Solid-State Lighting Research and Development:

Multi-Year Program Plan

April 2012

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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April 2012

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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 2011 in Washington, D.C:

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Preface

This is the ninth annual edition of the Multi-Year Program Plan for the U.S. Department of Energy program on Solid-State Lighting. This report focuses on Core Technology Research and Product Development, which is an important part of DOE's comprehensive approach to guide SSL technology from laboratory to marketplace. Other segments include Manufacturing R&D, and Market Development Support, separately reported in the Manufacturing Roadmap and the SSL Market Development Support Plan. In addition, the SSL program maintains an ongoing relationship with the Basic Energy Sciences and Small Business Innovation Research (SBIR) programs which complement the work described in this report.

This year's update highlights continuing progress on more energy efficient lighting, with especially promising advances in luminaire products that are reliable, useful, and cost effective. Most of the rapidly growing market is for LED products, but OLEDs have made significant advances as well, with a number of new (albeit expensive) products now available on the market.

Beyond the coordination of this and related government programs, the SSL effort is intended to be a cooperative partnership with the lighting community. This program is yours. The results highlighted in this report and the recommendations for future use come from academia, industry, and national labs in partnership with the DOE. A formal Partnership between DOE and the Next Generation Lighting Industry Alliance of for-profit lighting manufacturers provides structure. Administered by the National Electrical Manufacturers Association, the Alliance, together with SSL workshops accessible by all, provides input to shape R&D priorities. The Partnership also helps to communicate SSL program accomplishments; encourage development of metrics, codes, and standards; demonstrate SSL in general lighting applications; and support DOE voluntary market oriented programs.

DOE's SSL R&D Program is guided by several principles that ensure close cooperation with the SSL community and efficient allocation of supporting funding:

- Emphasis on competition for research funds
- Cost (and risk) sharing exceeding Energy Policy Act of 1992 cost-share requirements
- Involvement of SSL industry partners in planning and funding
- Targeted research for R&D needs
- Innovative intellectual property provisions
- Open and easily accessible information and process
- Measurable milestones for energy efficiency, long-life, and cost competitive products

Advances notwithstanding, the report also highlights remaining opportunities for further improvements. As in the past, DOE expects to issue competitive solicitations—the Core Technology Solicitation and the Product Development Solicitation—based on this plan, and closely focused on your consensus as to the most important priorities in the near term.

James R. Brodrick

James R. Brodrick

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List of Acronyms

ANSI	American National Standards Institute
ARPA-E	Advanced Research Projects Agency-Energy
ARRA	American Recovery and Reinvestment Act
BES	Basic Energy Sciences
BTP	Building Technologies Program
BTU	British Thermal Units
CCT	Correlated Color Temperature
cd/m^2	luminance - candelas per square meter
CFL	Compact Fluorescent Lamp
cm-LED	color-mixed LED
CRI	Color Rendering Index
DOE	Department of Energy
EERE	Energy Efficiency and Renewable Energy
EIA	Energy Information Administration
EISA 2007	Energy Independence and Security Act of 2007
EPACT 2005	Energy Policy Act of 2005
EQE	External Quantum Efficiency
EU	European Union
FY	Fiscal Year
GaN	Gallium Nitride
HB	High-Brightness
HID	High Intensity Discharge
IALD	International Association of Lighting Designers
IES	Illuminating Engineering Society
IQE	Internal Quantum Efficiency
IR	Infrared
ITO	Indium tin oxide
klm	kilolumen
L_{50}	Time to 50% initial luminance
L_{70}	Time to 70% initial luminance
LED	Light Emitting Diode
LER	Luminous Efficacy of Radiation
lm	lumens
lm/m^2	illuminance - lumens per square meter
lm/W	efficacy - lumens per watt
LMC	Lighting Market Characterization
MJ	Megajoule
MOCVD	metal organic chemical vapor deposition
MYPP	Multi-Year Program Plan
NETL	National Energy Technology Laboratory
NGLIA	Next Generation Lighting Industry Alliance
NIST	National Institute of Standards and Technology
OLED	Organic Light Emitting Diode
PAR	Parabolic Aluminized Reflector

pc-LED	phosphor-converted LED
Quad	quadrillion BTUs
R&D	Research and Development
SBIR	Small Business Innovation Research
SSL	Solid-State Lighting
TWh	Terawatt-hour
UV	Ultra Violet
W	Watt
QY	Quantum Yield
ZO	Zinc Oxide

The April 2012 edition of the Multi-Year Program Plan updates the May 2011 edition.

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 7.5 quads of primary energy in 2010.[3] A nationwide move toward solid-state lighting (SSL) for general illumination could save a cumulative total of 29 quads of primary energy between 2010 and 2030.[4] 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)[5] and the Energy Independence and Security Act of 2007 (EISA 2007)[6] issued a directive to the Secretary of Energy to carry out a "Next Generation Lighting Initiative" (conducted through the Next Generation Lighting Industry Alliance, or NGLIA) 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 NGLIA 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.

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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] 2010 U.S. Lighting Market Characterization. Prepared by Navigant Consulting, Inc. for the Department of Energy. Washington D.C. January 2012.
[4] Energy Savings Potential of Solid-State Lighting in General Illuminations Applications. Prepared by Navigant Consulting, Inc. for the Department of Energy. Washington D.C. January 2012.
[5] The legislation text for EPACT 2005 is available at - http://doi.net/iepa/EnergyPolicyActof2005.pdf
[6] 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

- 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.

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[7]:

> *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 (BES) 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

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

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.

The Building Technologies Program (BTP) within the Office of EERE, under which this Multi-Year Program Plan (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 and mission of EERE, BTP, and the SSL Program.

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 technologies, techniques, and tools for making residential and commercial buildings more energy efficient, productive, and affordable. This involves research, development, demonstration, and deployment activities in partnership with industry, government agencies, universities, and national laboratories. The portfolio of activities includes improving the energy efficiency of building components and equipment and their effective integration using whole-building system design techniques. It also involves the development of building energy codes and equipment standards as well as the integration of*

renewable energy systems into building design and operation.

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 Market Development Plan. 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 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 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,[8] 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 Market Development Plan.[9] 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 market development activities for high performance SSL products for the U.S. general illumination market. The DOE market development 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 Market

[8] DOE's SSL R&D Manufacturing Roadmap can be found at: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_manuf-roadmap_july2011.pdf
[9] DOE's Five-Year SSL Market Development Plan can be found at http://www1.eere.energy.gov/buildings/ssl/pdfs/ssl_5year-plan_09-13.pdf

Development Plan is updated regularly, drawing on input gathered from workshops and roundtable attendees, DOE partners, and market reconnaissance on products and issues.

1.2 Significant SSL Program Accomplishments to Date

1.2.1 Recent SSL Program Highlights

DOE Reopens L Prize® PAR 38 Competition

DOE announced in March that it has reopened the PAR 38 category of the L Prize® competition. Established by Congress in EISA 2007 and launched by DOE in 2008, the L Prize competition challenges industry to develop exceptionally high-performance, ultra-efficient LED alternatives for two of the most widely used light bulbs: 60W incandescent lamps and PAR 38 halogen lamps. The PAR 38 replacement category was temporarily closed in 2011. The new PAR 38 competition retains the original technical requirements established by Congress, but has been streamlined to keep pace with the speed of technology innovation and to move winning products into the market sooner. See www.lightingprize.org for more information.

DOE Hosts Ninth Annual SSL R&D Workshop: 2012 Transformations in Lighting

In February 2012, approximately 290 attendees—lighting industry leaders, chip makers, fixture manufacturers, researchers, academia, lighting designers, architects, trade associations, energy efficiency organizations, and utilities—gathered in Atlanta, Georgia, to share insights on today's products and tomorrow's lighting systems and explore the barriers and opportunities that will affect the speed of SSL market adoption. The annual DOE SSL workshop provides a forum for building partnerships and sharing strategies for continuing advances in high-efficiency, high-performance SSL technologies. Attendees also had an opportunity to provide input to guide updates to the DOE SSL R&D Multi-Year Program Plan. For more information, including workshop highlights and presentations see http://www1.eere.energy.gov/buildings/ssl/atlanta2012_materials.html.

Review of the Life-Cycle Energy Consumption of Incandescent, Compact Fluorescent, and LED Lamps

In February 2012, DOE released the first installment of a larger project to assess the life-cycle environmental and resource costs of LED lighting products in relation to comparable traditional lighting technologies. The published report compares the life-cycle energy consumed by LEDs, compact fluorescent lamps (CFLs) and incandescent lamps based on existing life-cycle assessment studies. The findings indicate that current LEDs and CFLs have a similar average life-cycle energy consumption of about 3,900 megajoules (MJ) per functional unit (20 million lumen-hours), which is about one quarter of an incandescent lamp energy consumption. It is further noted that, by 2015, if LED lamps meet their performance targets, their life cycle energy use is expected to decrease by approximately one half. Most of the uncertainty in life-cycle energy consumption of an LED lamp centers on the LED package manufacturing which was estimated to range from 0.1 to 27 percent of the total life-cycle energy consumption of the LED lamp with an average of 6.6 percent. The complete report is available for download on the DOE SSL website at: http://www1.eere.energy.gov/buildings/ssl/tech_reports.html

Energy Savings Potential of Solid-State Lighting in General Illumination Applications

In January 2012, the DOE released a report forecasting the potential energy savings offered by LED white-light sources over conventional white-light sources using an econometric model of the U.S. lighting market. Energy savings is estimated by comparing the outputs of the model under a scenario which features a growing market presence of LEDs to a baseline scenario with no additional market penetration of LEDs. The forecast indicates that LED lighting in general illumination applications has the potential to reduce national lighting energy consumption by nearly one half. If LED lighting technology meets its projected performance targets, it is expected that by 2030, LED lighting will represent 74 percent of lumen-hour sales of the general illumination market. Over the 20-year analysis period, from 2010 to 2030, the cumulative energy savings is estimated to total about 2,700 terawatt-hours (TWh), which at current energy prices and electricity generation mix conditions represents approximately $250 billion in savings and a greenhouse gas emission reduction of roughly 1,800 million metric tons of carbon. The complete report is available for download on the DOE SSL website at: http://www1.eere.energy.gov/buildings/ssl/tech_reports.html

2010 U.S. Lighting Market Characterization

In January 2012, DOE released a report providing estimates of the national inventory of installed lamps, their performance characteristics, associated energy use, and lumen production in the residential, commercial, industrial and outdoor sectors in 2010. The 2010 Lighting Market Characterization (LMC) is an update to the previous LMC, which modeled the 2001 U.S. lighting market inventory. It was found that in 2010 lighting accounted for approximately 700 TWh, or roughly 19 percent of total U.S. electricity use. The commercial sector, which is dominated by fluorescent lamps, is responsible for nearly half of the total lighting energy use and produced the majority of lumens. The second largest lighting energy consumer is the residential sector at 175 TWh per year. Residential buildings contain by far the most installed lamps with nearly six billion installations, over half of which contain incandescent lamps. The findings of the report support that the investments made in developing more energy efficient lighting solutions have been effective most notably by the transition from incandescent to CFLs in the residential sector, and the move from T12 to T8 and T5 fluorescent lamps in the commercial and industrial sectors. The complete report is available for download on the DOE SSL website at: http://www1.eere.energy.gov/buildings/ssl/tech_reports.html

DOE Joint Solid State Lighting Roundtables on Science Challenges

In October 2011, the EERE invited the Office of BES to jointly hold roundtable discussions of leading experts in SSL research. The BES program supports fundamental energy research at the electronic, atomic, and molecular levels. Discoveries from the research provide the foundations for new energy technologies which support DOE's missions. Two separate meetings were held on October 5 and 6, 2011 at the Bethesda Marriott Hotel in Bethesda, MD, one for LED technology, and one for OLED technology. The objectives of these roundtable discussions were to identify critical basic research needs for ongoing development of SSL, promote collaboration and enhance communication channels among basic science, applied science, and industry researchers and finally to maintain collaboration between EERE-BES SSL Programs. After two days of presentations and open floor discussions among experts in LED and OLED technology, several areas of research focus were recommended that the attendees believed could lead to significant advancements in SSL performance. LED carrier dynamics and droop, LED Nanostructures and OLED device architecture were the three principle areas identified. The outcome and discussions from these roundtables were used to develop proposed R&D task priorities for the DOE's annual SSL R&D Workshop. More information, including objectives, process and key conclusions, is available on the SSL website at: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl-bes-eere-roundtable-report_dec11.pdf.

