be some unavoidable inefficiency due to driving the device at a voltage required for blue emission while producing a significant amount of lower energy red and green light.

In addition to providing enough energy to create photons, the drive voltage must also ensure adequate current density across the device. The required current density in highly efficient devices with a single stack is approximately 2.5 mA/cm^2. Means to reduce the voltage between the electrodes include transport layers with lower resistance, for example through ion doping, and better interfaces, especially between the electrodes and injection layers.

Another major impact on the electrical efficiency of OLED panels comes from ohmic losses introduced in scaling the size of OLED devices from pixels to larger panels, which brings a significant challenge in ensuring efficient and uniform current spreading over the area of the panel. Analysis shows that good uniformity requires that voltage drops across the panel be limited to less than 0.1V. If this target is achieved, the ohmic losses in transporting current across the panel will be small (less than 4%). Accomplishment of this goal may require current spreading bus bars or metal grids and/or engineering of the transparent electrode, each of which have important secondary effects. The use of a grid or changes to the transparent electrode will impact light extraction from the panel. In addition, the current spreading approach needs to be low cost and must integrate with the light extraction approach and the entire OLED structure.

Opportunities for gains in internal quantum efficiency:

The cited status (85%) and target (95%) for IQE assume the use of phosphorescent materials and rely on the accuracy of the methods used to estimate IQE. Some analysts believe that these values are overestimated and that a more reliable means of measuring IQE is needed. The existing data for IQE indicate that a three-fold increase in brightness need not lead to a large penalty in efficacy. However, there may be a major impact on the operating lifetime, which could be reduced by a factor of five or more, unless steps are taken to reduce degradation. Additionally, several leading researchers have suggested that it may be too difficult to achieve lifetime targets with phosphorescent blue emitters. Since less than 25% of the photons needed to produce white light are blue, adequate efficiency may be possible using fluorescent blue emitters. IQE losses are reduced if the stack is engineered such that the blue emitters transfer the energy from triplet states to red or green phosphorescent emitters. Recent experiments have shown that such hybrid systems can reach at least 85% of the efficiency of all phosphorescent devices.[69]

Opportunities for gains in light extraction efficiency:

It is clear from Figure 5.9 that the greatest opportunity for efficacy gains lies in increasing extraction efficiency. Light trapping naturally occurs in a transition from one layer to another of lower refractive index. The index of refraction of the organic layers in which light is created is typically 1.8, as is that of the transparent anode (ITO). Most glass and plastic substrates have a lower index of about 1.5. The use of high index substrates is a demonstrated route to improving light extraction, but such substrates are too costly for use in large area panels. The loss of optical energy can be split into four components:

- Reflection at the substrate-air interface – This can be reduced by adding texture to the substrate – air interface. This can comprise random texturing such as a scattering layer or a roughened glass surface or patterned texturing such as a micro-lens array. Gains in total light extraction of 50% are typical;
- Reflection at the inner surface of the substrate – This can be reduced by introducing a scattering layer or other internal structures between the transparent electrode and substrate or between the transparent electrode and organic layers.

[69] S. Reineke, SID Digest 25.3 (2009)

Such structures are incorporated to deflect the light towards the normal direction. Gains of over 100% have been reported;

- Transfer of energy to the metal cathode – This is reduced by optimizing the reflectance of the cathode and adjusting the thickness of the organic layers. The severity of these losses is a matter of debate; and
- Absorption by all materials and internal reflections – there are many small effects, including absorption in the conducting materials, transport, scattering and substrate/encapsulation layers.

It seems likely that all four components must be reduced if the efficacy targets are to be met. Although many techniques have been suggested to enhance the light extraction efficiency, it has proved to be extremely difficult to find a method that can be manufactured inexpensively in large area panels with thin profile and without interfering with the operation of the OLED (for instance, by increasing voltage, reducing efficiency, leading to angular dependence of color, etc.).

Opportunities for Gains in Spectral Efficiency

Present OLED devices show a broad distribution in the red part of the spectrum that spills beyond the visible range. Designing or improving the emitters, changing their characteristics so as to have a tighter distribution in the red could lead to higher LER_{max}, and therefore higher efficacies. Additional gains could be made by optimizing the spectrum of the blue emitter. However, color quality must be maintained during adjustments to the spectra.

Trade-offs in Improving Efficiency

Analyses of efficacy improvements provide only part of the story. Meeting other targets for lifetime, color quality and manufacturing cost may mean that compromises are necessary. Short prevention is essential to ensuring reliable performance. Structures with thick injection layers provide added protection against shorting, but may also lead to increased drive voltage or reduced transmission.

Shelf life is also important in commercially viable products. OLEDs are sensitive to oxygen, moisture, and other pollutants in the operating environment which necessitate effective encapsulation of the OLED panel. This is particularly challenging in the case of OLEDs on flexible substrates, since plastic materials are extremely porous. In addition, oxygen, moisture, and other contaminants can get embedded into the OLED in the fabrication process reducing the panel lifetime. Even for panels with rigid substrate and cover, sealing of the edges is not trivial and a thin layer of dessicant or getter may be needed to absorb water or oxygen that is trapped during encapsulation or enters later through the edge seal.

As noted in Section 3.5.3, the cost of manufacturing panels with a specific light output can be reduced significantly by increasing the panel brightness. However, such increases in luminous emittance must be made without degradation of efficacy or operating lifetime.

5.4.3 OLED Panel Performance Targets

As described in Section 3.2, UDC has reported an efficacy of 66 lm/W for an OLED panel, and OLED pixels have been reported with efficacies as high as 124 lm/W in the laboratory (Technical University of Dresden with Novaled AG). In consideration of the need to move beyond laboratory scale OLED pixel results and the need to develop practical building blocks for OLED lighting products, DOE bases future projections only on results obtained with panels. Reasons for disregarding some pixel data include:

- Light extraction techniques are often not scalable to large areas within the physical constraints desirable for most lighting applications;
- Some small devices incorporate materials that would be too expensive for large area panels;
- Laboratory devices are sometimes too complex for affordable manufacturing or reliable performance; and
- Devices designed to maximize one characteristic often have unacceptable performance in other respects, for example in color quality.

Performance targets for future years are based partly on extrapolations of past data on devices that are scalable. Analyses of efficacy, stability and light quality, such as those described above, are used in setting the asymptotes on efficacy and other performance metrics. The updated projection for efficacy is shown in Figure 5.10, incorporating an asymptote of 190 lm/W.

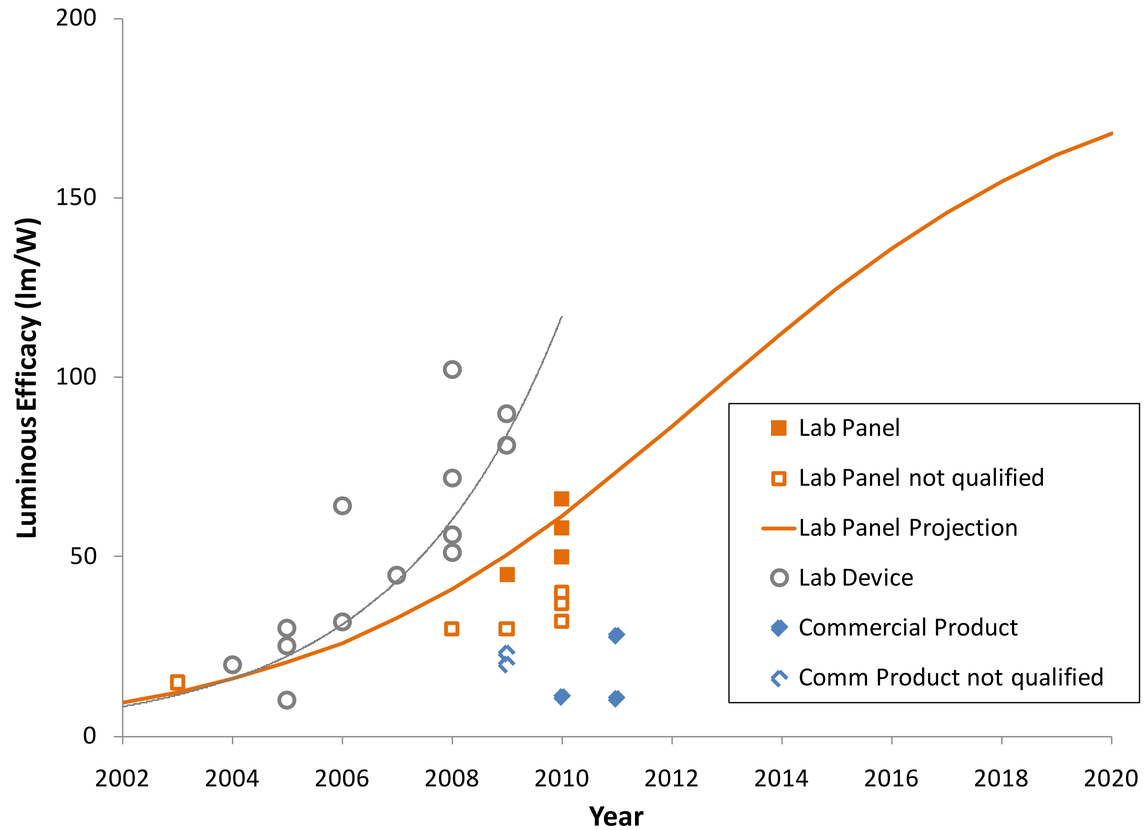

Figure 5.10: White Light OLED Panel Efficacy Projections

Figure 5.10 shows that the prototype panels that are commercially available fall far short of the performance levels achieved in the laboratory. Reducing that shortfall is one of the major goals of the SSL Manufacturing Initiative.

Intermediate targets for efficacy and lifetime are included in Table 5.8.

Table 5.8: Summary of OLED Panel Performance Projections

Metric	2010	2012	2015	2020
Panel Efficacy (lm/W)	62	86	125	168
Panel Life (L70) - (1000 hours)	10	25	50	100
Luminous emittance (lm/m^2)	3,000	6,000	10,000	10,000

Notes: 1. Projections assume CRI > 85, 2580-3710 K
2. Panel size of at least 200 cm^2

Achieving efficiency gains alone will not be sufficient to reach viable commercial lighting products. The films must also be producible in large areas at low cost, which highlights the importance of minimizing substrate and electrode losses over a large area, as noted above and in the figure, and may also limit materials choices.

Improvements to OLED panel and luminaire operating lifetime, as well as shelf life, also must be realized in order to ensure a commercially viable product. OLEDs are sensitive to oxygen, moisture, and other pollutants in the operating environment which necessitate extensive encapsulation of the OLED panel, particularly in the case of OLEDs on flexible substrates. In addition, oxygen, moisture, and other contaminants can get embedded into the OLED in the fabrication process reducing the panel lifetime.