DOE Awards First L Prize®

The L Prize competition reached a major milestone in 2011—the August announcement of the first winner in the 60W replacement category. The winning product, a 60W replacement bulb from Philips Lighting North America, successfully completed 18 months of intensive field, lab, and product testing to meet the rigorous requirements of the L Prize competition—ensuring that the product performance, quality, lifetime, cost, and availability meet expectations for widespread adoption and mass manufacturing. The winning product excelled through rigorous short-term and long-term testing carried out by independent laboratories and field assessments conducted with utilities and other partners. The product also performed exceedingly well through a series of stress tests, in which the product was subjected to extreme conditions such as high and low temperatures, humidity, and vibration. Visit www.lightingprize.org to learn more

As the winner, Philips received a $10 million cash prize, which the company has invested in domestic production and is marketing the winning lamp. The product is available for sale as of the end of February 2012. Philips is working with retailers, distributors, and more than 30 utility and energy efficiency program partners to implement coordinated promotional programs and incentives for the winning product.

DOE Hosts Sixth Annual DOE SSL Market Introduction Workshop

In July 2011, more than 275 lighting leaders—including industry, government, efficiency organizations, utilities, municipalities, designers, specifiers, retailers, and distributors—gathered in Seattle, Washington, to share the latest insights, updates, and strategies for the successful market introduction of high-quality, energy-efficient SSL products. The workshop itself was preceded by a day of tutorials for those new to SSL. More information, including tutorial and workshop highlights and presentations, is available on the SSL website at www.ssl.energy.gov/seattle11_highlights.html.

DOE Publishes Updated Recommendations for Testing and Reporting LED Luminaire Lifetime

In June 2011, DOE published an updated version of the guide *LED Luminaire Lifetime: Recommendations for Testing and Reporting.* Developed by a working group under the auspices of DOE and NGLIA, the guide is the latest edition in a series of publications on LED performance and lifetime. The recommendations are an important step toward consistent, industry-wide understanding of LED luminaire lifetime and are intended to support the Lighting Facts program and assist standards organizations in their work. The guide is available at: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/led_luminaire-lifetime-guide_june2011.pdf.

DOE Conducts Broad-Based Education Outreach

As part of DOE's ongoing commitment to SSL education, DOE hosted an informational booth and educational seminars at the 2011 LIGHTFAIR® International Trade Show, May 17–19, in Philadelphia, Pennsylvania. Co-sponsored by Illuminating Engineering Society (IES) and the International Association of Lighting Designers (IALD), 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. In addition, as part of the continuing education offerings prior to the show, DOE Lighting Program Manager Jim Brodrick participated in a special event panel on May 17 dedicated to "Creating a Vision for OLED Lighting." More information on SSL activities at LIGHTFAIR is available at http://www1.eere.energy.gov/buildings/ssl/news_detail.html?news_id=17395.

DOE Hosts Third Annual DOE SSL Manufacturing R&D Workshop

In April 2011, more than 250 industry leaders from all corners of the supply chain—chip makers, luminaire manufacturers, material and equipment suppliers, packagers, luminaire testers, and makers of testing equipment—gathered in Boston, Massachusetts, 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/boston11_highlights.html.

Next Generation Luminaires™ Announces LED Design Competition Winners

Winners of the third annual Next Generation Luminaires™ awards were announced in February 2011 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 138 entries were judged from 61 lighting companies. Of the entries, 37 were selected for recognition, with four of these products designated as Best in Class: fraqtir™ linear concealed LED cove luminaire from The Lighting Quotient; eW Burst® Powercore façade lighting fixture from Philips Color

Kinetics; Equo™ LED desk lamp from Koncept Technologies; and NanoLED™ recessed accent lighting fixture from USAI. An additional five products were deemed "notable," a new category created for those NGL entries that might not yet be considered specifiable but nevertheless have at least one outstanding characteristic deserving of recognition. More information on all the winning entries is available at www.ngldc.org.

Lighting Facts® Expands Product List and Online Resources

Continuing to grow rapidly, Lighting Facts is a voluntary pledge and labeling program to ensure accurate and consistent reporting of SSL product performance claims. 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. The Lighting Facts label presents independently verified LM-79 performance data in order to facilitate accurate product comparison. There are currently more than 3,450 products registered with Lighting Facts, and nearly 300 manufacturers have signed on as Lighting Facts partners, along with more than 210 retailers and distributors and over 210 lighting professionals, as well as more than 35 energy efficiency sponsors. Registered products are listed on the products page of the Lighting Facts website, along with their Lighting Facts label.

The website also offers a wide range of other tools to help users evaluate SSL products. The new Product Snapshot feature uses data from the Lighting Facts product list to compare the performance of LED replacement lamps to standard technologies and the new efficiency levels called for by the EISA 2007. The Commercial Product Performance Scale and the Residential Product Performance Scale compare LED lighting product performance to standard lighting sources. A new Energy Efficiency Partner Resource helps energy efficiency sponsors screen LED lighting products for incentive programs and shows which products are selected for which programs, with users able to search programs nationwide. For more information, see www.lightingfacts.com.

DOE Municipal Consortium on LED Street Lights Has Busy First Year

The goal of the Municipal Solid-State Street Lighting Consortium 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. To support this goal, the Consortium hosted a series of six workshops, designed to help cities, utilities, and other purchasers make informed decisions about LED street lighting. The 2011 workshops took place in Tampa, Kansas City (MO), Philadelphia, Detroit, Seattle, and San Jose. Each workshop included a core set of educational topics plus updates on Consortium tools and resources in development. Among those tools and resources are draft template specifications for LED roadway lighting, which is posted online and can be customized by the user as either a system specification or a material specification. The Consortium is also working with the Clinton Climate Initiative to modify a workbook that can be used by municipalities or others to help them figure out the cost and impact of switching over to LED street lighting. For more information, see www.ssl.energy.gov/consortium.html.

DOE Partners with IALD to Offer SSL Workshops in Three Cities
DOE and IALD have teamed up to offer a series of free one-day workshops on SSL technology. Entitled "Fact Versus Fiction: SSL Technology," the workshops are led by recognized experts in the field and provide immediately applicable knowledge to enable participants to know where and how to make use of SSL technology. By exploring such topics as the subtleties of LM-79 and LM-80 reports and how to use them to make informed product selections, lighting designers and specifiers learn how to better educate clients about solid-state lighting, and also gain the tools and background to deal with an increasing flood of information about SSL products. The first workshop took place June 15 in San Francisco; the second, July 20 in New York.; the third, October 11 in Chicago. The first three workshops were so successful that attendees requested that a fourth one be added to the schedule—a more advanced session—for those who are already familiar with SSL and want to increase the depth of their knowledge. This fourth workshop was held December 1 in New York. More information can be found at: www.iald.org/FACTVERSUSFICTIONSSLTECHNOLOGY.asp.

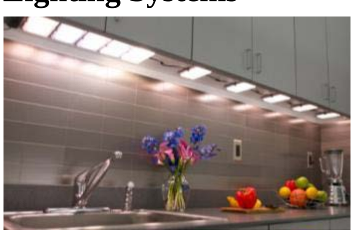
1.2.2 Recent Research Highlights

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 2011.

OSRAM SYLVANIA Demonstrates 87 lm/W MR16 Prototype

Under the DOE project, "Highly Efficient Small Form Factor LED Retrofit Lamp." a team at OSRAM SYLVANIA has successfully demonstrated an MR16 prototype with an instant-on efficacy of 87 lumens per watt (lm/W). The lamp was powered by 12 VAC 60 Hz, the total flux for the lamp was 409 lumens, the color correlated temperature (CCT) was 3285K, and the color rendering index (CRI) was 87. (September 2011)

Universal Display Corporation Completes Pre-Prototype OLED Undercabinet Lighting Systems



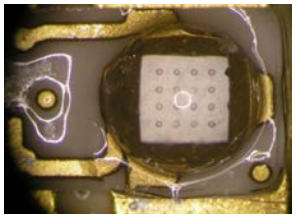
UDC completed an important OLED product development project and eclipsed planned performance expectations by delivering two complete, pre-prototype undercabinet lighting systems based on their proprietary phosphorescent materials. The systems successfully demonstrated more than 420 total lumens at greater than 55 lm/W efficacy with an estimated lifetime (L_{70}) in excess of 10,000 hours and a CRI >85. Built with early versions of UDC's out coupling efficiency improving technology, each delivered system includes ten OLED panels (each panel 15cm x 7.5cm), an integrated power supply, special interconnects, dedicated low voltage wiring and dimming control. Continuing development of advanced out coupling concepts currently under consideration by the

UDC team are expected to produce even higher system efficacies with concurrent improvements in CRI. (September 2011)

Philips Lumileds Demonstrates Bright-White LED at 149 lm/W

Philips Lumileds Lighting Company successfully fabricated a prototype packaged, bright-white LED that delivers 149 lm/W. Based on the Rebel ES platform, the prototype LED package produces about 600 lumens, with a CCT of 3911K and a CRI of 65. This project received funding under the American Recovery and Reinvestment Act. (September 2011)

Philips Lumileds Demonstrates LED Device Grown on Silicon Substrate



Philips Lumileds has demonstrated a blue LED device fabricated from epitaxy grown on silicon with a light output and efficiency approaching industry state of the art LEDs. The light output of the device was 437 mW at a current of 350 mA (current density ~35 A/cm^2), wavelength of 448 nm, forward voltage of 3.06 V, and packaged LED wall plug efficiency of 40.7 percent. This project received funding under the American Recovery and Reinvestment Act. (August 2011)

RTI Wins Prestigious R&D 100 Award in Energy-Efficient Lighting

RTI International's nanofiber lighting improvement technology (NLITe™) has been honored with a 2011 R&D 100 Award. RTI's technology, which was funded in part by DOE's SSL Program under the core technology category, has led to the development of high-performance, nanofiber-based reflectors that allow highly efficient light transmission. It also has led to the development of photoluminescent nanofibers (PLN™) that can be used to produce an aesthetically pleasing light with excellent color rendering properties. At the core of RTI's invention is an advanced polymer nanofiber structure with strong lighting management and color rendering properties. Powered by a blue LED, the RTI device uses a highly reflectant nanofiber mat, treated with photoluminescent coatings, to produce white light. (July 2011)

Cree's XLamp MT-G: New Lighting Class LED Product for High Efficiency General Illumination

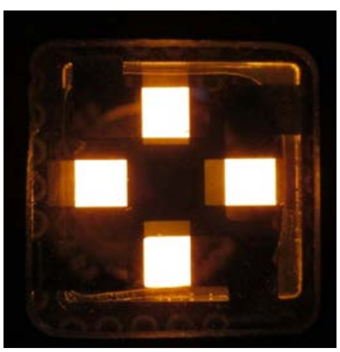
Cree has announced a new lighting class LED designed for small form-factor directional lighting applications such as MR16 bulbs. The XLamp MT-G LED is binned and tested at 85°C, which can simplify luminaire design calculations and speed time to market. With a 9mm x 9mm footprint, the MT-G LED delivers up to 560 lumens at 1.1A at 85°C or up to 1,525 lumens at 4A at 85°C in warm white (3000K). This component was designed under Cree R&D funding, and its feasibility in the MR16 form factor was demonstrated in part with funding from DOE. This component is a good first step at enabling the industry to make viable 35–50W halogen replacements for some applications, but further development of some elements of the technology are being funded by DOE to bring a high efficiency MR16 lamp with high CRI to market. This project will continue to tackle that next-generation technology not achievable in the marketplace today. This project received funding under the American Recovery and Reinvestment Act. (April 2011)