Operation at higher lumen outputs can also dramatically reduce the lifetime of OLED devices if the increase is achieved solely by raising the drive current rather than by improvements in efficacy. It is estimated that an increase in luminous emittance from 3000 lm/m^2 to 10,000 lm/m^2 could reduce the lifetime of the OLED by as much as 80%. However, tandem OLED architectures or improvements to light extraction efficiency could lead to higher emittance without increased applied current, thus possibly avoiding this problem. Furthermore, it is important that efficacy is improved along with the increase in brightness so that the addition of costly thermal management components will not be necessary. Most likely, some combination of improved light extraction efficiency and higher operating current will be required to increase the luminous emittance.

In summary, OLED panels have the potential to become much more efficient. There is significant headroom for improvement, particularly in light extraction efficiency and reduced operating voltage. There is also room for improvement in IQE and spectral efficiency of OLED panels and in driver and optical efficiency of the luminaire. If all of the improvements can be developed as planned then OLED panel performance can increase from 66 lm/W to 190 lm/W. However, all of these gains need to be developed while keeping the cost of the OLED panels and luminaires competitive with alternative lighting technologies. Increasing the lumen density of the OLED panels can have a large impact on the cost of OLED panels and luminaires. However, as the lumen density of OLED panels is increased, the lifetime of the OLED panels needs to remain competitive with other lighting technologies. This could be particularly challenging.

5.4.4 OLED Luminaire Performance Targets

The conversion of an OLED panel to a luminaire is likely to be simpler than that of LED packages. At a minimum, one needs to add a driver to connect to the available power supply and mechanical structures to hold the panel in position, to afford physical protection against damage while in use, and to meet local building codes. Luminaires with multiple panels will need a framework to maintain the desired separation and relative orientation of each panel in a form that is pleasing to the eye.

The inclusion of the driving circuitry will certainly lead to electrical losses. It is possible to design luminaires with no additional optical losses. However if the distribution of light emerging from the panel(s) is not appropriate for the application, some form of optical lens may be needed.

The progress anticipated in Figure 5.9 would raise the efficiency of an OLED luminaire from 13% (49 lm/W) up to a limit of about 46% (171 lm/W). It should be noted that while no fundamental roadblocks to the OLED efficacy performance projections have been identified, there is also very little performance data for large panels and luminaires. As more integration of OLEDs into panels and luminaires occurs, additional loss mechanisms may be identified similar to LED luminaires, such as current droop and sensitivity to the operating temperature.

Since OLED luminaires have only been manufactured as prototypes in small quantities, the values in this chart are estimates. Ongoing discussions between OLED developers and luminaire manufacturers are urgently needed to define the electrical, optical, mechanical, and possibly, thermal requirements of the OLED panel. For example, some OLED proponents believe that optical losses outside the panel will be minimal. However the Lambertian distribution of light emitted by OLEDs may be unacceptable for most general illumination applications and external optical elements will be needed to redirect the light, resulting in some losses.

Table 5.9, below, details a summary of the performance projections for OLED luminaires. The column for 2010 is based upon a prototype luminaire developed by UDC in collaboration with Armstrong Industries. The efficiency of the driver is 88% and there are no optical structures outside the panel. However, this luminaire has not been tested commercially and customers may judge that the light is spread too widely. So in the projections for years beyond 2015, allowance is made for beam shaping optics to redistribute the light.

Table 5.9: Summary of OLED Luminaire Performance Projections

Metric	2010	2012	2015	2020
Panel Efficacy (lm/W)	58	86	125	168
Optical Efficiency of Luminaire	100%	100%	90%	95%
Efficiency of Driver	88%	90%	93%	93%
Total Efficiency from Device to Luminaire	88%	90%	84%	88%
Luminaire emittance (lm/m^2)	3,000	6,000	9,000	9,500
Resulting Luminaire Efficacy (lm/W)	51	77	105	148

Note: Efficacy projections assume CRI > 80, CCT 2580-3710
The values of optical efficiency quoted for 2010 and 2012 assume no light shaping optics

Since no experience has been obtained concerning the reliability of OLED driver circuits, their effect on luminaire lifetime is unknown. Ensuring that driver failures do not lead to substantial reductions in luminaire lifetimes will be important to the success of OLED lighting technology.

5.4.5 OLED Adoption Barriers

The following lists some of the technical, cost, and market barriers to OLEDs.

1. Cost: Although some cost savings can be achieved through device simplification and new fabrication processes, the most significant reductions will result from gaining experience in manufacturing and in scaling to higher

production volumes. Especially in initial production, synergy with OLED production for display applications will be important as the leading manufacturers retool for large area television screens. As noted above, increases in luminous emittance will also be important in reducing material costs and increasing the yield of good products and waste minimization will be critical to reduce material cost.

OLED stakeholders have suggested that the cost of converting OLED light sources into luminaires may be less than for LEDs and many traditional light sources. This may be true, but panel makers and luminaire manufacturers will need to work closely together to develop designs that provide excellent functionality and an attractive appearance, without adding significant cost.

2. Extraction efficiency: Reaching the targets listed above for extraction efficiency without significant increase in panel thickness or cost will be challenging. Extracting all the light that is currently lost to the metal electrode or is trapped between the electrodes is particularly difficult.

3. Drive voltage: Another critical step in increasing efficacy is to reduce the drive voltage by reducing the effective resistance between the electrodes. It may be difficult to do this without increasing the risk of shorting across the electrodes.

4. Lifetime: Substantial improvement will be needed in both shelf life and operating lifetime. Achieving long shelf life requires that all elements that may damage the active materials, such as oxygen and water, be removed in the fabrication process and that ingress is not possible after encapsulation. The use of a plastic substrate or cover exacerbates this problem. However, even if non-porous materials, such as glass or metal foils, are used to encase the device, the integrity of the edge seals must be assured.

   Operating lifetime depends mainly on the total amount of current that flows through the device. The use of tandem structures helps to achieve high brightness and efficacy at low current density, but such architectures are rather complex. In addition to novel architectures, the development of more robust materials is essential. While red and green emitters have demonstrated exceptionally long lifetimes, systems involving blue phosphorescent emitters have relatively short lifetimes. Furthermore, deleterious interactions between neighboring layers can be just as harmful as the decay of individual components.

5. Testing: The comments in Section 5.1.5 regarding testing of LEDs will apply also to OLEDs. Specific techniques will need to be developed for real-time testing of OLED panels during production, especially if roll-to-roll methods are used. For example, the cleanliness and smoothness of substrates and electrode layers must be assured before expensive organic materials are added.

6. Lumen Output: In order for OLEDs to produce the lumen output required for most general illumination applications without creating excessive glare, large emission areas are needed. The implications of higher emittance must be studied in practice, for example with respect to thermal management, lifetime and decreased efficacy. Due to the relatively small substrates used in initial production and the difficulty of fabricating large panels with no defects, most luminaires produced in the next few years will contain multiple panels.

7. Light Distribution: OLEDs produce light with a broad angular distribution.[70] However, this is rarely appropriate for lighting applications. Many luminaires are designed to focus the light in specific areas. Others produce bat-wing like patterns in which the luminance peaks off-axis to give uniform illumination over a larger area of floor space. Similar effects may be attained in luminaires containing several OLED panels with different orientations.

Figure 5.11: Luminaire using multiple panels with varying orientation
Source: WAC Lighting

8. Investment in Manufacturing: Asian manufacturers of OLED displays may be able to adapt their fabrication lines to produce OLED light sources, but the lower cost constraints will require important modifications. For example, the borosilicate glass used in active matrix displays is too expensive for lighting applications. Alternative types of glass substrates may be required. Although European and American companies have shown considerable interest in OLED R&D, they have been reluctant to invest the $50 to $100 million necessary to produce light sources economically.

9. Codes and Standards: The same problems will be faced as for LEDs. The path to commercialization for LEDs has required the development of numerous testing and performance standards. Many of these standards will be suitable for OLED-based light sources, but it is expected that some new standards will need to be developed specifically for OLEDs based on the technological differences between OLEDs and LEDs.

[70] The distribution is usually close to Lambertian, which implies that the intensity is proportional to the cosine of the angle between the light ray and the normal direction

10. Market Competition: OLED proponents have often assumed that although inorganic LEDs will dominate the markets for compact, bright light sources, OLEDs will capture a significant fraction of the market for diffuse sources. However, in many indoor environments it will be extremely difficult to compete with a combination of modern fluorescent fixtures combined with LED-based compact task lights or downlights. In addition, the success of LED backlights in replacing cold cathode fluorescent light sources as the primary light source for LCD screens may soon lead to a flood of large area LED-based light sources for general illumination.

For more information about individual research tasks that address these technical, cost and market barriers, refer to the following Section 5.5.

5.5 OLED Critical R&D Priorities

In order to achieve the projected target performance levels for OLED-based SSL, progress must be achieved in several research areas. The original task structure and initial priorities were defined at a workshop in San Diego in February 2005. These priorities have been updated in subsequent editions of the MYPP, based upon input from industry representatives and academic researchers. In creating the 2011 MYPP, one of the goals was to reduce the number of tasks to concentrate research on the most urgent issues. DOE first held SSL roundtable sessions Washington, D.C. in November of 2010 to gather input on task prioritization from industry stakeholders (see Appendix D for the entire task list). The tasks were further discussed and refined at the February 2011 "Transformations in Lighting" workshop in San Diego, CA. Using these recommendations, and after further internal review, the DOE defined the task priorities for 2011 as follows:

For OLED Core Technology:

- Subtask C1.2 (Novel materials and structures) will support the development of stable white light OLED materials and structures to reduce voltage, increase EQE, and improve lifetime that have the potential for large scale, low-cost production and processing. The principal function of the new materials can be to create light or transport charge, but they must be compatible with all other elements of an efficient, long-lived OLED. The purpose of structural changes may be to improve the performance of the device or to provide a better match with the requirements of luminaire manufacturers; and
- Subtask C.6.3 (Light extraction approaches) supports the development of new optical designs within the OLED device structure and in the panel to improve OLED panel light extraction. The structures should not lead to significant increases in the thickness or the cost of large area panels.

For OLED Product Development:

- Subtask D.6.1 (Large area OLED) will support efforts to tackle the significant challenges transitioning OLED pixel performance to larger area OLED panels; and

- Subtask D.6.3 (Panel light extraction) supports development of low cost, scalable light extraction approaches that can be applied to OLED panels.

The sections that follow provide a description of the tasks and defined metrics. There is also an estimate of the current status and a target for year 2020.

5.5.1 OLED Priority Core Technology Tasks for 2011

C1.2 Novel OLED Materials and Structures

Description: Develop novel materials and structures that demonstrate a significant improvement in at least one of the following areas: a) More efficient and balanced charge injection and white light emission; b) improved EQE; c) voltage reduction; d) longer lifetime; e) radically reduced cost (for example through increased material robustness or through materials and architectures that enable simpler device fabrication); f) greater control of the color or directionality of light. Materials/structures developed should be demonstrated in OLED devices which are characterized to ascertain the performance as compared to the metrics below. Novel materials/structures should demonstrate a significant improvement in at least one area while maintaining or improving upon all other metrics.