Arkema Demonstrates Novel Integrated Substrates for OLEDs

Arkema and its sub-contractor, Philips Lighting, have successfully developed novel integrated substrates for OLEDs. Typically, OLEDs are fabricated on rigid, borosilicate glass substrates, sputter-coated with a transparent indium tin oxide (ITO) electrode. Arkema has developed an alternative substrate comprised of doped zinc oxide (ZnO) on inexpensive residential glass, where the doped ZnO is deposited using low-cost atmospheric pressure chemical vapor deposition processes. Arkema has demonstrated that their doped ZnO electrodes have comparable performance to ITO in terms of transparency (> 90 percent transmission in the visible region for doped ZnO, compared with > 85 percent for ITO) and conductivity. Further, they have demonstrated compatibility with OLED structures by fabricating 6x6 inch OLED panels on prototype substrates. Low-cost integrated substrates can significantly reduce the overall cost of OLED production by as much as 70 percent. (April 2011)

Cambrios Develops Alternative Transparent Conductors for OLED Devices

Cambrios has developed a roll-to-roll compatible alternative transparent electrode for OLED devices using silver nanowires embedded in a polymeric matrix. These electrodes are highly flexible and can be manufactured on plastic or glass substrates using solution-processing techniques such as slot-die coating or spin-coating. Supporting Cambrios' efforts, Plextronics has developed solution processable hole injection layers that work in conjunction with these silver nanowire films to planarize the rough nanowire layer and promote charge injection. These transparent conductive hole injection layers have demonstrated performance comparable to that of ITO on glass with sheet resistance as low as ten ohms/square and transmission of 85 percent. Preliminary experiments have further demonstrated OLEDs on these novel electrodes. The use of solution-processable, indium-free electrodes can lead to significantly reduced costs for OLEDs. (February 2011)



2.0 Lighting Market and Energy Use

The Energy Information Administration (EIA) estimated world primary energy consumption for electricity use to be around 200 quadrillion BTU (quads) in 2010.[10] It is also estimated that the U.S. is responsible for 20 percent of the global consumption or approximately 40 quads.[11] In early 2012, the DOE released a report[12] providing detailed estimates of the installed lighting stock, energy consumption and lumen production of all lamps operating in the U.S. in 2010. DOE estimates that lighting technologies across all U.S. sectors (residential, commercial, industrial, and outdoor) were responsible for nearly 7.5 quads of primary energy in 2010. In residential buildings lighting was the fourth largest end-use of energy while in commercial buildings lighting was the main consumer of primary energy. Lighting constituted approximately ten percent of residential building primary energy consumption and 14 percent of commercial building primary energy consumption. [13] New lighting technologies, especially solid-state sources, offer one of the greatest opportunities for electricity savings within the building sectors 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

In 2010, there were approximately eight billion lamps installed in the U.S. consuming nearly 7.5 quads of primary energy or equivalently about 700 TWh of site electricity. The residential and commercial sectors were responsible for the majority of lighting electricity consumption and light installations. The distribution of lamp quantity, lighting energy consumption and lumen production across the four sectors is illustrated in Figure 2.1. Residential buildings housed almost three times as many lamps as the commercial sector yet were responsible for only half as much of the lighting energy consumption and a little more than one tenth of the lumen production. Commercial buildings accounted for a greater portion of lumen production and energy consumption than residential buildings despite its smaller share of the total lamp stock due to the longer average operating hours and higher lamp wattages.

[10] International Energy Outlook 2011, U.S. Energy Information Administration, Available at: http://www.eia.gov/forecasts/ieo/index.cfm

[11] Annual Energy Outlook 2012 Early Release. U.S. Energy Information Administration. Available at: http://www.eia.gov/forecasts/aeo/er/

[12] 2010 U.S. Lighting Market Characterization. Prepared by Navigant Consulting, Inc. for the Department of Energy. Washington D.C. January 2012. Available at: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/2010-lmc-final-jan-2012.pdf

[13] 2011 Building Energy Data Book, U.S. Department of Energy, Office of Planning, Budget and Analysis, Energy Efficiency and Renewable Energy. Available at: http://buildingsdatabook.eren.doe.gov/docs/DataBooks/2011_BEDB.pdf

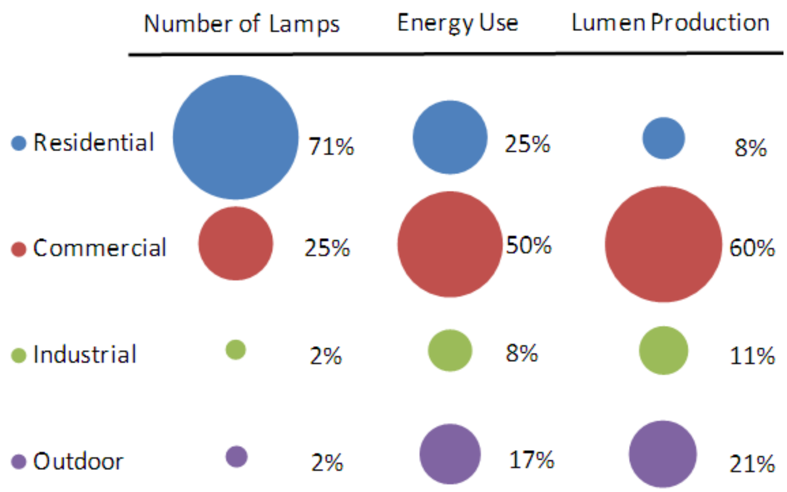


Figure 2.1: 2010 U.S. Lighting Inventory, Electricity Consumption and Lumen Production

Source: 2010 U.S. Lighting Market Characterization. Prepared by Navigant Consulting, Inc. for the Department of Energy. Washington D.C. January 2012.

Across all sectors, incandescent, linear fluorescent and CFLs comprised the greatest portion of the installed lamp base in 2010. Incandescent lighting constituted 45 percent, linear fluorescent lamps represented approximately 29 percent and CFLs were 19 percent of the total 2010 U.S. lamp inventory. Of the total 3.7 billion installations of incandescent lamps, residential buildings housed the greatest by far, totaling around 3.6 billion. The majority of linear fluorescent lamps were located in commercial and industrial establishments, while CFLs were primarily used in residential applications. However, as was demonstrated by Figure 2.1, quantity of lamps is not a direct correlation to energy consumption.

Figure 2.2 illustrates the distribution of electricity consumption in 2010 by lamp type and sector. Overall linear fluorescent lighting claimed the largest portion of national electricity consumption for lighting in 2010 at roughly 42 percent, followed by high intensity discharge (HID) lighting at 26 percent and incandescent lamps at around 22 percent. The large contribution of HID to the total consumption was mainly due to its presence in commercial, industrial and outdoor installations. These applications are all characterized by longer average operating hours as well as high wattage (and high lumen output) HID lamps. The lamps in residential buildings typically have a lower average wattage than the other sectors and are operated for much less time averaging about two hours per day in 2010. This accounts for the residential sector’s relatively small contribution to national lighting electricity consumption despite its significantly larger installed lamp base.

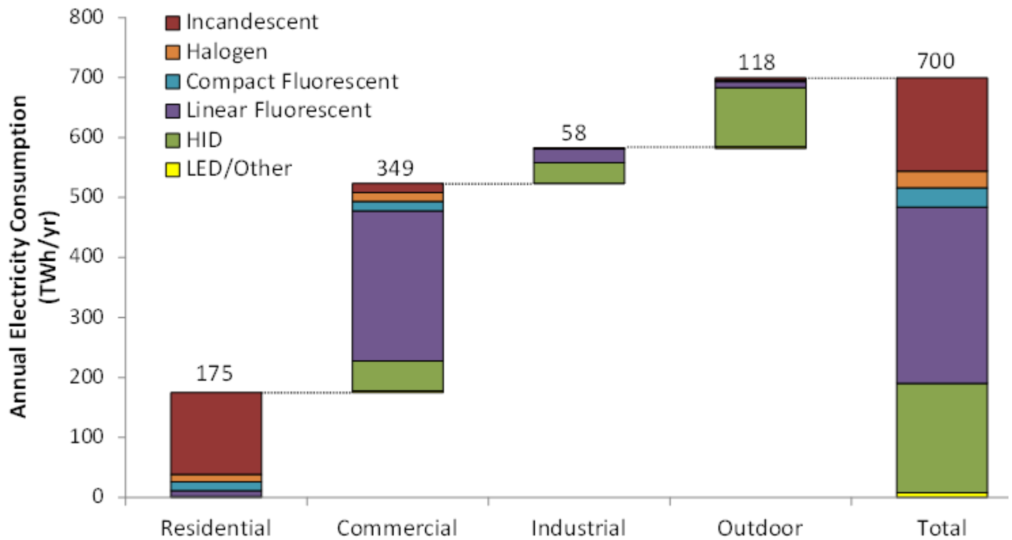


Figure 2.2: U.S. Lighting Electricity Consumption by Sector and Lamp Type in 2010
Source: *2010 U.S. Lighting Market Characterization. Prepared by Navigant Consulting, Inc. for the Department of Energy. Washington D.C. January 2012.*

The lighting market has shown a gradual trend towards energy savings over the course of the last decade. Despite an approximately 18 percent increase in the quantity of installed lamps from 2001 to 2010, annual lighting electricity consumption has decreased by about nine percent. Although incandescent and linear fluorescent lights still dominate the national inventory of lamps in 2010 as they did in 2001, there have been some major shifts towards more efficient lighting solutions during that time. The number of incandescent lamp installations has decreased from approximately 62 percent in 2001 to 45 percent in 2010 while CFL’s market share rose from about three percent in 2001 to nearly 19 percent a decade later. The transition from general service incandescent lamps to CFLs is most significant in residential buildings. Although the number of incandescent lights dropped across all sectors, the largest decrease was in the residential sector which shed over 300 million incandescent lamps from 2001 to 2010 despite a 26 percent increase in the total number of lamps. This trend is expected to continue with the implementation of the EISA 2007 general service incandescent lamp standards. These maximum wattage standards will take effect between 2012 and 2014 and effectively require the efficacy of general service incandescent lamps to increase approximately 25 percent. Halogen incandescent lamps that meet these standards are currently commercially available, however, 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, HID and LED-based lighting.

Commercial and industrial buildings have also demonstrated a movement toward more energy efficient lighting sources. In 2001, linear fluorescent lighting was approximately 71 percent of the total installed lamp base in commercial and industrial buildings. This percentage has grown to 81 percent in 2010 indicating that linear fluorescent lamps have become an even greater majority of commercial installations. In addition, there has also been a distinct trend from low-efficiency magnetic T12 linear fluorescent systems toward high efficiency T8 and T5 electronic systems in the commercial sector. For example, in 2001, T12 lamps constituted approximately 64 percent of the linear fluorescent installed base; while in 2010 these less efficient T12 lamps only represented 32 percent of the total. Likewise, in 2001, T8 and T5 lamps combined comprised only 36 percent of all linear fluorescent lamps. While in 2010, the portion of T5 and T8 lamps in commercial and industrial buildings grew to approximately seven percent and 60 percent, respectively. More recently, there has also been a trend toward an increased use of low wattage metal halide lamps in these sectors as replacements for higher wattage halogen lamps in applications such as track and down lighting.

Similar to the residential, commercial and industrial sectors, there has been a significant trend towards efficient lighting options for outdoor applications. HID lamps such as mercury vapor, high-pressure sodium and metal halide are common lighting technologies used for outdoor area lighting applications. Yellow/orange high-pressure sodium lamps are still very common across a variety of outdoor lighting applications including roadway and parking lot. However, in recent years, metal halide lamps have become the light source of choice for outdoor applications where color rendering is of importance. For example in 2001, 19 percent of all outdoor HID lamps were mercury vapor and 24 percent were metal halide. But in 2010, only four percent of outdoor HID lamps were mercury vapor and metal halide lamps had risen to 32 percent of the total. This change is significant because on average, metal halide lamps have efficacies at least twice those of mercury vapor lighting.