Metric(s)	2010 Status(s)	2020 Target(s)
EQE without external extraction enhancement	~22%	25-30%
Lifetime (L70)	10,000 hrs at 3000 lm/m^2	>50,000 hrs at 10,000 lm/m^2
Voltage[71] @ $2mA/cm^2$	~3.4V	<3V
CRI	84	>90[72]
Cost		Factor of 10 reduction in cost of OLED panel
Light Distribution	N/A	Directional beam shaping

[71] This value assumes the use of a single voltage to drive each of the emitters. It should be regarded as an average value for tandem structures or those with separate drive for the RGB components.
[72] CCT 2580 to 3710K; CIE coordinates within 2-step MacAdam ellipse

C6.3 Light Extraction Approaches		
Description: Devise new optical and device designs for improving OLED light extraction while retaining the thin profile and state of the art performance of OLED panels (for example, extraction layers should not lead to voltage increases, reduction in device efficacy, angular dependence of color). The proposed solution could involve modifications within the OLED stack, within or adjacent to the transparent electrode, and external to the device. The approach should provide potential for low cost and should be demonstrated in a device of at least 1 cm^2 in size to demonstrate applicability and scalability to large area (panel size) devices.		
Metric(s)	**2010 Status(s)**	**2020 Target(s)**
Extraction Efficiency	40% (laboratory, small area)	70%
Angular Dependence of Color		2 step MacAdam ellipse

5.5.2 OLED Priority Product Development Tasks for 2011

D6.1 Large Area OLED		
Description: Demonstrate a high efficiency OLED panel, with a white light output of at least 200 lm and an area of at least 200 cm^2. The OLED panel should have high brightness and color uniformity as well as a long operating lifetime. The panel should employ low cost designs, processes, and materials and demonstrate a potential for high-volume manufacturing.		
Metric(s)	**2010 Status(s)**	**2020 Target(s)**
Lumen Output	300 lm	> 200 lm
Efficacy	50 lm/W	>150 lm/W
Lifetime (L70)	7,000 hrs	>50,000 hrs
Color uniformity		2 step MacAdam ellipse
Brightness uniformity	10% over a small sample	10% over 200 cm^2
Cost of panel	N/A	<$10/klm

D6.3 Light extraction		
Description: Demonstrate manufacturable approaches to improve light extraction efficiency and possibly directionality for OLED panels while retaining the thin profile and state of the art performance of OLED panels (for example, extraction layers should not lead to voltage increases, reduction in device efficacy, angular dependence of color). The proposed solution could involve modifications within the OLED stack, within or adjacent to the transparent electrode, and/or external to the device. The approach should be demonstrated over large areas (> 25cm^2) and provide potential for low costs.		
Metric(s)	**2010 Status(s)**	**2020 Target(s)**
Extraction Efficiency	40%	70%
Incremental Cost		<$10/m^2

5.6 OLED Interim Product Goals

Table 5.10 shows the overarching DOE milestones for OLED-based SSL. DOE milestones for OLEDs have transitioned from OLED pixel results to OLED panel results. OLED panels are expected to be building block components of OLED luminaires and it is necessary to advance the performance of these larger area emitters to demonstrate the feasibility of OLED-based luminaires. Although particular characteristics are highlighted at each stage, it is assumed that progress continues in all respects and specific targets are not met through unacceptable compromises in other parameters.

Table 5.10: OLED Panel Milestones

Milestone	Year	Target
Milestone 1	FY08	> 25 lm/W, < $100/klm, 5,000 hrs pixel
Milestone 2	FY10	> 60 lm/W panel
Milestone 3	FY12	< $45/klm panel
Milestone 4	FY15	> 100 lm/W panel @ 10,000 lm/m^2
Milestone 5	FY18	50,000 hour lifetime; 10,000 lm/m^2 panel

Assumptions: CRI > 80, CCT < 2580-3710 K for an OLED panel >200 cm^2. All milestones assume continuing progress in the other overarching parameters - lifetime and cost.

The FY2008 OLED milestone was to produce an OLED niche product with an efficacy of 25 lm/W, an OEM price of $100/klm (device only), lifetime of 5,000 hours from 1000cd/m^2, CRI greater than 80, CCT between 2,700K and 4,100K and total output of at least 500 lumens.

In 2008 UDC produced a 225 cm^2 prototype panel, with efficacy of 39lm/W, CRI of 86 and CCT below 3000K. Lifetime tests were not reported for this panel, but all similar devices produced by UDC at that time exhibited lifetimes (L70) over 10,000 hours. When operated at the nominal luminance of 1000 cd/m^2, the light output of this panel was only about 60 lumens, but UDC's intention was to use multiple panels in luminaires. There was no commercial production of OLED panels in 2008 and so no cost data was available.

By 2010, the efficacy of UDC panels reached 58 lm/W, with CRI of 84, CCT of 3320K and lifetime (L70) of 10,000 hours. The output was still small and the cost unspecified. UDC also produced a panel with efficacy of 66 lm/W, but with CRI relaxed to 79. The commercial panels offered by foreign suppliers were produced in small volume on laboratory lines and their price was well above the SSL cost target for 2008.

Since large volume manufacturing has still not been established, it seems unlikely that the 2012 cost target of $45/klm will be met. Low volume production from the prototype line in Canandaigua, New York should commence before the end of FY2012. The goal will be to ensure that the incremental cost of production will be less than $45/klm, but depreciation of fixed costs will be larger than this amount.

5.7 Unaddressed Opportunities for SSL

DOE's support of SSL R&D has largely kept the focus on high efficiency in SSL lighting. The inclusion of the manufacturing initiative in 2009 was a welcome addition to the portfolio, but has increased the competition for limited funding among submitted project proposals. Unfortunately, since the manufacturing initiative was initially funded by the ARRA of 2009, which has expired, additional support is needed just to continue the manufacturing effort and maintain our previous levels of funding of Core and Product Development, at a time when the number of applications has increased. There are also always new topics that could benefit from additional funding.

Reliability and color quality have received increasing attention recently, as we move beyond efficacy as the primary driver. Some work in these areas is now among the priority tasks, but in order to avoid compromising efficiency for the benefit of these other performance criteria, significant invention and creativity is required and would be a good use of DOE investment in R&D.

Some of these opportunities are as follows, and are similar to those cited last year:

1. *Funding of additional projects.* As the DOE SSL R&D Program has grown in size and prominence, the number of applicants for funding R&D projects continues to increase. While selection is a good thing, and a number of unsuccessful projects have even ended early, there is always room to explore additional directions. Now, with the addition of the manufacturing initiative it will become even more difficult to fund all of the worthwhile projects proposed. This could be a very large lost opportunity.

2. *Devise methods to accelerate life testing of luminaires.* This remains a problem with no evident means of solution. While methods of testing normal lumen depreciation in

SSL packages have advanced, there is no substitute for testing SSL lighting products in operation as a complete luminaire. Thermal, chemical, and electrical differences in steady state operation can accelerate lumen depreciation or even cause premature failures. For small luminaire makers, especially, testing complete luminaires for a long period of time may be prohibitively expensive, not to mention delaying product introduction in a rapidly evolving market. There is not a good method to accelerate this testing. Many standard approaches such as high temperatures, for example, may actually introduce new failure mechanisms. Because of the expense and difficulty, this is an area where industry could use significant support.

3. *Understanding of failure mechanisms.* This topic is of rapidly increasing importance. The use of chemicals in luminaire assembly that are incompatible with SSL and overstress of SSL due to improper driver design or aging of electronic controls have been cited as prime causes of catastrophic or accelerated SSL failures, to name some specific examples. However, we do not have a clear understanding of all of the types or frequency of premature failures.

4. *Efficient driver and control subsystems*. With the appearance of hybrid chip solutions to improve color, especially for warm color temperatures, control of the diodes has become more complex, in some cases compromising overall system efficacy. At the same time, considerable interest has been developing for the idea of using the unique control capabilities for LEDs to add significant energy savings. These two issues are not unrelated as similar controls can be applied for both purposes. It is difficult in periods of tight funding to have such projects rise to the level of a priority project, as there is considerable work being done without DOE's intervention, and the technology is somewhat beyond the scope of solicitations normally undertaken by the program. Nonetheless, with the significant potential savings, it would be worth deeper study to determine exactly what types of controls and what tradeoffs might result in the highest system energy savings and reliability.

6.0 Solid-State Lighting Portfolio Management Plan

The U.S. DOE's SSL Portfolio draws on DOE's long-term relationships with the SSL industry and research community to guide SSL technology from laboratory to marketplace. DOE's comprehensive approach includes Basic Energy Sciences, Core Technology Research, Product Development, Manufacturing R&D, Commercialization Support, and an SSL Partnership. Figure 6.1 shows the connections and interrelationships between these elements of the program.

Figure 6.1: Interrelationships within DOE SSL Activities

Basic Energy Sciences research advances fundamental understanding. Projects conducted by the Basic Energy Sciences Program focus on answering basic scientific questions that underlie DOE mission needs. These projects target principles of physics, chemistry, and materials sciences, including knowledge of electronic and optical processes that enable development of new synthesis techniques and novel materials.

The SBIR Program sets aside funding solely for competitions among small businesses. Small businesses that win awards in these programs keep the rights to any technology **s** developed and are encouraged to commercialize the technology. Each year DOE issues a solicitation inviting small businesses to apply for SBIR Phase I grants. It contains technical topics in such research areas as energy production, fundamental energy sciences, Environmental Management, and Nuclear Nonproliferation. For research projects encompassing SSL technology, funding is provided by the Office of Science, and projects are then managed by DOE's SSL R&D Program.

Core Technology Research fills knowledge gaps. Conducted primarily by academia, national laboratories, and research institutions, Core Technology research involves scientific research efforts to seek more comprehensive knowledge or understanding of a subject. These projects fill technology gaps, provide enabling knowledge or data, and represent a significant advancmente in our knowledge base. They focus on applied research for technology development, with particular emphasis on meeting technical targets for performance and cost.

Participants in the Core Technology program perform work subject to what is termed an "exceptional circumstance" to the Bayh-Dole Act, and any resultant intellectual property is open, with negotiated royalties, to all Partnership members with a non-exclusive license. At DOE's discretion, Core Technology projects are peer-reviewed by government personnel, independent organizations, and consultants.

Product Development utilizes knowledge gains. Conducted primarily by industry, Product Development is the systematic use of knowledge gained from basic or applied research to develop or improve commercially viable materials, devices, or systems. Technical activities focus on a targeted market application with fully defined price, efficacy, and other performance parameters necessary for success of the proposed product. Project activities range from product concept modeling through development of test models and field ready prototypes.