Solid-state lighting represents one of the most efficacious lighting options available. In 2001, the number of LED lamps installed in the U.S. was just under 1.6 million, which equates to less than 0.1 percent of the total lamp base. Almost 90 percent of the 2001 LED lights were exit signs from the commercial and industrial sectors and traffic lights from the outdoor sector. In 2010, the installed base soared to an estimated 67 million LEDs, but still only represented roughly one percent of the total lighting inventory. Nearly half of these LEDs were installed in commercial and industrial exit sign applications, while the remaining 36 million represent installations of LED lamps and luminaires. The outdoor sector claims the majority of LED lamp and luminaire installations as they have become increasingly competitive with conventional HID lamps. In 2010, it is estimated that LED-based lamps accounted for roughly ten percent of the total U.S. installed 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 is a rapidly growing segment of the lighting market. LED-based lights match or exceed the performance of conventional products in many lighting applications, and significant strides toward cost competitiveness have been made. DOE cosponsors the “Next Generation Luminaires” design competition to encourage the use of SSL products in a variety of applications in the residential and commercial sectors.[14] The Next Generation 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.

Figure 2.3: Entries to the 2012 Next Generation Luminaires – Indoor Competition

In its first year, 2008, the Next Generation Luminaires competition recognized 22 products from among a total of 68 entries. In 2009, the number of entries nearly doubled – to 126. Of these entries, 43 were chosen as "recognized" winners and four of were chosen as "best in class." Most recently, in 2010, 42 products were recognized out of a field of 138 judged entries with four of these products again receiving "best in class" designations. Due to this growing participation, the 2012 Next Generation Luminaires design competition has been broken into two separate competitions for outdoor and indoor products.[15] Having reviewed and judged 114 pre-approved entries from 45 companies, the 2012 Indoor Competition is now complete. Several of the 2012 Indoor Competition entries are shown in Figure 2.3. Winners will be announced at the

[14] Details about the “Next Generation Luminaires” competition is available at: http://www.ngldc.org/.
[15] http://www.ngldc.org/background.stm

upcoming LIGHTFAIR International on May 10, 2012. The DOE is expected to send out its call for entries for the 2012 Outdoor Competition this spring.

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 Asheville and Raleigh, NC, Austin, TX, and Ann Arbor, MI, have installed LED-based roadway and area lights to save on energy and maintenance costs.[16] The DOE SSL GATEWAY program has demonstrated installations of outdoor SSL systems in several other areas across the country.[17]

2.3 SSL Growth and Projected Energy Savings

Globally, sales of high brightness (HB) LED packages grew from $11.3 billion in 2010 to $12.5 billion in 2011, a growth rate of 9.8 percent, according to a market report by Strategies Unlimited.[18] The revenue growth in 2011 was driven mainly by LED demand for applications in TV backlight units. TV supply and demand conditions in 2011 led to a significant reduction in LED prices. As a result, the demand for packaged LEDs in lighting applications increased from $1.2 billion in 2010 to $1.8 billion in 2011, a growth of 44 percent.

A 2011 study[19] analyzed the energy savings potential of LED-based lighting products in seven market segments that included outdoor and indoor general illumination.[20] Figure 2.4 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, LED-based products are achieving significant energy savings for several applications.

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[16] Details about the LED city program are available at: http://www.creeledrevolution.com/.
[17] DOE's Solid-State Lighting GATEWAY program is available at: http://www1.eere.energy.gov/buildings/ssl/gatewaydemos.html
[18] Strategies Unlimited, Worldwide LED Market Grew 9.8% to $12.5 Billion in 2011 with 44% Growth in LED Lighting, According to Strategies Unlimited, http://www.strategies-u.com/articles/2012/02/worldwide-led-market-grew-98-to-125-billion-in-2011-with-44-growth-in-led-lighting-according-to-strategies-unlimited.html
[19] 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_january2011.pdf
[20] 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.

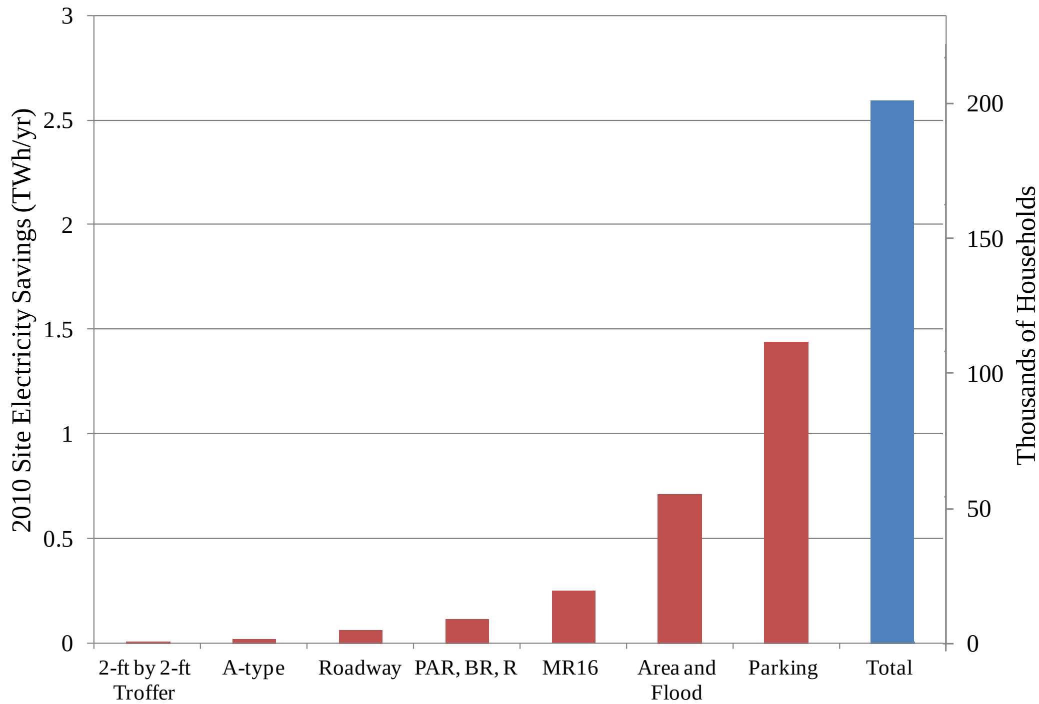

Figure 2.4: 2010 Electricity Saving from the Selected Niche Applications
Source: Energy Savings Estimates of Light Emitting Diodes in Niche Lighting Applications. Prepared by Navigant Consulting, Inc. for the Department of Energy. Washington D.C. January 2011.

Figure 2.4 shows that in 2010, the penetration of LED-based luminaires 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 LED-based luminaires in 2010 were dominated by outdoor parking lighting, where such products have achieved an estimated 4.3 percent market penetration. This application represents about 56 percent of the total energy savings from the use of LED-based luminaires in 2010. After parking lighting,[21] the market application with the second greatest energy savings in 2010 was area and flood lighting,[22] which contributed to 27 percent of the total site electricity savings in 2010 and has an LED-based luminaire penetration of about 0.72 percent. LED MR16, PAR, BR and R, as well as roadway lamps, also demonstrated significant energy savings, in total representing 16 percent of the total 2010 savings. Other sectors such as 2'x2' troffer fixtures and A-type replacement lamps have low levels of LED-based luminaire 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.

In an effort to demonstrate the potential energy savings from continued market penetration of LED lighting, DOE released a study in January 2012 that forecasts the

[21] Parking lighting only includes off-street parking and has been divided into covered parking garage lighting and parking lot lighting.
[22] 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.

energy savings potential of LED white light sources as compared to conventional white light sources.[23] Using an econometric model of the U.S. lighting market through the year 2030, the annual lighting energy consumption under a scenario considering the growing market presence of LED-based luminaires is compared to energy consumption under a baseline scenario, which hypothesizes no additional market penetration of LED lighting in general illumination applications. As shown in Figure 2.5 this analysis finds that the energy savings potential, represented by the difference in energy consumption between the two scenarios, is significant.

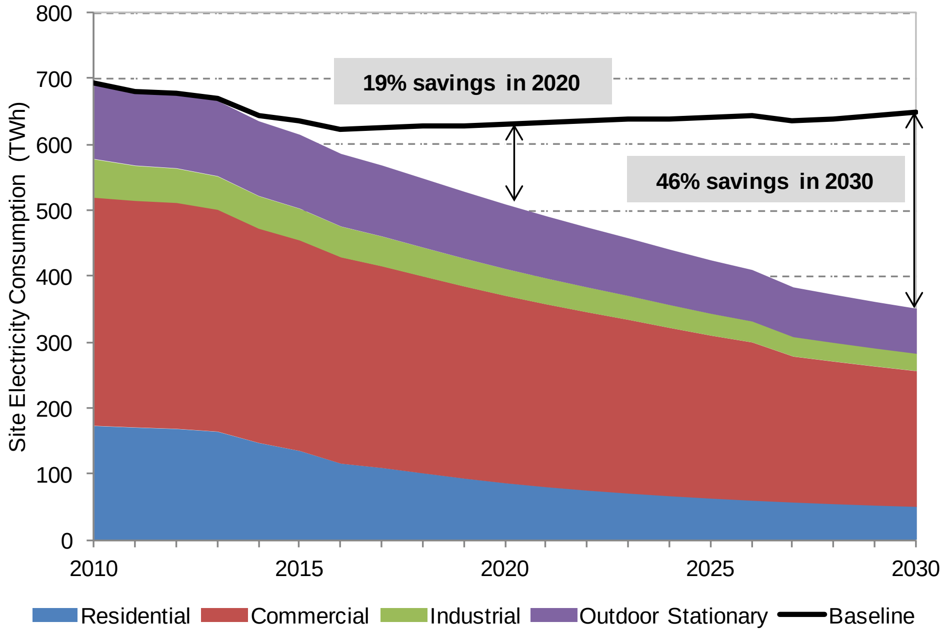

Figure 2.5: Forecasted U.S. Lighting Energy Consumption and Savings, 2010 to 2030
Source: Energy Savings Potential of Solid-State Lighting in General Illumination Applications. Prepared by Navigant Consulting, Inc. for the Department of Energy. Washington D.C. January 2012.

The analysis indicates that if LED lighting technology meets its expected efficacy, lifetime, and price targets, by the year 2030, LED lighting would save the U.S. approximately 300 terawatt-hours of site energy, or the equivalent annual electrical output of about fifty 1,000-megawatt power plants. At today's energy prices, that would equate to approximately $30 billion in energy savings in 2030 alone. Assuming the current mix of generating power stations, these energy savings would reduce greenhouse gas emissions by 210 million metric tons of carbon. As illustrated in Figure 2.5, by 2030, the total electricity consumption for lighting is expected to decrease by roughly 46 percent relative to a scenario with no additional penetration of LED lighting in the market—enough electricity to completely power nearly 24 million homes in the U.S. today.

[23] For more information on these scenarios, please see the DOE report. 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. January 2012. Available at: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_energy-savings-report_jan-2012.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 LED components and luminaires are typically based on one of three approaches: (a) phosphor-conversion, (b) discrete color-mixed or (c) a hybrid approach which combines the phosphor conversion and color mixed approaches. Figure 3.1 shows these three approaches to white light production.

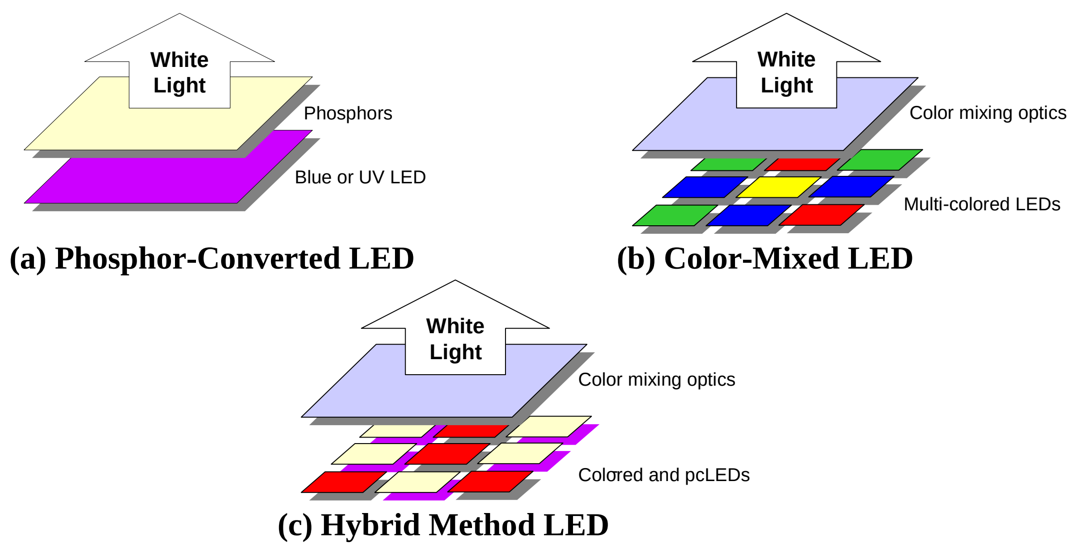

Figure 3.1: General Types of White Light from LEDs

Currently, most LEDs use the phosphor-converted (pc) approach to create white light. White light is generated by mixing a portion of the blue light emitted directly from a GaN LED die with down-converted yellow light emitted by a phosphor. The phosphor can be located on the LED emission surface, within the encapsulant, or spaced away from the LED (remote phosphor). Many manufacturers have successfully lowered the CCT and increased the CRI by blending red emitting phosphor with yellow phosphor. Phosphor-converted LEDs have demonstrated efficacies of up to 144 lm/W for cool white emitters and 111 lm/W for warm white emitters.[24]

Discrete color-mixed packages blend together the light output from multiple monochromatic LED sources with different emission wavelengths, creating white light.

[24] See tables in Section 5.0 for specific CCT, CRI, and current density ranges

With the discrete color-mixed approach phosphor conversion efficiency losses (quantum efficiency, scattering, and Stokes' loss) are entirely avoided, so the color mixed approach offers the highest theoretically attainable efficacy. However, green and amber LEDs, required for the color-mixed approach, suffer from poor internal quantum efficiency themselves. For practical white light emitters, the phosphor-converted approach typically achieves higher efficacy, but efficiency improvements to green and amber emitters could pave the way for efficacy advancements with the color-mixed approach.

A hybrid approach using both phosphor-converted and discrete monochromatic LEDs can achieve some of the benefits of both approaches. For the hybrid approach phosphor-converted white LEDs are used with direct emitting LEDs to achieve higher efficacy and improved color quality. The hybrid approach can be done at the luminaire level or within a single LED package that contains pc-LED and direct emitting dies. Some excellent examples of hybrid LED designs are on the market today with very good color quality and efficacy.

For all of the approaches to generate white light from LEDs, color stability is an important consideration. The output from the different LED and phosphor emitters will change differently with time and temperature. For discrete color-mixed and hybrid approaches the output of different emitters may need to be monitored and controlled to compensate for these effects and maintain a stable color point.

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 emission 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 thin layers of organic materials confined between planar electrodes. 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 below. The benefit of a single stack OLED (Figure 3.2a) is simpler fabrication due to the reduced number of layers and minimal patterning required. Many companies are exploring more complex stacked or tandem OLED structures (Figure 3.2b) which allows for light generation in two or three OLED emissive regions separated by charge generation and transport layers. The advantage of this approach is that higher luminance levels can be achieved at lower current densities. Considering the high luminance levels required for general illumination and the typically observed large drop in lifetime with increasing current density, these complex structures can be appealing. Striped OLED structures (Figure 3.2c) require patterning and reduce the active area of a device (depending on fill factor), but are attractive because they allow for color tunability. For white OLED devices for general illumination, this feature benefits yield - as it enables panel to panel color correction - and color maintenance – as it allows for color correction over time as the different emitters decay at different rates. For OLED luminaires which rely on panel tiling, panel-to-panel color uniformity is essential.

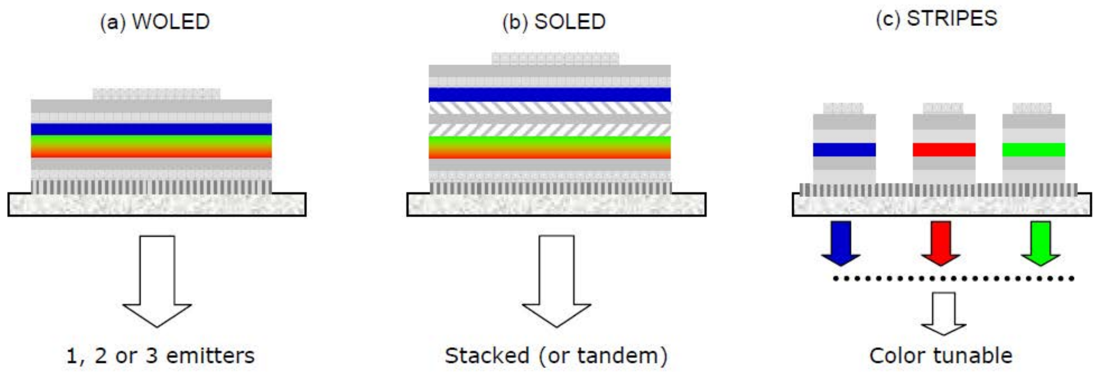

Figure 3.2: Three arrangements of red, green, and blue emission layers
Source: *UDC*

In order for the light to escape from the device, at least one of the electrodes must be transparent. When both electrodes are transparent, an OLED can be made to be transparent in the off-state and emit light from both faces of the panel in the on-state, allowing for unique luminaire design opportunities and light distribution profiles. Because of the high sensitivity of organic materials and cathode metals to oxygen and water, the OLED structure must be encapsulated using a non-porous substrate, cover and edge seals. 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 waveguiding 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 displays 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 reduction of the production cost to levels appropriate for general illumination. In the past few years, an increasing number of prototype luminaires and panels for lighting design kits have become available. The performance of these devices has improved considerably and laboratory panel results indicate that further performance improvements are imminent. Cost remains a key issue with the marketability of OLED technology for lighting applications. For use in general illumination, severe manufacturing cost reductions need to be made. While mass production can lead to reduced manufacturing costs, this is not an appropriate avenue until a sufficient OLED lighting demand is in place. To create this market demand and justify the value proposition for OLEDs, breakthrough luminaires need to be developed that can differentiate OLEDs from other lighting technologies and demonstrate how OLEDs are complementary to other lighting technologies.

The focus of current OLED lighting research is the development of materials, structures, light extraction techniques, current distribution approaches and encapsulation schemes that are appropriate for large area panels. Much advancement has been made in the past year, resulting in the efficacy of best-in-class panels more than doubling from 28 lm/W (Verbatim Velve) to panels with 60 lm/W efficacies expected to ship in spring 2012 (LG Chem). Further, the brightness of OLED panels is increasing. In the past year, many companies have begun reporting efficacy and lifetime of their OLED lighting panels at high brightness levels considered appropriate for general illumination. Specifically, the industry is moving toward reporting performance at luminance of 3,000 cd/m^2 (usually equivalent to luminous emittance of 9,000 lm/m^2). Previously, performance has been reported at 1,000 cd/m^2 (or about 3,000 lm/m^2). Higher brightness is needed to provide the lumen output required by general illumination devices, but performance in terms of efficacy and lifetime is generally drastically reduced by the increase in current density associated with high brightness operation. In 2011, panels emerged that can achieve high efficacies and long lifetimes even at high illuminance. Despite these advances, there is still a long way to go in terms of performance and cost before OLEDs are able to compete for use in general illumination applications. Lumen output, lifetime, color point and rendering, color and brightness uniformity and stability, efficacy, and cost are all considerations. 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 per kilolumen will be reduced significantly by 2020.

3.3 Worldwide R&D in SSL Technology

LED-based SSL technology has its roots in the initial demonstration of a high performance blue emitter 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 yttrium aluminum garnet phosphor. This set the scene for general lighting applications of 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[25] 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 spread globally.

As reported in the 2011 MYPP, R&D activity in Europe is generally coordinated through industry consortia such as the European Photonics Industry Consortium[26] and voluntary cross-border associations such as Photonics21.[27] Much of the government funding is channeled through European Union collaborative R&D projects. In the area of LED-

[25] "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.
[26] www.epic-assoc.com
[27] www.photonics21.org. Note that their Strategic Research Agenda (SRA) "Lighting the way ahead" was published in January 2010.

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 European Union (EU), and are typically three years in duration. The two largest programs (SSL4EU and SMASH) are funded by OSRAM. The most closely related project is SSL4EU (www.ssl4.eu) comprising ten partners from seven different states and running to 2013. This project has very similar aims, i.e. to explore high quality multi-chip LED light sources for high quality and color-adaptable light sources utilizing warm white LEDs with ceramic phosphor converters, and multi-color LEDs. Furthermore, the project retains a focus on increasing system efficiency by exploring smart electronics, improved thermal management, and optimized optics for color-homogeneity and low losses. The SSL4EU project aims to determine the optimum light source spectral power distributions for different situations in homes, offices and shops; to find out correlations between light intensity and spectrum for different activities; and to set user preferences for LED lighting for optimizing the achievable extra benefits in changing to LED lighting.

EU funding for SSL Pilots under the Competitiveness and Innovation Framework Programme was also launched in 2011 with a specific objective to develop 'Innovative lighting systems based on Solid State Lighting'. This program funds large scale pilot actions to demonstrate the best use of innovative lighting systems based on SSL for better light quality and control with a substantial reduction in energy consumption. Projects are currently under negotiation in the areas of exterior lighting (streets, restaurant areas and public buildings) as well as interior lighting (museums and other visitor centers), and are expected to start early in 2012. It is anticipated that two to three projects will be supported with a total EU funding of up to $13 million (50 percent cost share).

In addition, IMEC (Belgium) launched an industrial affiliation program 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 200 mm Si wafers. This multi-partner GaN R&D program includes Micron Technology, Applied Materials and Ultratech. Large multi-national companies headquartered in Europe, such as Philips BV, also perform their industrial R&D at various locations worldwide including US subsidiaries such as the Philips Lumileds operation in San Jose, CA.

In Taiwan, the primary source of R&D funding is the business sector, at around 70 percent, followed by the government, at around 30 percent. The main research institute for LED R&D is the Industrial Technology Research Institute 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 R&D spending in the LED industry was thought to top $600 million in 2010. Much of this will be to improve manufacturing 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.[28]

The private sector is a key player in Korean R&D activities, contributing around 74 percent 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 metal organic chemical vapor deposition (MOCVD) equipment (up to $1.8 million per machine). Consequently, China's installed base of such equipment has risen from 135 in 2009 to around 300 at the end of 2010, and was previously anticipated to rise to 900 by 2012 and 1500 by 2015, although recent reports predict a 40 percent decline in 2012 spending on MOCVD systems.[29] 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 percent on applications and thirteen percent on packaging.[30]

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.

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). Both LG Chemical and Sumitomo Chemical are now pursuing the development of OLED lighting panels in addition to their work with displays.

Research specific to lighting has been promoted through several government programs in

[28] Mutek International Co, http://www.mutek.com/news/industry-news/44-taiwan-led-investment-top.html
[29] "Opto/LED Fab Forecast", SEMI, January 2012, see: www.semi.org/en/Store/MarketInformation/OptoLEDFabForecast
[30] "China SSL Technology and Industry Development Strategies" Yuan-Fu, CSA Consulting, Jan 2011

Asia, Europe and the U.S. In addition to national programs, several multinational projects have been supported through the EU. The three-year project OLED100.eu that was completed in 2011 successfully stimulated collaborative efforts but the results fell short of the program's aggressive targets of a square meter panel with an efficacy of 100 lm/W and lifetime of 100,000 hours at a cost of €100. The goal of a one square meter area panel was essentially met by tiling nine panels of sizes 33cm x 33cm. The efficacy of these panels was 27 lm/W at 1,000 cd/m^2. The lifetime to half-luminance (L_{50}) of these panels was estimated to be only 10,000 hours, although one team member (Novaled) has developed technology that is capable of reaching the targeted 100,000 hour lifetime. The project was unable to address manufacturing costs, so that the target of €100/m^2 remains elusive.