DOE expects these proposals to include comprehensive work plans to develop a specific SSL product or product family. Because the ultimate goal is to manufacture energy efficient, high performance SSL products, each work plan should address the abilities of each participant or manufacturer throughout the development process. These participants must not only have all the technical requirements to develop the desired SSL technology, but also must also have reasonable access to U.S. manufacturing capabilities[73] and targeted markets to quickly move their SSL product from the industry laboratory to the marketplace.

Manufacturing R&D addresses the challenges of a maturing market. Also conducted primarily by industry, these projects work to improve product consistency and quality and to accelerate cost reduction by improving manufacturing processes. A secondary objective is to maintain, in the case of LEDs, or establish, in the case of OLEDs, the manufacturing and technology base within the U.S. Pre-competitive cooperation in understanding best practices, common equipment needs, process control, and other manufacturing methods and issues can yield great rewards for all.

Commercialization Support activities facilitate market readiness. To ensure that the DOE investments in Core Technology and Product Development lead to SSL technology commercialization, DOE has also developed the Federal government commercialization support strategy. Working with the SSL Partnership and other industry and energy organizations, DOE is implementing a full range of activities, including:

- Design competitions for lighting fixtures and systems using SSL;
- Technical information resources on SSL technology issues, test procedures, and standards;
- Testing of commercially available SSL products for general illumination;
- Technology demonstrations to showcase high performance SSL products in appropriate applications;
- Technology procurement programs that encourage manufacturers to bring high quality, energy efficient SSL products to the market and that link these products to volume buyers; and

[73] The Patent and Trademark Law Amendments Act, more commonly known as the Bayh-Dole Act, requires that federally funded inventions and resulting products to be manufactured in the U.S. http://www.access.gpo.gov/nara/cfr/waisidx_01/37cfr401_01.html

- Coordination with utility, regional, and national market transformation programs.

SSL Partnership provides manufacturing and commercialization focus. Supporting the DOE SSL Portfolio is the SSL Partnership between DOE and the NGLIA, an alliance of for-profit lighting manufacturers administered by NEMA. DOE's Memorandum of Agreement with NGLIA, signed in 2005, details a strategy to enhance the manufacturing and commercialization focus of the DOE Portfolio by utilizing the expertise of this organization of SSL manufacturers. The Partnership members confer among themselves and communicate their R&D needs to the DOE program managers, who in turn, shape these needs into the project solicitations. A Memorandum of Understanding (MOU) was recently sign to extend the partnership into 2012 (for a complete version of the MOU, see Appendix G).

The SSL Partnership provides input to shape R&D priorities, and accelerates implementation of SSL technologies by:

- Communicating SSL program accomplishments;
- Encouraging development of metrics, codes, and standards;
- Promoting demonstration of SSL technologies for general lighting applications; and
- Supporting DOE voluntary market oriented programs.

As of October 2010, the NGLIA comprised of seventeen corporations 羊3M, Acuity Brands Lighting, Applied Materials Inc., Bayer Material Science LLC, CAO Group Inc., Corning Inc., Cree Inc., Eastman Kodak Company, GE-Lumination, Light Prescriptions Innovators, LLC (LPI, LLC), LSI Industries, Luminus Devices Inc., OSRAM Sylvania Inc., Philips SSL Solutions, QuNano Inc., Ruud Lighting Inc., and UDC[74] 羊though NEMA is actively seeking to extend membership to any firms active in SSL R&D.

For more information on NGLIA, see their website at: http://www.nglia.org.

6.1 SSL R&D Strategy and Operational Plan

DOE's SSL R&D Program is guided by the seven principles of a government – SSL Industry Partnership. Working through the competitive solicitation process, these seven guiding principles position DOE's research partners and projects for success through:

- Emphasis on competition for research funds;
- Cost (and risk) sharing between Government and research partners, exceeding Energy Policy Act of 1992 cost-share requirements;
- SSL industry partners involved in planning and funding;
- Targeted research for focused R&D needs;
- Innovative intellectual property provisions;
- Open information and process; and

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[74] Current NGLIA Members.October 19, 2010. Available at: http://www.nglia.org/membership.html

- Success determined by milestones met and energy efficient, long-life, and cost competitive products developed.

DOE has structured an operational plan for SSL R&D, depicted in Figure 6.2 that outlines the various activities in which DOE, industry, and researchers engage in order to facilitate the commercialization of SSL products. Each of these activities is discussed in further detail in the following sections. First, through collaboration with the SSL Partnership and a series of workshops and roundtables, DOE identifies and prioritizes core technology, product development, and manufacturing needs. Based on the priority areas, DOE then issues competitive solicitations to industry, academia, national laboratories, and research institutions. Subject to an "exceptional circumstance" to the Bayh-Dole Act (discussed in the previous section), intellectual property and royalties can be exchanged between core technology researchers and the SSL Partnership. DOE annually tracks the status of SSL technology and reports progress toward program milestones to the United States Congress. See Appendix F for a full version of the Exceptional Circumstances Determination.

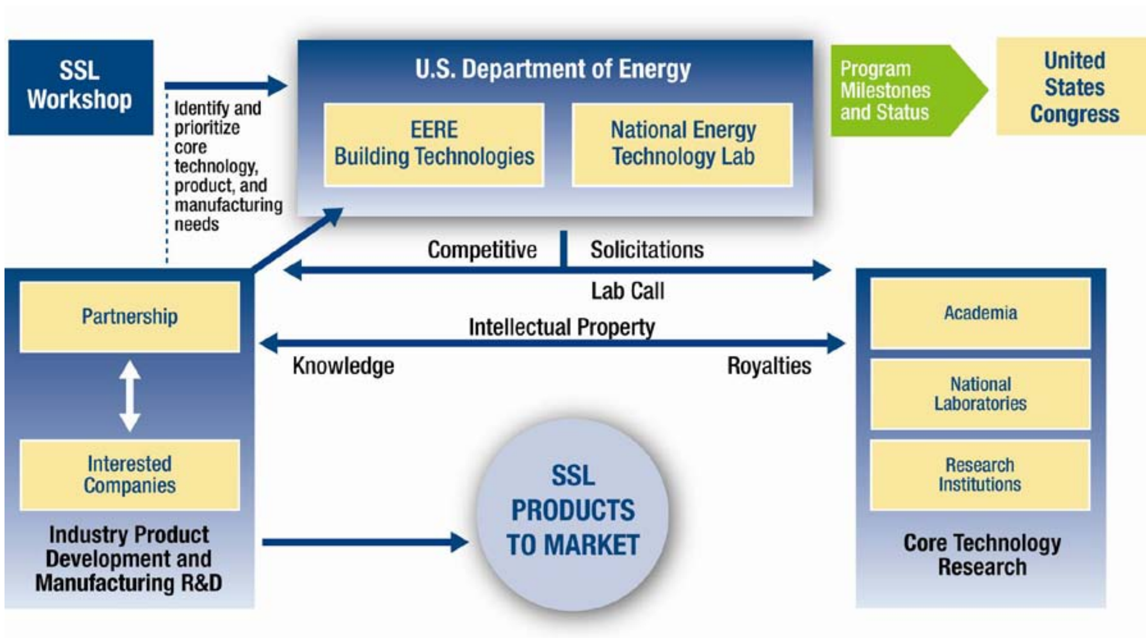

Figure 6.2: Structure of DOE SSL R&D Operational Plan

Figure 6.2 details the high-level timeline for the SSL R&D operational plan. Each year, DOE expects to issue at least three competitive solicitations: the Core Technology Solicitation, the Product Development Solicitation, and the Manufacturing R&D Solicitation. A number of annual meetings are held to provide regular DOE management and review checks and to keep all interested parties adequately informed. More specifically, these meetings:

- Provide a general review of progress on the individual projects (open meeting);
- Review/update the R&D plan for upcoming "statement of needs" in future solicitations (open meeting);

- At DOE's discretion, provide a peer review of Core Technology, Product Development, and Manufacturing R&D projects; and
- Provide individual project reviews by DOE.

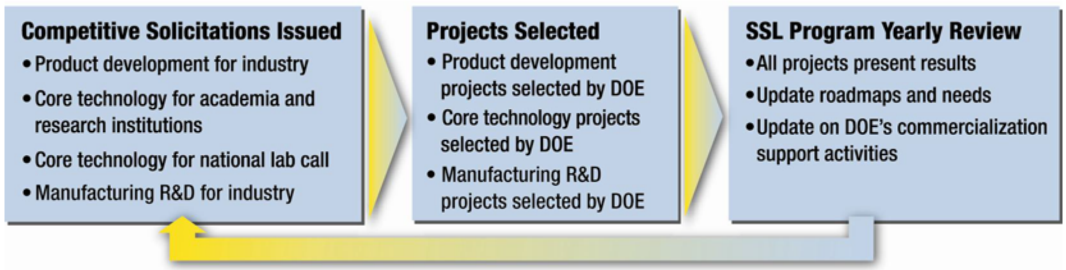

Figure 6.3: SSL Operational Plan Process

6.2 Portfolio Decision-Making Process

DOE establishes its SSL R&D priorities and projects through a consultative process with industry, expert technical reviewers and other interested parties and then adjusts them based on the existing portfolio of projects. The portfolio decision-making process is based upon: (1) the output of consultative workshops; (2) a competitive solicitation process based on the seven guiding principles of the SSL R&D Program; and (3) consultation with the SSL partnership. Each of these three components of the portfolio decision making process is discussed below.

6.2.1 Consultative Workshops

The SSL R&D program relies heavily on stakeholder consultation and participation in the R&D agenda planning process. DOE hosted several consultative workshops to solicit input from stakeholders representing industry, national laboratories, and academia in order to prioritize near-term R&D activities:[75]

- **Basic Energy Sciences Workshop:** This workshop was jointly held by the DOE's Basic Energy Sciences Program and the Building Technologies Program in Bethesda, Maryland in 2006. The workshop focused on basic research needs for SSL and provided the forum for a coordinated approach to R&D between the two programs that include Core Technology Research, Product Development, Commercialization Support, DOE ENERGY STAR® criteria for SSL, Standards Development, and the SSL Partnership with industry.

- **Manufacturing Workshops**: The manufacturing workshops, preceded by roundtable sessions convened in Washington, D.C., gathers SSL manufacturers in order to seek guidance on updates to the SSL Manufacturing Roadmap and a DOE Manufacturing R&D initiative. This guidance leads to the priority tasks which are then used to shape the competitive solicitations in the Manufacturing R&D Program. The last manufacturing workshop took place in San Jose, California in April 2010.

[75] A listing of past DOE consultative workshops can be found at: http://www1.eere.energy.gov/buildings/ssl/past_conferences.html

- **R&D Planning Workshops**: The R&D planning workshops, preceded by roundtable sessions in Washington, D.C., bring together lighting industry leaders, chip makers, fixture manufacturers, researchers, academia, lighting designers, architects, trade associations, energy efficiency organizations, and utilities in order to share insights and updates on technology advances and market developments. The workshops give attendees an opportunity to provide input and research areas in need of DOE funding which then guides updates to this R&D MYPP. The last R&D planning workshop took place in February 2011, in San Diego, California.

6.2.2 Competitive Solicitations

Since FY2009, three competitive solicitations have been released in accordance with the three operational pathways: Core Technology, Product Development, and Manufacturing Support. These solicitations are conducted by the National Energy Technology Laboratory (NETL) and are open to all industry participants.

Proposals received through the solicitation process are reviewed by expert reviewers and DOE staff. DOE expects product proposals to include comprehensive work plans to develop a specific SSL product or product family. Core Technology proposals should support the SSL R&D Program by providing problem solving research to overcome barriers identified by the SSL Partnership.

6.2.3 Consultation with the SSL Partnership

The NGLIA's mission involves public advocacy on issues related to SSL, promotion and support of SSL technology and DOE's SSL R&D Program, and facilitation of communications among members and other organizations with substantial interest in the NGLIA activities. In selecting the NGLIA to serve as its partner, DOE improved its access to the technical expertise of the organization's members. The Alliance participates in a variety of the joint activities with DOE, including:

- Providing input to shape DOE's SSL R&D Program priorities.
- Providing technical expertise for proposal reviews and individual project reviews for research projects in DOE's SSL Core Technology Program, as well as participating in project review meetings; and
- Providing recommendations from individual NGLIA members on the direction of research, development, and demonstration of SSL technologies for general illumination.

6.3 Internal DOE Portfolio Evaluation Plan

Government Performance and Results Act (GPRA)

The SSL R&D Portfolio evaluation plan must support the establishment of performance goals, measures, and expectations as required by GPRA. To develop this evaluative plan, the BT Program Manager performs a Situation Analysis (the context for planning), identifies and makes explicit all planning assumptions (constants), and identifies and assesses the impact of current and emerging market trends (variables).

PNNL estimates the fiscal year energy, environmental, and financial benefits (i.e., metrics) of the technologies and practices for DOE's Office of Building Technologies. This effort is referred to as GPRA Metrics because the Government Performance and Results Act of 1993 mandates such estimates of benefits, which are submitted to EE's Office of Planning, Budget, and Management as part of EE's budget request. The metrics effort was initiated by EE in 1994 to develop quantitative measures of program benefits and costs.

The BTS GPRA estimates are calculated using the National Energy Modeling System (NEMS). NEMS can link the cost and benefit characteristics of a technology and its market penetration. The NEMS commercial and residential demand modules generate forecasts of energy demand (energy consumption) for those sectors. The commercial demand module generates fuel consumption forecasts for electricity, natural gas, and distillate fuel oil. These forecasts are based on energy prices and macroeconomic variables from the NEMS system, combined with external data sources. The residential model uses energy prices and macroeconomic indicators to generate energy consumption by fuel type and census division in the residential sector. NEMS selects specific technologies to meet the energy services demands by choosing among a discrete set of technologies that are exogenously characterized by commercial availability, capital costs, operating and maintenance costs, efficiencies, and lifetime. NEMS is coded to allow several possible assumptions to be used about consumer behavior to model this selection process. For the GPRA effort, the menu of equipment was changed to include relevant BTS program equipment, technological innovations, and standards.[76]

Peer Review

A formal review of the twenty one FY2010 funded projects was conducted in the summer of 2010, the fifth in an annual series since 2005. These reviews are conducted by panels of highly qualified scientists, engineers, and independent technical consultants who evaluate each project based on technical approach, accomplishments, productivity, and relevance of the work to DOE's goals. The panels identify areas of concern and areas to be commended, and the results of the peer review process are shared with the project team and DOE.

6.4 External DOE Portfolio Evaluation Plan

National Academies of Science Review

EPACT, passed in August 2005, requires the SSL R&D Program enter into an agreement with the National Academy of Sciences to conduct periodic reviews of the Solid-State Lighting Initiative. In addition, section 321(h)(3) of EISA 2007 requires the SSL R&D Program to enter into an agreement with the National Academy of Sciences to conduct two additional peer reviews of the Solid-State Lighting Initiative to be completed by December 31, 2013, and July 31, 2015 (See Appendix B). The first review is beginning in FY2011. The report should include the following:

[76] Documentation for FY2003 BTS GPRA Metrics, Building Technology, State and Community Programs, Energy Efficiency and Renewable Energy, U.S. Department of Energy.

- The status of advanced SSL research, development, demonstration, and commercialization;
- The impact on the types of lighting available to consumers of an energy conservation standard requiring a minimum of 45 lm/W for general service lighting effective in 2020; and
- The time frame for the commercialization of lighting that could replace current incandescent and halogen incandescent lamp technology and any other new technologies developed to meet the minimum standards required under section 321(a)(3).

However, even before the passage of EPACT 2005 and EISA 2007, the National Research Council (NRC) was tasked by Congress with developing a methodology for the prospective assessment of DOE program impacts. Starting in December 2003, the NRC developed a conceptual framework and applied it to a review of three DOE programs as the first step in developing a recommendation for a methodology for future program reviews. The committee appointed expert panels to apply the methodology to these programs as case studies.

One of these programs was the LR&D program, and in particular the SSL R&D Program. Although the intent of the NRC study was not specifically to review these programs, some of the reported findings point to the benefits of investing in SSL R&D. The NRC published a report, *Prospective Evaluation of Applied Research and Development at DOE (PHASE ONE): A First Look Forward* [77] with the following findings.

- The committee found that, if successful, the program would yield a projected national economic benefit of $84 billion through 2050, discounted to 2005 dollars. This is for annual DOE funding of $25 million for 20 years ($500 million, undiscounted). Even allowing for program risk, the projected risk-adjusted benefit is $50 billion. This benefit is above projections for private and foreign R&D funding during these years, which itself is twice the assumed DOE funding.
- The panel noted that the large projected benefits were for a relatively conservative reference scenario and that the scenarios not analyzed would have shown even larger benefits. It noted that the projected benefits, even under baseline conditions, are high enough to justify the authorized $500 million DOE SSL R&D Program.
- The panel concluded that the achievement of DOE's technical goal depends on an increase in funding from $10 million per year at the time of the study to $50 million per year. Without DOE funding, the panel believed the technical goals will not be achieved.

The panel believed that DOE funding is an important catalyst to other R&D funding and is a catalyst to spur non-DOE funding. The panel estimated that huge environmental benefits would also flow from the program results, once implemented. Estimates of these

[77] To download a PDF version of this report, please visit http://www.nap.edu/books/0309096049/html.

benefits are given in the report, though they were not the focus of the study, and they are not included in the $50 billion economic benefits cited above.

Appendix A Legislative Directive: EPACT 2005

Subtitle A – Energy Efficiency

Sec. 911. Energy Efficiency.

(c) Allocations. – From amounts authorized under subsection (a), the following sums are authorized:

(1) For activities under section 912, $50,000,000 for each of fiscal years 2007 through 2009.

(d) Extended Authorization. – They are authorized to be appropriated to the Secretary to carry out section 912 $50,000,000 for each of fiscal years 2010 through 2013.

Sec. 912. Next Generation Lighting Initiative.

(a) Definitions. – In this section:

(1) Advance Solid-State Lighting. – The term “advanced solid-state lighting” means a semiconducting device package and delivery system that produces white light using externally applied voltage.

(2) Industry Alliance. – The term “Industry Alliance” means an entity selected by the Secretary under subsection (d).

(3) Initiative. – The term “Initiative” means the Next Generation Lighting Initiative carried out under this section.

(4) Research. – The term “research” includes research on the technologies, materials, and manufacturing processes required for white light emitting diodes.

(5) White Light Emitting Diode. – The term “white light emitting diode” means a semiconducting package, using either organic or inorganic materials, that produces white light using externally applied voltage.

(b) Initiative. – The Secretary shall carry out a Next Generation Lighting Initiative in accordance with this section to support research, development, demonstration, and commercial application activities related to advanced solid-state lighting technologies based on white light emitting diodes.

(c) Objectives. – The objectives of the Initiative shall be to develop advanced solid-state organic and inorganic lighting technologies based on white light emitting diodes that, compared to incandescent and fluorescent lighting technologies, are longer lasting, are more energy-efficient and cost competitive, and have less environmental impact.

(d) Industry Alliance. – Not later than 90 days after the date of enactment of this Act, the Secretary shall competitively select an Industry Alliance to represent participants who are private, for-profit firms that, as a group, are broadly representative of the United States SSL research, development, infrastructure, and manufacturing expertise as a whole.

(e) Research. –

(1) Grants. – The Secretary shall carry out the research activities of the Initiative through competitively awarded grants to –

(A) researchers, including Industry Alliance participants;

(B) National Laboratories; and

(C) institutions of higher education.

(2) Industry Alliance. – The Secretary shall annually solicit from the Industry Alliance –

(A) comments to identify solid-state lighting technology needs;

(B) an assessment of the progress of the research activities of the Initiative; and

(C) assistance in annually updating solid-state lighting technology roadmaps.

(3) Availability to Public. – The information and roadmaps under paragraph (2) shall be available to the public.

(f) Development, Demonstration, and Commercial Application. –

(1) In General. – The Secretary shall carry out a development, demonstration, and commercial application program for the Initiative through competitively selected awards.

(2) Preference. – In making the awards, the Secretary may give preference to participants in the Industry Alliance.

(g) Cost Sharing. – In carrying out this section the Secretary shall require cost sharing in accordance with section 988.

(h) Intellectual Property. – The Secretary may require (in accordance with section 202(a)(ii) of title 35, United States Code, section 152 of the Atomic Energy Act of 1954 (42 U.S.C. 2182), and section 9 of the Federal Nonnuclear Energy Research and Development Act of 1974 (42 U.S.C. 5908)) that for any new invention developed under subsection (e) –

(1) that the Industry Alliance participants who are active participants in research, development, and demonstration activities related to the advanced solid-state lighting technologies that are covered by this section shall be granted the first option to negotiate with the invention owner, at least in the field of solid-state lighting, nonexclusive licenses and royalties on terms that are reasonable under the circumstances;

(2) (A that, for 1 year after a United States patent is issued for the invention, the patent holder shall not negotiate any license or royalty with any entity that is not a participant in the Industry Alliance described in paragraph (1); and

(B) that, during the year described in clause (i), the patent holder shall negotiate nonexclusive licenses and royalties in good faith with any interested participants in the Industry Alliance described in paragraph (1); and

(3) such other terms as the Secretary determines are required to promote accelerated commercialization of inventions made under the Initiative.

(i) National Academy Review. – The Secretary shall enter into an arrangement with the National Academy of Sciences to conduct periodic reviews of the Initiative.