Both Osram and Philips have been producing panels for evaluation by luminaire manufacturers. Osram spent €20M on a new prototype line in Regensburg during 2011, providing employment for 220. Philips committed €40M to expand the production capacity at their Aachen facility in 2012. Astron FIAMM is producing OLED lighting panels on 370mm x 470mm substrates in Toulon, France. The company has shown several concept cars using OLED lighting, but the panels are currently available only as complete lamps through their subsidiary, Blackbody.

Philips has recently released their OLED roadmap showing two tracks. For color-changeable decorative panels, which will be produced on flexible substrates of area up to one square meter, the 2018 target efficacy is only 35 lm/W. The maximum luminance will be 3,000 cd/m^2, but the target lifetime (L_{70}) of 40,000 hours is quoted from only 1,000 cd/m^2. Their high performance panels should be available in sizes up to 40cm x 40cm with CRI greater than 95 and efficacy of 130 lm/W. The lifetime (L_{70}) target is 40,000 hours from 3,000 cd/m^2.

European researchers have been very active in the development of flexible OLEDs, primarily through two cooperative programs at the Holst Centre in Eindhoven and the Fraunhofer IPMS in Dresden. The work at the Holst Centre involves over 220 researchers from both industry and academia and is focused on solution processing on plastic substrates, both in sheet and roll-to-roll modes. Several teams from the US and Asia are involved with European partners in these projects. The Fraunhofer Institute is exploring the use of vacuum processing techniques on both metallic and plastic webs.

Several Japanese companies have introduced prototype panels. Perhaps the most distinctive are the color-tunable Velve panels from Verbatim, which are made by Pioneer using materials from Mitsubishi Chemicals. Konica-Minolta has terminated its partnership with GE and contracted with Philips to produce its panel with the name Symfos which could be purchased in 2011. Idemitsu Kosan has a long history of production of OLED materials and has purchased an interest in Global OLED Technology, the company formed by Korea's LG Chem after its purchase of the OLED IP portfolio from Eastman Kodak in 2009. Idemitsu has formed a joint venture with Panasonic, Panasonic Idemitsu OLED Lighting, combining Idemitsu's technology with Panasonic's strong distribution channels and brand image. They are currently shipping

8cm x 8cm panels with 30 lm/W efficacy at approximately 10,000 lm/m^2 with a lifetime L_{70} of 10,000 hours. Their roadmap for 2019 aims for an efficacy of 130 lm/W on a 60cm x 60cm panel with 40,000 hour lifetime from 15,000 lm/m^2. Panasonic has developed pixel sized white devices with efficacy of 128 lm/W. Sumitomo is another Japanese company beginning to produce OLED lighting panels. Their panels are expected to be polymer OLED devices based on the IP acquired from CDT. Sumitomo plans to invest about $60-70 million in equipment for this effort.

The greatest investments in OLED technology have been made in Korea. Samsung's OLED investments have averaged about five billion dollars per year recently. Although how much of this is aimed at lighting applications is unclear, the manufacturing experience that they are gaining for displays will be of great value in reducing the cost of OLED lighting. Although LG has lagged behind Samsung in sales of OLED displays, they are enthusiastically competing for the lighting markets. Their production facility came on-line in January 2012 and their panels will soon be available through Acuity and others at highly competitive prices. The LG roadmap is more aggressive than that of Philips, aiming for efficacy of 135 lm/W and lifetime of 40,000 hours on 20cm x 20cm panels by 2015. They also are promising flexible and transparent panels.

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 3.3, developed from historical lighting catalogues and the SSL projections discussed in Section 5.0, depicts this potential.

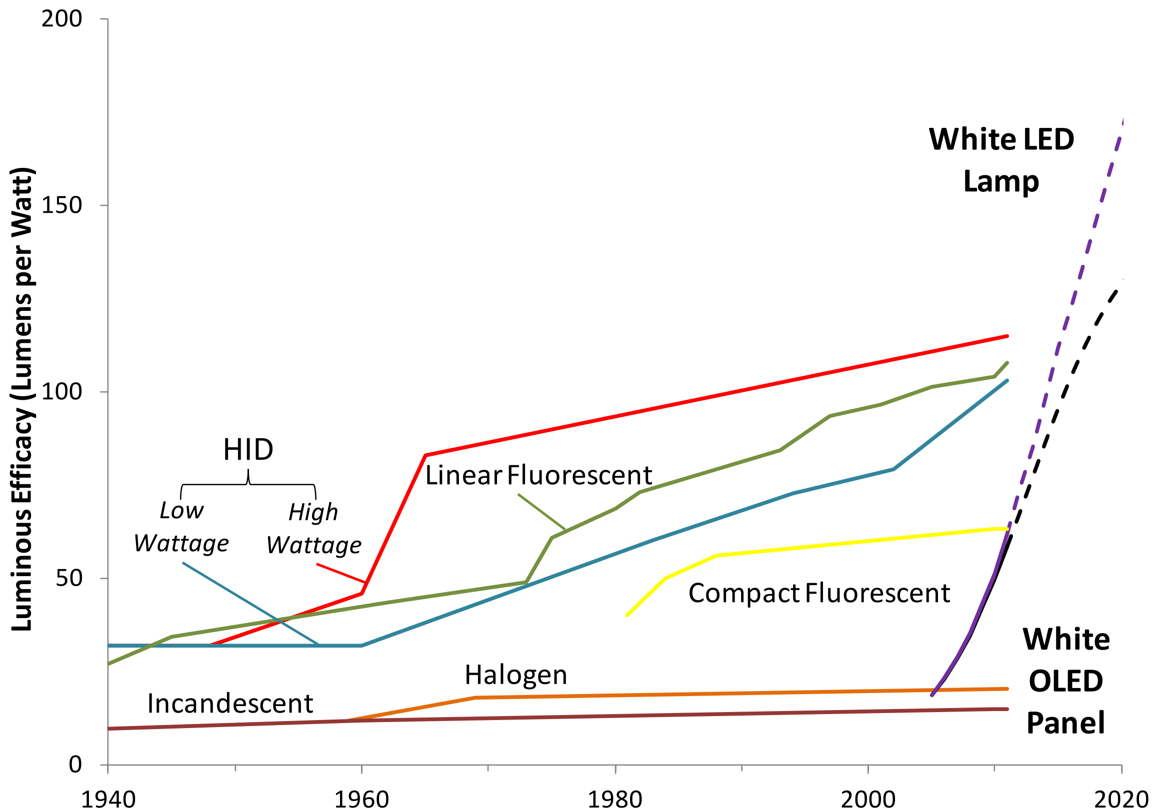

Figure 3.3: Historical and Predicted Efficacy of Light Sources[31]
Source: Navigant Consulting, Inc - Updated Lumileds chart with data from product catalogues and press releases
Note: Efficacies for HID, fluorescent, and LED sources include driver or ballast losses.

Halogen-incandescent, fluorescent (which includes CFLs and linear fluorescent) and HID light sources have evolved to their present performance levels over the last 70 years. As LED and OLED research progresses, these more conventional energy efficient lighting technologies continue to improve in efficacy 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 typically range in efficacy from 10 to 20 lm/W.[32] In an effort to incrementally raise the efficacy of these lamps, basic and applied research is being conducted on advanced infrared reflectors and

[31] LED Luminaire and OLED panel projections based on Section 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;	400 Watt HID lamp (high Wattage);
75 Watt halogen lamp;	100 Watt HID lamp (low Wattage);
15 Watt CFL;	4-foot MBP 32 Watt T8 lamp.

[32] 2010 U.S. Lighting Market Characterization. Prepared by Navigant Consulting, Inc. for the Department of Energy. Washington D.C. January 2012 available at: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/2010-lmc-final-jan-2012.pdf

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.[33] These efficacies are thought to be achievable through combinations of burner design, infrared reflective (IR) coating design and deposition process and, in some instances, filament temperature increase. The latter can be accompanied by reductions in operating lifetime. In a research report for the European Council for an Energy Efficient Economy, typical efficacies of IR coated capsules range from 16 to 26 lm/W. It was claimed that laboratory prototypes have demonstrated efficacies of 45 lm/W;[34] however, these results have not been independently verified.

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. The inclusion of ballast losses results in overall fluorescent system efficacies 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 30 to 120 lm/W, while efficacies for HID systems can be as high as 115 lm/W (see Table 3.1). However, the highest efficacies are often achieved at the expense of color quality. Ceramic metal halide lamps, some of which achieve color rendering comparable to halogen-incandescent and fluorescent light sources, have achieved efficacies as high as 123 lm/W and laboratory results have reported efficacies exceeding 150 lm/W.[35] Further improvements in ceramic metal halide lamps are expected through improved driver efficiencies and breakthroughs in microwave technology.[36]

Commercial LED-based light sources have the potential to surpass the efficacy of the most efficient conventional light sources. Commercially available A19 LED-based replacement lamps typically achieve efficacies of around 70 lm/W but certain products, such as the L-prize winning lamp produced by Philips, are able to achieve values in the 90 to 100 lm/W range. Prototype lamps have also been reported with efficacies exceeding 150 lm/W.[37] An LED-based lamp refers to an integrated assembly comprised of LED packages (components) or LED arrays (modules), LED driver, ANSI standard base and

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[33] Deposition Sciences Incorporated, 2010.

[34] European Council for an Energy Efficient Economy. (2011, March). *Evaluating the potential of halogen technologies*. Retrieved from: http://www.eceee.org/Eco_design/products/directional_lighting/halogen_technologies_report/eceee_report_halogen_technologies

[35] 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.

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

[37] Cree press release. August 2011. Available at: http://www.cree.com/press/press_detail.asp?i=1312203835951

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-based luminaire products with optimized form factors are able to better utilize the inherent benefits of LED technology, and can in principle achieve significantly higher efficacies. A good example is the CR-series troffer introduced by Cree in 2011 which is available in 1ft x 4ft, 2ft x 2ft and 2ft x 4ft variants, and achieves efficacies of up to 110 lm/W at an output of 4,000 lumens.

While the performance of commercially available OLED panels has not yet met lumen output or cost targets, considerable progress has been made within the past year. Panels with efficacies up to 60 lm/W (LG Chem) are shipping as of spring 2012. These energy-saving devices have efficacies surpassing some conventional technologies such as incandescent and halogen lighting and are approaching efficacies of linear fluorescent luminaires. Laboratory efficacies for OLED panels have been reported up to around 66 lm/W (UDC), though smaller (1in x 1in) devices have demonstrated efficacies up to 87 lm/W (Osram), and pixel efficacy has reached 128 lm/W (Panasonic).

As indicated above, SSL offers extraordinary potential, with efficacies far in excess of traditional incumbent incandescent lighting sources. However, costs need to be reduced to further accelerate adoption, and still higher efficacies are needed 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 2011 SSL products on the market[38] 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.

[38] 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 Other Lighting Technologies

Product Type	Luminous Efficacy	Luminous Output	Wattage	CCT	CRI	Lifetime
LED White Package (Cool)	144 lm/W	144 lm	1.0 W	2600-3700K	70	50k hours
LED White Package (Warm)	111 lm/W	111 lm	1.0 W	5000-8300K	80	50k hours
LED A19 Lamp (Warm White) [1]	93 lm/W	910 lm	9.3 W	2727K	93	25k hours
LED PAR38 Lamp (Warm White) [2]	74 lm/W	1,000 lm	13.5 W	3000K	92	25k hours
LED 2'x4' Troffer (Warm White) [3]	110 lm/W	4000 lm	36 W	3500K	90	75k hours
OLED Panel [4]	60 lm/W	76 lm	1.3 W	3500K	80	15k hours
HID (High Watt) Lamp and Ballast	123 lm/W 115 lm/W	38700 lm	315W 337W	3100K	90	30k hours
Linear Fluorescent Lamp and Ballast	118 lm/W 108 lm/W	3050 lm 6100 lm	26W 56W	4100K	85	25k hours
HID (Low Watt) Lamp and Ballast	110 lm/W 103 lm/W	7700 lm	70W 75W	3000K	89	16k hours
CFL	63 lm/W	950 lm	15W	2700K	82	12k hours
Halogen	22 lm/W	1100 lm	50 W	3000K	100	5k hours
Incandescent	15 lm/W	890 lm	60W	2760K	100	1k hours

Notes: *Source: Cree 2012, Philips Lighting 2012, OSRAM Sylvania 2012 product catalogs, LED lamp based on Lighting Facts product registrations.*

1. Based on Philips' L-Prize winning A19 lamp.
2. Based on Lighting Facts Label data for Cree LRP38-10L-30KCree
3. Based on Cree CR24-40L-HE-35K-S.
4. LG Chem, 2012.