Appendix B Legislative Directive: EISA 2007

Subtitle B – Lighting Energy Efficiency

Sec. 321. Lighting Energy Efficiency.

(g) Research and Development Program. –

(1) In General. —The Secretary may carry out a lighting technology research and development program —

(A) to support the research, development, demonstration, and commercial application of lamps and related technologies sold, offered for sale, or otherwise made available in the United States; and

(B) to assist manufacturers of general service lamps in the manufacturing of general service lamps that, at a minimum, achieve the wattage requirements imposed as a result of the amendments made by subsection (a).

(2) Authorization of Appropriations. —There are authorized to be appropriated to carry out this subsection $10,000,000 for each of fiscal years 2008 through 2013.

(3) Termination of Authority. —The program under this subsection shall terminate on September 30, 2015.

(h) Reports to Congress. –

(3) National Academy Review. —

(A) IN GENERAL. — Not later than December 31, 2009, the Secretary shall enter into an arrangement with the National Academy of Sciences to provide a report by December 31, 2013, and an updated report by July 31, 2015. The report should include —

(i) the status of advanced SSL research, development, demonstration and commercialization;

(ii) the impact on the types of lighting available to consumers of an energy conservation standard requiring a minimum of 45 lumens per watt for general service lighting effective in 2020; and

(iii) the time frame for the commercialization of lighting that could replace current incandescent and halogen incandescent lamp technology and any other new technologies developed to meet the minimum standards required under subsection (a)(3) of this section.

(B) Reports. —The reports shall be transmitted to the Committee on Energy and Commerce of the House of Representatives and the Committee on Energy and Natural Resources of the Senate.

Appendix C Definition of Core Technology, Product Development, and Manufacturing R&D

DOE defines Core Technology, Product Development, and Manufacturing R&D as follows:

Core Technology – Core Technology is applied research encompassing scientific efforts that focus on comprehensive knowledge or understanding of the subject under study, with specific application to SSL. Within Core Technology research areas, scientific principles are demonstrated, technical pathways to SSL applications are identified, and price or performance advantages over previously available science/engineering are evaluated. Tasks in Core Technology fill technology gaps, provide enabling knowledge or data, and represent a significant advancement in the SSL knowledge base. Core Technology research focuses on gaining pre-competitive knowledge for future application to products by other organizations. Therefore, the findings are generally made available to the community at large to apply and benefit from as it works collectively towards attainment of DOE's SSL R&D Program goals.

Product Development – Product Development involves using basic and applied research (including Core Technology research) for the development of commercially viable SSL materials, devices, or luminaires. Product Development activities typically include evaluation of new products through market and fiscal studies, with a fully defined price, efficacy, and other performance parameters necessary for success of the proposed product. Product Development encompasses the technical activities of product concept modeling through to the development of test models and field ready prototypes.

Manufacturing R&D – Manufacturing R&D provides support for manufacturing projects that target improved product quality and consistency, and accelerated cost reduction. The idea is to take LEDs and OLEDs developed under product development and provide a means to manufacture these products. This could include development of material production, subsystems, tools, processes, and assembly methods specific to SSL manufacturing

Appendix D MYPP Task Structure

Priority tasks for 2011 shown in red.

LED Core 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 materials and 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

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**
- **B6.4 Novel Luminaire Systems**

B.7.0 Electronic Components
- B.7.1 Color maintenance
- B.7.2 Color tuning
- B.7.3 Smart controls
- B.7.4 Electronics component research

OLED Core Research Tasks

C.1.0 Materials and Device Architectures
- C.1.1 Novel device architectures
- **C.1.2 Novel OLED materials and structures**
- 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 Light extraction approaches**

OLED Product Development Tasks

D.1.0 Materials and Device Architectures
- D.1.1 Implementation of materials and device architectures
- D.1.5 Device failure

D.2.0 Substrate and Electrode
- D.2.1 Substrate materials
- D.2.2 Low-cost electrodes

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 Luminaire integration
- 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 outcoupling**
- D.6.4 Panel reliability
- D.6.5 Panel mechanical design

Non-Prioritized Tasks

LED Core 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.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.
A2.2	Novel emitter materials and architectures	**(1)** Devise novel emitter geometries and mechanisms that show a clear pathway to efficiency improvement; **(2)** Demonstrate a pathway to increased chip-level functionality offering luminaire or system efficiency improvements over existing approaches; **(3)** 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, system on a chip)
A.3.4	Thermal control research	Simulation of solutions to thermal management issues at the package or array level. Innovative thermal management solutions.
A.4.4	Manufacturing simulation	Develop manufacturing simulation approaches that will help to improve yield and quality of LED products.
A.5.1	Optical component materials	Develop optical component materials that last at least as long as the LED source (50k hours) under lighting conditions which 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.

LED Product Development Tasks		
	Task	**Description**
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.

LED Product Development Tasks (Cont)		
	Task	**Description**
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 multishadowing or color rings.
B.5.2	Color Maintenance	Ensure luminaire maintains the initial color point and color quality over the life of the luminaire. Product: Luminaire/ replacement lamp
B.5.3	Diffusion and beam shaping	Develop optical components that diffuse and/or shape the light output from the LED source(s) into a desirable beam pattern and develop optical components that mix the colored outputs from the LED sources evenly across the beam pattern.
B.6.1	Luminaire mechanical design	Integrate all aspects of LED-based 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.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	Smart 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.
B.7.4	Electronics component research	Develop compact, long-life LED driver electronics and power converters that efficiently convert line power to acceptable input power of the LED source(s) while maintaining an acceptable power factor; encourage standardization in the long term.

OLED Core Technology 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 outcoupling strategies to optimize light extraction. Could include studying material interfaces.
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.
C2.2	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.
C3.1	Fabrication Technology Research	Develop new practical techniques for materials deposition, device fabrication, or encapsulation. Should show potential for scalability and low cost.
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 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.
D2.2	Low-Cost Electrodes	Demonstrate a high-efficiency OLED panel employing a transparent electrode technology that is low-cost, low-voltage, and stable, with the potential for large-scale manufacturing. The electrode surface should be smooth enough to prevent shorting. Design could include a conducting grid or segmented structures.
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.

OLED Product Development Tasks		
	Task	**Description**
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.
D.4.1	Light utilization	Maximize the ratio of useful light exiting the luminaire to total light from the OLED sources. This includes all optical losses in the luminaire; including optical losses from beam distribution and color mixing optics.
D.4.2	Luminaire integration	Integrate one or more OLED panels into a luminaire, with thermal, mechanical, optical, and electrical design to achieve a cost-effective, long-life, energy-saving, and marketable luminaire suitable for general lighting applications. All components should be as robust as the OLED. This task is to include maximizing light output, thermal management to limit OLED source temperature, and electrical interconnections with driver and among OLED panels.
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.
D6.2	Panel Packaging	Scale up practical, low-cost packaging designs that result in improved resistance to the environment (particularly water and oxygen impermeability) and thermal management. Encapsulation considerations should involve compatible materials, appropriate processes, etc. Edge effects should also be considered. Demonstrate a high-efficiency OLED panel that employs such a packaging design and exhibits improved lifetime.
D6.4	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-based luminaire design: thermal, mechanical, optical, and electrical. The design must be cost-effective, energy-efficient and reliable.

Appendix E List of Patents Awarded Through DOE-Funded Projects

As of January 2011, a total of thirty four SSL patents have been granted as a result of DOE-funded research projects. This demonstrates the value of DOE SSL projects to private companies and notable progress toward commercialization. Since DOE began funding SSL research projects in 2000, a total of 113 patents applications have been applied for as follows: large businesses - 43, small businesses - 34, universities - 32, and national laboratories - 4.

Primary Research Organization	Title of Patent Application (Bolded titles indicates granted patents)
Agiltron, Inc.	Two patent applications filed.
Boston University	**Optical Devices Featuring Textured Semiconductor Layers** Formation of Textured III-Nitride Templates for the Fabrication of Efficient Optical Devices Formation of Textured III-Nitride Templates for the Fabrication of Efficient Optical Devices Nitride LEDs Based on Flat and Wrinkled Quantum Wells
Cree, Inc.	**Light Emitting Diode with Porous SiC Substrate and Method for Fabricating** **Light Emitting Diode with High Aspect Ratio Sub-Micron Roughness for Light Extraction and Methods of Forming** Light emitting diode with high aspect ratio submicron roughness for light extraction and methods of forming Light emitting diode package element with internal meniscus for bubble free lens placement One other patent application filed.
Dow Corning	Four patent applications filed
Eastman Kodak	**Ex-Situ Doped Semiconductor Transport Layer** **Doped Nanoparticle-Based Semiconductor Junction** **Device Containing Non-Blinking Quantum Dots** Two other patent applications filed.
Fairfield Crystal Technology	Method and Apparatus for Aluminum Nitride Monocrystal Boule Growth
GE Global Research	**Light-Emitting Device with Organic Electroluminescent Material and Photoluminescent Materials** **Luminaire for Light Extraction from a Flat Light Source** **Mechanically Flexible Organic Electroluminescent Device with Directional Light Emission** **Organic Electroluminescent Devices and Method for Improving Energy Efficiency and Optical Stability Thereof** **Series Connected OLED Structure and Fabrication Method** **Organic Electroluminescent Devices having Improved Light Extraction** **Electrodes Mitigating Effects of Defects in Organic Electronic Devices** **OLED Area Illumination Source** Hybrid Electroluminescent Devices Eleven other patent applications filed.
Georgia Tech Research Corporation	One patent application filed.

Primary Research Organization	Title of Patent Application (Bolded titles indicates granted patents)
International Technology Exchange	One patent application filed.
Light Prescriptions Innovators	**Optical Manifold for Light-Emitting Diodes** **Optical Manifold for Light-Emitting Diodes** **Optical Manifold** Four other patent applications filed.
Maxdem Incorporated	Polymer Matrix Electroluminescent Materials and Devices
Nanosys	Nanocrystal Doped Matrices
OSRAM Opto Semiconductors, Inc.	**Integrated Fuses for OLED Lighting Device** **Novel Method to Generate High Efficient Devices, which Emit High** **Polymer and Small Molecule Based Hybrid Light Source** Novel Method to Generate High Efficient Devices, which Emit High Quality Light for Illumination OLED with Phosphors Polymer Small Molecule Based Hybrid Light Source Two other patent applications filed
Pacific Northwest National Laboratory	Organic Materials with Phosphine Sulphide Moieties having Tunable Electric and Electroluminescent Properties Organic Materials with Tunable Electric and Electroluminescent Properties
Philips Electronics North America	High Color-Rendering-Index LED Lighting Source using LEDs from Multiple Wavelength Bins Three other patent applications filed.
Philips Lumileds Lighting	Two patent applications filed
PhosphorTech Corporation	**Light Emitting Device having Selenium-Based Fluorescent Phosphor** **Light Emitting Device having Silicate Fluorescent Phosphor** **Light Emitting Device having Sulfoselenide Fluorescent Phosphor** **Light Emitting Device having Thio-Selenide Fluorescent Phosphor**
Purdue University	Metalized Silicon Substrate for Indium Gallium Nitride Light-Emitting Diode One other patent application filed
RTI	Six patent applications filed
Sandia National Laboratory	**Cantilever Epitaxial Process** **Nanowire-Templated Lateral Epitaxial Growth of Non-Polar Group III Nitrides**
UDC	**Binuclear Compounds** **Organic Light Emitting Device Structure for Obtaining Chromaticity Stability** **Organic Light Emitting Device Structure for Obtaining Chromaticity Stability** Stacked OLEDs with a Reflective Conductive Layer One other patent application filed.
University of California, San Diego	Rare-earth activated nitrides for SSL applications Two additional patent applications filed.
University of California, Santa Barbara	**Plasmon Assisted Enhancement of Organic Optoelectronic Devices** Silicone Resin Encapsulants for Light Emitting Diodes Enhancing Performance Characteristics of Organic Semiconducting Films by Improved Solution Processing Six other patent applications filed.
University of North Texas	Three patent application filed.