- For LED packages (defined in Section 5.1.1) - drive current density = 35 A/cm2, Tj=85°C., batwing distribution, lifetime measured at 70 percent lumen maintenance.
- Sodium lamps are not included in this table.

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 have dropped considerably during 2011 but the challenge facing SSL in the marketplace remains:

Halogen Lamp (A19 43W; 750 lumens)	$2.5	per kilolumen
CFL (13W; 800 lumens)	$2	per kilolumen
CFL (13W; 800 lumens dimmable)	$10	per kilolumen
Fluorescent Lamp and Ballast System (F32T8)	$4	per kilolumen[39]
LED Lamp (A19 60W; 800 lumens dimmable)	$30	per kilolumen[40]
OLED Luminaire	$1,700	per kilolumen[41]

On a normalized light output basis (dollars per kilolumen), LED lamps remain around twelve times the cost of the halogen bulb and around three times the cost of an equivalent dimmable CFL,[42] but the price of LED lamps is expected to continue its rapid decline 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, an increasing number of products and manufacturers have been realized in 2011, demonstrating growth and interest in this technology applied to lighting. 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[43] in actual operating environments. These economic analyses use the National Institute of Standards and Technology (NIST) has developed the Building Life-Cycle Cost software, which calculates the lifecycle costs for energy conservation projects that have significant upfront costs, but save energy over the long term. A good example is the assessment of LED retrofit lamps for the San Francisco Intercontinental Hotel reported in November 2010. This study concerned the replacement of 287 existing 20W premium halogen MR16 lamps and 40W PAR30 lamps with LED equivalents rated at 6W and 11W 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 LED lamps reduce, 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

[39] 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 2011 prices.
[40] Philips EnduraLED A19 with a typical selling price of $39.97.
[41] Revel 6400 from Acuity Brands as announced in March 2012
[42] Because LEDs can be more directional than conventional technologies, comparing them on a 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.
[43] 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 3.4 shows a comparison of an integrated white light LED replacement lamp to a 13W compact fluorescent lamp, and to the current MYPP projection. The most aggressive pricing is associated with A19 style 60W equivalent replacement lamps and the figure reflects typical retail prices for such lamps. It should be noted that these prices have been lowered further in certain regions of the U.S. through subsidies. During 2011 we have seen a marked reduction in prices as manufacturing costs are reduced and competition intensifies. Typical retail prices have dropped to around$16 for a 400 lumen (40W equivalent) warm white A19 replacement lamp and around $24 for an 800 lumen (60W equivalent) product. As a consequence, normalized prices in 2011 have dropped to around $30/klm, somewhat ahead of the MYPP projection as illustrated in Figure 3.4. Further price reductions are anticipated during 2012 with one company predicting a price as low as $15[44] corresponding to a normalized price of around $19/klm.

Price reductions have also continued for directional PAR and MR16 style lamps. For MR16 lamps these reductions have been most dramatic for the higher light output versions with prices in the $25 range for 415 lumen (35W equivalent) MR16 lamps. Prices for PAR style lamps have dropped into the $25 to $30 range for a 17 to 18 W PAR38 lamp (750-850 lumens). Downlights have also benefited from significant price reductions with products now available for as little as $37 ($50/klm).

Resistance to the first-cost price barrier is less of an issue in the commercial/industrial sector where greater emphasis is placed on lifecycle costs. Nevertheless, the payback period is continuing to shorten as new products are introduced with improved efficacy.

Outdoor lighting is another area where lifecycle costs are an important consideration. Over the past few years the base price for LED-based outdoor fixtures providing around 8,000-10,000 lm (i.e. typical replacements for 150W High Pressure Sodium or 175W Metal Halide) has dropped from around 150 $/klm to around 80 $/klm and the efficacy has increased from around 50 lm/W to around 80 lm/W. In conjunction with the reduced maintenance overhead and lower power consumption, the simple payback period for many installations has reached around 8-10 years.[45]

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[44] Lighting Science Group Press Release “Lighting Science Group's New 60-Watt Equivalent LED World Bulb Receives Consumer Electronics Show Innovations Honor”, December 9, 2011 http://investor.lsgc.com/releasedetail.cfm?releaseid=632244
[45] http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/2011_gateway_fdr-drive.pdf

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.

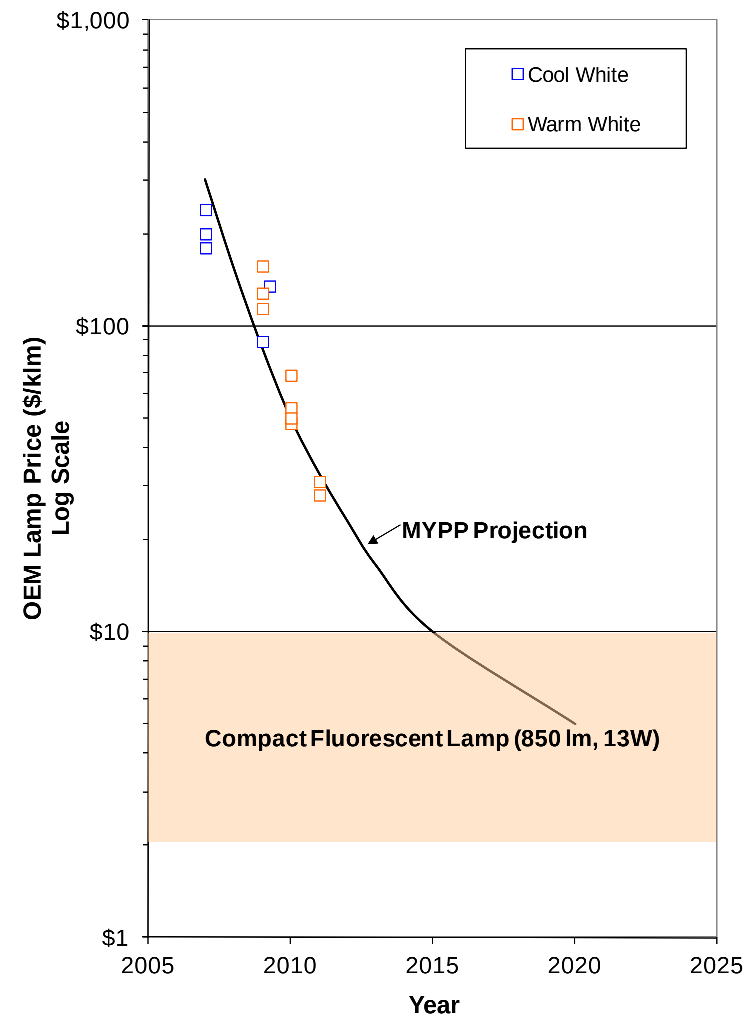

Figure 3.4: White Light Integrated LED Lamp Price Projection (Logarithmic Scale)
Note: Assumes current prices for compact fluorescent price range (13W self-ballasted compact fluorescent; non-dimmable at bottom, and dimmable at top).

3.5.2 LED Package Prices

The following price estimates represent typical retail prices for LED packages purchased in quantities of 1,000 from major commercial distributors such as Digi-Key, AVNET, Newport, and Future Electronics. Each LED manufacturer produces a number of variants for each package design covering a range of color temperatures and lumen output. The selected data represents devices in the highest efficacy bins, 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 and a temperature of 25°C unless otherwise indicated.

The changes in 2011 have been more modest. Prices have continued to fall, but the performance has tended to stagnate, especially for cool white LED packages. This behavior is illustrated in Figure 3.5. 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 approximate mean and standard deviation of each distribution. The distributions are tighter for 2011 and generally fall within the 2010 distributions but show a distinct shift to lower prices. For warm white LED packages we have seen a modest overall improvement in both efficacy and price, with the price at \$12/klm and the efficacy at 99 lm/W (Cree XM-L). For cool white LED packages the prices are in good agreement with the 2011 MYPP projection at \$8/klm and the efficacy is 124 lm/W (Philips Lumileds Rebel) compared with a projection of 135 lm/W. The price-efficacy projections are included in Figure 3.5 for comparison purposes. It should be noted that significant progress on efficacy reduction has occurred during the first few months of 2012 with values of 111 lm/W for warm white and 144 lm/W for cool white reported (Cree XT-E), in excellent agreement with the revised projections. Also noteworthy is the fact that many recently introduced products such as the Cree XT-E are routinely measured at 85°C rather than 25°C, with operation at the higher temperature normally introducing a reduction in efficacy by around ten percent.

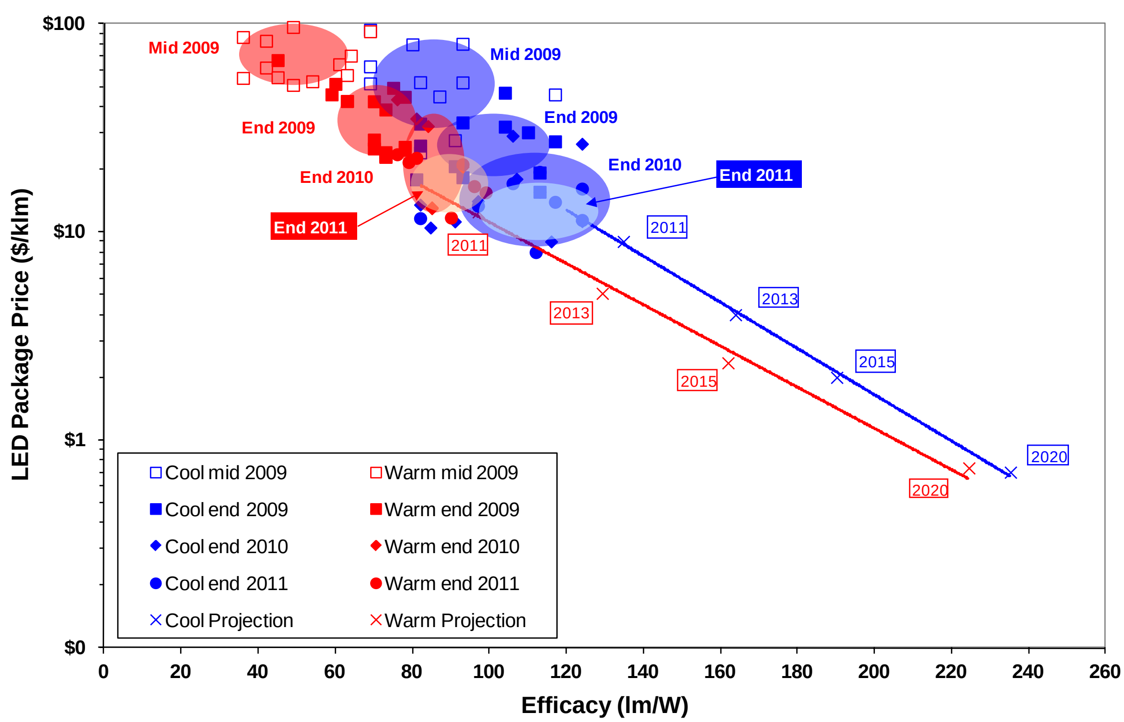

Figure 3.5: Price-Efficacy tradeoff for LED Packages at 35 A/cm^2

Notes:

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	2011	2013	2015	2020	Goal
Cool White Efficacy (lm/W)	135	164	190	235	266
Cool White Price ($/klm)	9	4	2	0.7	0.5
Warm White Efficacy (lm/W)	98	129	162	224	266
Warm White Price ($/klm)	12.5	5.1	2.3	0.7	0.5

Notes:

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 percent lumen maintenance at a drive current density of 35 A/cm^2.