Primary Research Organization	Title of Patent Application (Bolded titles indicates granted patents)
University of Southern California	**Fluorescent Filtered Electrophosphorescence** **Fluorescent Filtered Electrophosphorescence** **OLEDs utilizing macrocyclic ligand systems** Materials and architectures for efficient harvesting of singlet and triplet excitons for white light emitting OLEDs Organic vapor jet deposition using an exhaust Phenyl and fluorenyl substituted phenyl-pyrazole complexes of Ir Low Index Grids (LIG) To Increase Outcoupled Light From Top or Transparent OLED Three additional patent applications filed.

Appendix F Approval of Exceptional Circumstances Determination for Inventions Arising Under the SSL Program

[APPENDIX STARTS ON NEXT PAGE]

MEMORANDUM FOR: **DAVID K. GARMAN**
ASSISTANT SECRETARY FOR ENERGY EFFICIENCY AND RENEWABLE ENERGY

DAVID N. HILL
DEPUTY GENERAL COUNSEL FOR ENERGY POLICY

FROM: **MICHAEL J. MCCABE**
BUILDING TECHNOLOGIES PROGRAM MANAGER

PAUL A. GOTTLIEB
ASSISTANT GENERAL COUNSEL FOR TECHNOLOGY TRANSFER AND INTELLECTUAL PROPERTY

SUBJECT: **Approval of Exceptional Circumstances Determination for Inventions Arising Under the Solid State Lighting (SSL) Program**

This Memorandum requests that you approve the attached Exceptional Circumstances (E-C) Determination for Inventions Arising Under the SSL Program. The E-C Determination, drafted by the National Energy Technology Laboratory (NETL) patent counsel in consultation with Headquarters patent counsel, finds that circumstances surrounding the SSL Program are exceptional and justify modified intellectual property arrangements as allowed by the Bayh-Dole Act (35 U.S.C. 202(a)(ii)). As the Manager of the Building Technologies Program, I ask that you approve the attached E-C Determination.

Background

The Department of Energy (DOE) is implementing the SSL Program through the Building Technologies Program. In partnership with NETL, the Building Technologies Program will, through the SSL Program, 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. It is envisioned that SSL products of this quality will have substantial market penetration and with their improved performance would save significant energy.

The SSL Program has a multi-tier structure. One tier consists of a competitively selected SSL Partnership whose membership includes organizations that have or will have the capacity to manufacture SSL systems, i.e. the entire package from wall plug to illumination. This group includes a significant portion of the United States manufacturing base of SSL products for general lighting applications. Another tier is the Core Technology Program, which will enter into funding agreements with DOE to develop solutions to the more difficult shared technical barriers identified by the SSL Partnership.

A Memorandum of Agreement (MOA) was entered into between DOE and the SSL Partnership, under which no federal funding will be provided to the Partnership. The Partnership will provide a manufacturing and commercialization focus for the SSL Program and accelerate the commercialization of SSL technologies through DOE access to the technical expertise of the organization's members, communication of SSL Program accomplishments within the SSL community, and cooperative efforts of the Partnership to develop and promote demonstrations of SSL technologies. Some members of the Partnership may also be selected for the award of cost shared cooperative agreements under the SSL product development solicitations, the third tier of the SSL Program structure.

In order for the link between the SSL Partnership and the Core Technology Program to succeed, the members of the SSL Partnership will require a guaranteed right to license the technologies developed by Core Technology Program participants. However, most of the Core Technology Program participants are expected to be domestic small businesses or domestic nonprofit organizations, such as universities, including DOE laboratories and those laboratories subject to a class waiver. These entities are entitled under the Bayh-Dole Act, or their laboratory operating contracts, to retain title to any inventions they conceive or first actually reduce to practice under their government-funded awards. Fortunately, the Bayh-Dole Act also allows an agency to make a determination of exceptional circumstances when it finds that encumbering the right to retain title to any subject invention will better promote the policy and objectives of the Bayh-Dole Act.

Specifics of SSL Program Exceptional Circumstances Determination

The proposed intellectual property arrangement will allow members of the Core Technology Program to retain title to inventions made under their SSL Program awards, but will require them to offer to each member of the SSL Partnership the first option to enter into a non-exclusive license upon terms that are reasonable under the circumstances, including royalties, for these inventions. Field of use of the license could be limited to solid state lighting applications, although greater rights could be offered at the discretion of the invention owner. In addition, any entity having the right to use or sell any subject invention in the United States and/or any other country — including the Core Technology Program participant — must agree that any products embodying the subject invention or produced through the use of the subject invention will be substantially manufactured in the United States.

Participants in the Core Technology Program must hold open license offers to SSL Partnership members for at least 1 year after the U.S. patent has issued on a new invention made under the Core Technology Program. Up to and during this one year period, the invention owner can enter into licensing negotiations for solid state lighting applications only with members of the Partnership. The invention owner must agree to negotiate in good faith with any and all members of the Partnership that indicate a desire to obtain at least a non-exclusive license. Exclusive licensing may be considered if only one Partnership member expresses an interest in licensing the invention. If no agreement is reached after nine months of negotiations, the individual Partnership member can take action in a court of competent jurisdiction to force licensing on reasonable terms and conditions.

In developing the E-C Determination, the SSL Program strove to minimize the licensing obligations that the Core Technology Program participants would have to agree to. They would retain title to their inventions and would be free to enter into additional licenses in other fields of use (besides solid state lighting) at any time. Additionally, one year after the U.S. patent issues, they would be free to enter into licenses in any field of use with any interested party. The licensing of background patents owned by the invention owner is not required.

Separately, under the SSL Program, a number of product developers will receive cost shared cooperative agreements as a result of competitive Product Development solicitations. This E-C Determination also imposes a requirement that any entity having the right to use or sell any subject invention under one of these cooperative agreements in the United States and/or any other country — including the Product Developer — must agree that any products embodying the subject invention or produced through the use of the subject invention will be substantially manufactured in the United States.

The term of the E-C Determination will be 10 years from the date it is approved by the General Counsel or her designee. However, the Government reserves the unilateral right to cancel or revoke this Determination in the event that the SSL Partnership organization dissolves or becomes bankrupt or insolvent, or in the event that the MOA between DOE and the SSL Partnership is terminated by either party for any reason. In addition, if any of these events occurs and DOE subsequently enters into a similar agreement with another partnership, DOE reserves the unilateral right to continue the E-C Determination, with the benefits accruing to the successor partnership.

Justification for Approving the SSL Program Exceptional Circumstances Determination

Exceptional circumstances determinations are authorized by the Bayh-Dole Act when the agency determines that restricting of the right to retain title to an invention resulting from federally sponsored research and development will better promote the goals of the Act, e.g., to use the patent system to:

- Promote collaboration between commercial concerns, and nonprofit organizations and small businesses, universities, and non-profit laboratories;

- Ensure that inventions made by such organizations are used to promote free competition and enterprise; and
- Promote the commercialization and public availability of inventions made in the United States by United States industry and labor.

As discussed in the E-C Determination, the Building Technologies Program believes the proposed modification to the standard intellectual property allocation meets these goals.

Potential Concerns

- Some members of the SSL Partnership may prefer to submit a proposal to the Product Development solicitation and thus keep most development work in-house. However, the Building Technologies Program feels this is not necessarily the best technical approach or best use of public funds. Individual companies would typically not possess a concentration of the best talent; redundant equipment and facilities would have to be purchased; and redundant research and development efforts would have to be performed. This would negate the SSL Program goal of leveraging the most difficult problems to accelerate commercialization of this nationally important technology.

- Some small businesses may object to this E-C Determination because they want to reserve the right to practice their inventions themselves, rather than to license them to the SSL Partnership members. DOE has a large Small Business Innovative Research (SBIR) program to which this Determination does not apply. Small businesses have the option to apply for an award through the DOE SBIR program if they want to pursue a more entrepreneurial path towards commercialization.

- Some affected entities, especially universities, may object in principle to any restrictions of their intellectual property rights, no matter how compelling the logic is. Entities who believe that the Determination is contrary to the intent of Bayh-Dole may: (a) complain to Departmental officials and/or members of Congress; (b) pursue an administrative appeal to DOE; or (c) file a petition for review in the United States Court of Federal Claims. In addition, the Secretary of Commerce has the statutory authority to object to this Determination, but no right to disapprove, if he believes that the Determination is contrary to the policies of the Act. In that event, the Secretary of Commerce shall so advise the Secretary of Energy and the Administration of the Office of Procurement Policy and recommend corrective action. The Building Technologies Program feels that DOE can adequately justify its action in the face of such a challenge.

A similar Exceptional Circumstances Determination was approved in November 2000 under Fossil Energy's Solid State Energy Conversion Alliance (SECA) program. Neither the Secretary of Commerce nor the industry raised concerns regarding that E-C Determination.

Conclusion

The Building Technologies Program believes that approval of the Exceptional Circumstances Determination will benefit DOE program objectives, the SSL Partnership, and the Core Technology Program participants.

Approved ____________________ Date. 6-6.05

ASSISTANT SECRETARY FOR ENERGY EFFICIENCY AND RENEWABLE ENERGY

Approved: ____________________ Date: 3-18-05

DEPUTY GENERAL COUNSEL FOR ENERGY POLICY

Attachment

cc: J. Brodrick
B. Marchick, GC-62
C. E. Christy, NETL
D. F. Gyorke, NETL
R. R. Jarr, NETL
L. A. Jarr, NETL

Appendix G Memorandum of Understanding between the U.S. Department of Energy and the Next Generation Lighting Industry Alliance

[APPENDIX STARTS ON NEXT PAGE]

MEMORANDUM OF UNDERSTANDING
BETWEEN
THE UNITED STATES DEPARTMENT OF ENERGY (DOE)
AND
THE NEXT GENERATION LIGHTING INDUSTRY ALLIANCE (NGLIA)

ARTICLE I – PURPOSE

This Memorandum of Understanding (MOU) is entered into by and between the Next Generation Lighting Industry Alliance (NGLIA) and the Building Technologies Program in the Office of Energy Efficiency and Renewable Energy within the U.S. Department of Energy (BT) ("the Parties") for the purpose of establishing a mutual framework governing the respective responsibilities of the Parties. The Parties intend to conduct activities in support of research, development, demonstration and commercial application of advanced solid-state lighting (SSL) technologies for general lighting applications.

ARTICLE II - AUTHORITY

BT enters into this MOU under the authority of, among others, the Department of Energy Organization Act, sections 301 (42 U.S.C. §§ 7151; the Energy Reorganization Act of 1974, section 103 (42 U.S.C. § 5813) and the Energy Policy Act of 2005, section 912 Next Generation Lighting Initiative (42 U.S.C. § 16192).

ARTICLE III - OBJECTIVE

The objective of this MOU is to provide a framework for conducting various activities in support of core technology research, development, demonstration and commercial application targeted to the application of SSL technologies in energy efficient general lighting applications. In particular, this collaboration is intended to support and enhance the Solid State Lighting Program of the Building Technologies/Lighting R&D Program within DOE's Office of Energy Efficiency and Renewable Energy. The Parties believe that this effort will provide DOE with a manufacturing and commercialization focus in the development of research needs and goals for the DOE SSL Program. The Parties intend for the quality of the Solid State Lighting Program to be enhanced through the NGLIA's willingness, at DOE's discretion, to provide technical expertise in identifying SSL technology needs; an assessment of the progress of the research activities of the Next Generation Lighting Initiative; and assistance in updating SSL technology roadmaps. The Parties further believe that the effort will accelerate the implementation of SSL technologies for the public benefit through communicating of SSL Program accomplishments within the SSL community, and through encouraging the development and dissemination of metrics, codes and standards. This MOU is intended to stimulate the implementation of SSL technologies through the Parties' efforts to promote and communicate success stories of SSL technologies for general lighting applications.

ARTICLE IV – SCOPE OF COLLABORATIVE ACTIVITIES

The Parties intend for the collaboration under this MOU to include, but not be limited to, SSL activities in support of:

- Core Technology Research;
- Product Development;
- Manufacturing
- Demonstration; and
- Market Conditioning and Outreach

The SSL technologies that are the subject of this MOU include light emitting diodes (LEDs), organic light emitting diodes (OLEDs), and other semiconductor white-light producing devices.

ARTICLE V – FORMS OF COLLABORATIVE ACTIVITIES

Collaboration under this MOU may include, but is not limited to, the following forms of joint activities:

- Participating in and providing input to DOE workshops and roundtables for SSL technologies. These workshops will be open to the public;
- Encouraging the development of metrics, codes, standards for measurement and utilization of SSL products for general illumination, and providing input for voluntary DOE deployment programs such as Lighting Facts™; and
- Planning and promoting outreach activities by NGLIA members for SSL technologies used for general illumination applications.

The NGLIA may designate a third party (e.g., contractor or organization member) to act on its behalf to conduct these collaborative activities. Due to conflict of interest considerations, some members of the NGLIA and/or their employees may be unable to participate in certain activities of the MOU.

ARTICLE VI – RESPONSIBILITES OF THE PARTIES

A. Responsibilities of BT:

- Identify a Federal employee as the point of contact (POC) to function as the interface between the SSL Program and the NGLIA to ensure that the activities under this MOU are coordinated with the schedule and progress of the SSL Program, and are free of conflicts of interest.
- Maintain a log of Core Technology Program projects and their selection dates.

- Arrange to provide the NGLIA with SSL Program- and project-related releasable information in accordance with the purpose, terms, and conditions of this MOU and as available from DOE's SSL projects. This activity may be accomplished through activities such as the technical poster session at the annual R&D workshop and the annual Project Portfolio document.
- As set forth in the document titled "Statement of Analysis of Determination of Exceptional Circumstances for Work Proposed Under the Solid State Lighting Program," provide the NGLIA with information regarding patents and other intellectual property available for licensing from SSL Core Technology Program participants, as that information becomes available to NETL.
- Notify the NGLIA when DOE announces funding opportunities available to its membership and the public for research, development, and demonstration of SSL technologies.
- Participate with the NGLIA in planning of SSL outreach activities by their members, and create criteria for voluntary market conditioning programs, such as Lighting Facts or other certification program designated by BT.
- Government employees are bound by the provisions of the Trade Secrets Act (18 USC 1905) to not disclose confidential or proprietary information obtained during the course of their Government employment

B. Responsibilities of the NGLIA:

- Identify an individual as the POC to function as the interface between the NGLIA, its membership, and DOE to ensure that the activities under this MOU are coordinated with the SSL Program and are free of conflicts of interest.
- Maintain a log of membership, including the effective dates of each company's membership.
- Provide a membership including a significant portion of the United States manufacturing base of SSL products for general lighting applications that, together with the staff of the NGLIA, will:
  - Provide administrative expertise and staffing to organize and support technical meetings and workshops related to SSL technologies.
  - At DOE's discretion, participate in SSL project review meetings, and provide recommendations from individual NGLIA members on the direction of research, development, and demonstration of SSL technologies for general illumination.
  - Encourage efforts to develop metrics and standards for the application of SSL products for general lighting.
  - Recommend, develop, and support outreach activities for SSL technologies, emphasizing those technologies developed in the DOE SSL Program.

- NGLIA representatives and members with access to confidential or proprietary information under this MOU must sign and submit to DOE non-disclosure agreements.

Develop processes and/or procedures to safeguard any business, programmatically or technically sensitive information provided under the terms of this MOU

C. The Parties express their intentions to implement the following:

- Within statutory limits and DOE regulations, work to promote SSL technologies to the common benefit of the DOE program and NGLIA membership.
- At times and locations acceptable to the NGLIA and DOE POCs, meet to discuss and plan the activities under this MOU. At the discretion of the POCs, these meetings may also include representatives of the NGLIA members, SSL Core Technology Program participants, and other DOE contractors. This responsibility may be fulfilled through participation in annual workshops and roundtables, and the recurring bimonthly NGLIA meetings.

ARTICLE VII – PUBLICATIONS

The Parties intend to seek pre-publication review and comment from each other prior to any planned publication under this MOU by the Parties to this MOU. The Parties intend that any such publications shall not include Confidential Information, including as designated confidential by a third party. Inaction in providing a written response within thirty (30) calendar days from the date the document is provided for review shall satisfy this pre-publication provision. The author of any such publication shall not be obligated to incorporate or address any comments received from the other Party. In case of failure to agree on the manner of publication or interpretation of results, either Party publishing the results will give due credit to the cooperation of the other Party, but will assume full responsibility for any statements in which a difference of opinion exists.

Any public information release concerning the activities related to this agreement shall describe the contribution of both Parties to the activity. This does not apply to reports or records released pursuant to the Freedom of Information Act.

Publication may be joint or separate, always giving due credit to the cooperation and recognizing, within proper limits, the rights of individuals, including employees of NGLIA members and employees of SSL Program participants, who performed the work.

ARTICLE VIII - INTELLECTUAL PROPERTY

DOE will use its best efforts to require each awardee under its SSL Core Technology Program to enter into negotiations with NGLIA members intended to lead to the non-exclusive licensing of any patented subject invention made under its DOE agreement. To accomplish this, DOE will maintain its determination of exceptional circumstances under the Bayh-Dole Act for domestic nonprofit and small business participants in the DOE Core Technology Program. In addition, in the Core Technology Program, DOE will continue to include comparable provisions in any patent waivers granted to entities such as large businesses that do not qualify for a statutory patent waiver under the Bayh-Dole Act. DOE will use its best efforts to ensure that information is provided to the NGLIA concerning inventions and other intellectual property developed by SSL Core Technology Program participants.

The Parties understand that:

- Individual companies will receive rights under the determination of exceptional circumstances and/or any patent waivers granted commencing on the date they become a member of the NGLIA. The NGLIA shall maintain a log of membership, including the effective date of each company's membership.
- An individual company will be entitled to the licensing benefits described above for subject inventions made under SSL Core Technology Program projects that have been selected for award after the time the company's membership in the NGLIA becomes effective. A project is selected for award when the DOE source selection official has signed the selection statement for the core technology solicitation under which it is proposed. The DOE will maintain a log of Core Technology Program projects and their selection dates.
- If an individual company elects to discontinue its membership in the Partnership, it will receive licensing benefits only for patent applications filed at the time when the company's membership ends.

All representatives of the NGLIA and its members must agree to non-disclosure of any and all confidential or proprietary information prior to participation in partnership activities such as technical evaluation or any activity that may disclose confidential or proprietary information from DOE SSL Program participants. Government employees are bound by the provisions of the Trade Secrets Act (18 USC 1905) to not disclose confidential or proprietary information obtained during the course of their Government employment.

ARTICLE IX – GENERAL PROVISIONS

This MOU is strictly for internal management purposes for each of the parties. It is not legally enforceable and shall not be construed to create any legal obligation on the part of either party. This MOU shall not be construed to provide a private right or cause of action for or by any person or entity.

NGLIA understands that the activities it undertakes herein are not intended to provide services to the Federal Government and that it will not seek compensation from DOE in connection with its participation hereunder.

NGLIA will not claim or imply that DOE endorses the sale and purchase of its products and services or those of its member companies pursuant to this MOU.

This MOU is neither a fiscal nor a funds obligation document. Nothing in this MOU authorizes or is intended to obligate the parties to expend, exchange, or reimburse funds, services, or supplies, or transfer or receive anything of value.

All agreements herein are subject to, and will be carried out in compliance with, all applicable laws, regulations and other legal requirements.

ARTICLE XI – AMENDMENT, MODIFICATION, AND TERMINATION

This MOU shall remain in effect for the period of 5 years from its effective date, and, if agreed upon by the Parties, may be extended for three additional 2-year periods for a total of eleven years. This MOU may be modified or amended only by written agreement of the Parties. Either Party may terminate this MOU by providing written notice to the other Party. The termination shall be effective upon the sixtieth calendar day following notice, unless an earlier or later date is agreed to by the Parties.

ARTICLE XII – EFFECTIVE DATE

This MOU will become effective upon the latter date of signature of the Parties.

Executed in duplicate on the dates indicated below:

By: Roland J. Risser Date: 4/5/10

Roland J. Risser
Building Technologies Program Manager
U.S. Department of Energy
Office of Energy Efficiency and Renewable Energy

By: Keith R. Cook Date: 4/6/10

Keith Cook
Chair
Next Generation Lighting Industry Alliance