3.5.3 OLED Costs

Figure 3.6: Revel™ OLED Panel Clusters
Source: Acuity Brands

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. In 2011, the cost per kilolumen varied from about $2,500 to $25,000, with the Hanger lamp from Lumiotec at the lower end of this range. The first good indicator of future OLED costs may come from the Revel luminaire from Acuity Brands (see Figure 3.6), which should reach the market in the US early in the second quarter of 2012. The fixture contains five 4” panels from LG Chem in Korea, with a total active area of 405 cm^2. Preliminary guidance on the market price of the luminaire was $600 for a system providing 360 lumens.

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.

Making the lamps brighter by increasing the drive current generally leads to significant reduction in operating lifetime. For example, Lumiotec claims a half-life (L_{50}) of 100,000 hours for their panels from a luminance of 1,000 cd/m^2, but only 20,000 hours from 3,000 cd/m^2. Starting from this higher luminance, values of L_{70} of 10,000 hours or more have been claimed by several companies, including LG Chem, Philips and Panasonic.

Manufacturing improvements to reduce the cost of OLEDs from the 2012 target of $180 will be discussed in the 2012 update to the Manufacturing Roadmap. However, design changes can facilitate the achievement of lower costs. These include:

- Structural simplification, for example through the use of fewer layers
- Use of solution-processable materials to reduce waste
- Minimization of patterning requirements
- Development of materials that are less sensitive to O_2 and H_2O
- Yield improvement through layer thickness control or structures allowing for larger variations
- Yield improvement through robust architectures (for example, using planarization layers to reduce shorts in devices)
- Higher efficacy through the use of advanced materials, architectures (usually complex), and extraction techniques

While some designers emphasize the cost reductions that come from simple structures, others argue for larger numbers of layers, primarily to increase efficacy and lifetime. For example, the use of tandem or stacked OLED structures (as shown in Figure 3.1c) with separate regions for creating light reduces the required current density, which can have a significant effect in slowing device degradation.

Similarly, while vapor deposition techniques have provided devices of highest performance, many groups are exploring the use of solution deposition techniques for some or all of the organic layers (and in some cases the electrodes as well). Solution deposition techniques such as printing, can improve materials utilization, and reduce manufacturing equipment costs. Efficient printed OLED devices have been realized with efficacy 52 lm/W and lumen maintenance (L_{50}) of 20,000 hrs at 1,000 cd/m^2 (Mitsubishi/Pioneer).

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 Section 5.0.

4.1 Current SSL Project Portfolio

This section provides an overview of the current projects in the SSL portfolio (as of March 2012). The SSL Project Portfolio is grouped into six topic areas.[46]

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 Section 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[47]

Figure 4.1 presents the congressional appropriation for the SSL portfolio from FY2003 through FY2011 and the FY2012 appropriation request. The funding received for the 2011 fiscal year (FY2011, which began in October 2010) totaled $26.5 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 $25.8 million in funding for FY2012. As of the date of this publication, the 2012 Federal budget is operating under a continuing resolution, while Congress completes negotiations on a final agreement for the remainder of fiscal year 2012.

[46] 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.
[47] Figures and charts in this section may not sum to stated cumulative values due independent rounding.

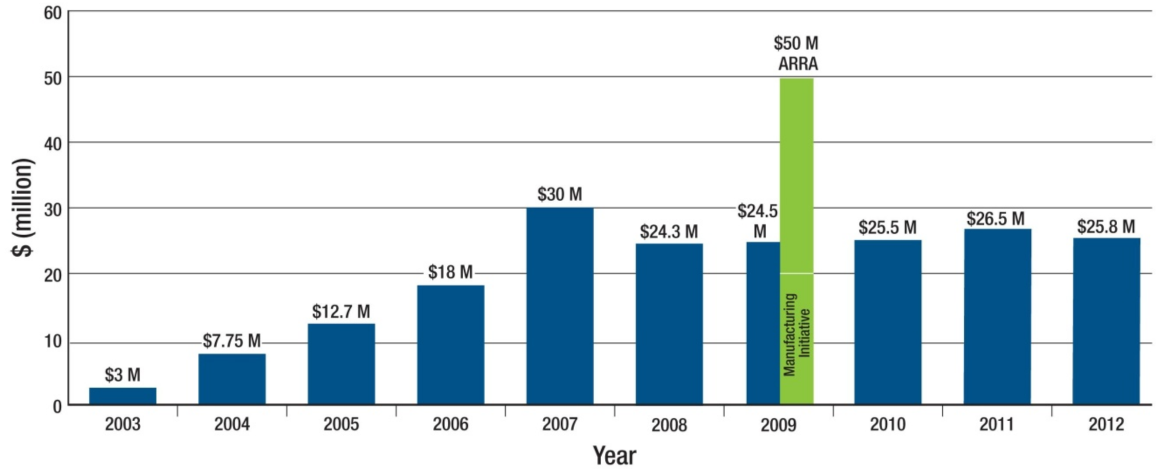

Figure 4.1: Congressional Appropriation for SSL Portfolio, 2003-2012

The active DOE SSL R&D Portfolio as of March 2012 includes 37 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 $110.3 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 2012. DOE is currently providing $64.5 million in funding for the projects, and the remaining $45.8 million is cost-shared by project awardees. Of the 37 projects active in the SSL R&D portfolio, 23 are focused on LED technology and 14 are focused on OLEDs.

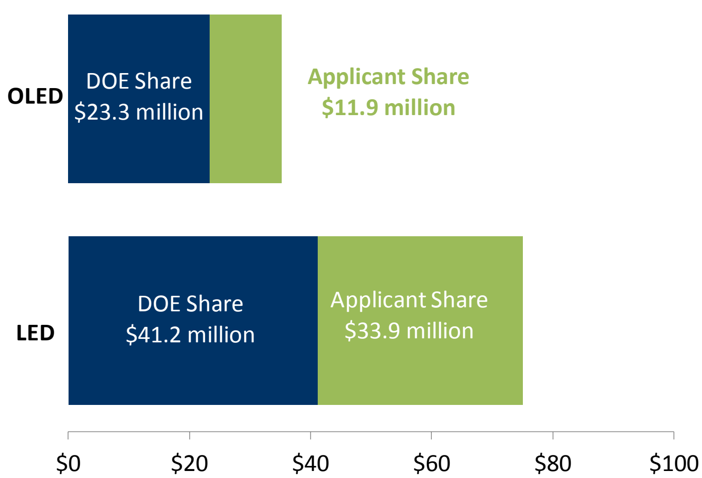

Figure 4.2: Funding of SSL R&D Project Portfolio by Funder, March 2012

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; 32 projects receive $105.4 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 five projects for a total of $4.9 million.

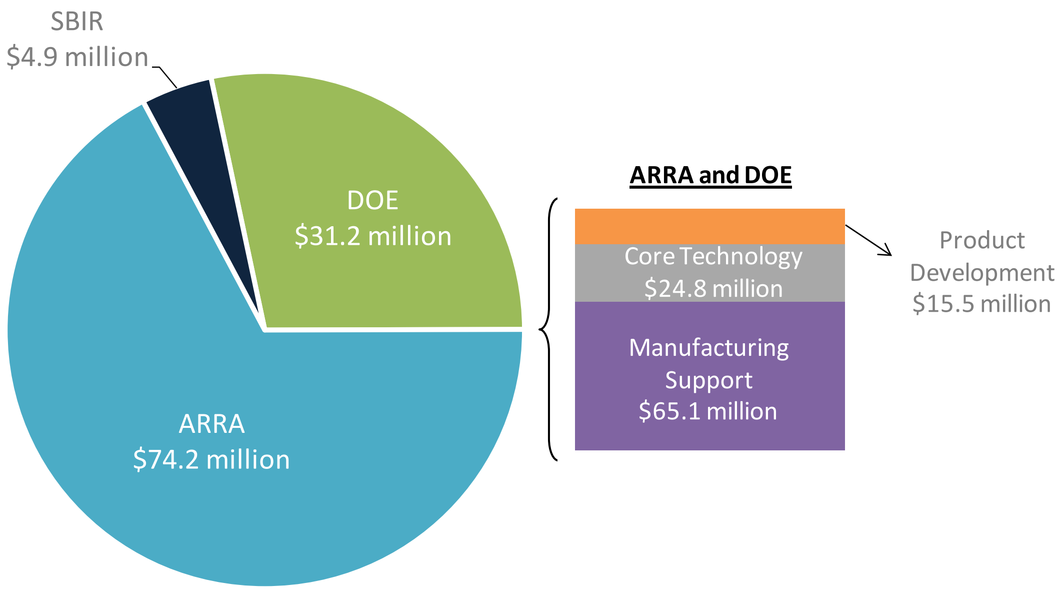

Figure 4.3: Cumulative SSL R&D Portfolio Funding Sources, March 2012

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 67 percent of portfolio funding, with $74.3 million in R&D activities. Small businesses comprise the next largest category and receive 20 percent, or $21.8 million, in research funds. Finally, universities and national laboratories comprise nine percent and four percent of the R&D portfolio and receive $9.8 million and $4.4 million, respectively.

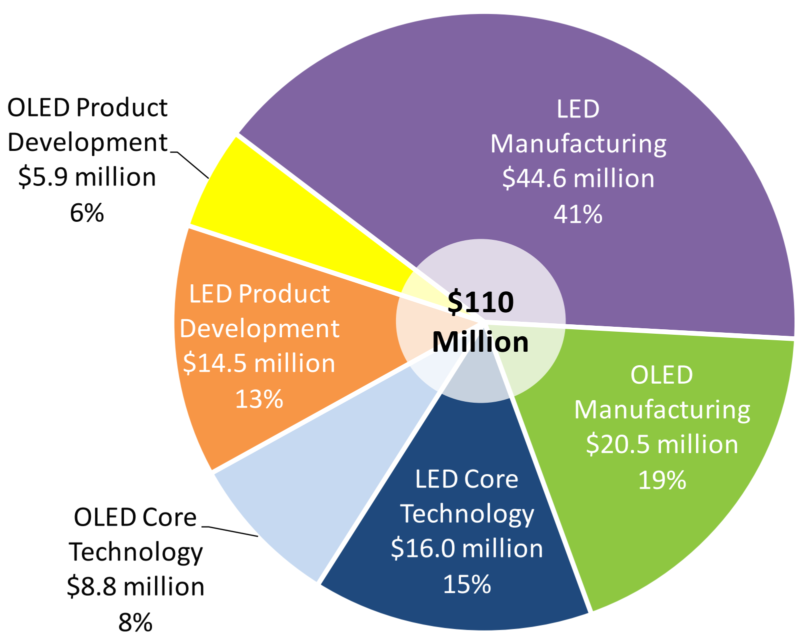

Figure 4.4: DOE SSL Total Portfolio Summary, March 2012

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 4.1 shows 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: 15 Core Technology Projects, April 2012

	Number of Projects	**$ Funding (Million)**
Light-Emitting Diodes		
Emitter Materials	5	$8.4
Down-Converters	2	$3.5
Optical Component Materials	1	$2.0
Optimizing System Reliability	1	$2.1
Total LED	**9**	**$16.0**
Organic Light-Emitting Diodes		
Novel Materials	4	$4.2
Electrode Research	1	$2.0
Light Extraction Approaches	1	$1.5
Total OLED	**6**	**$7.7**
TOTAL	**15**	**$23.8**

Table 4.2: SSL R&D Portfolio: 13 Product Development Projects, April 2012

	Number of Projects	**$ Funding (Million)**
Light-Emitting Diodes		
Substrate Development	1	$0.2
Semiconductor Materials	3	$6.9
Phosphors	1	$2.5
LED Thermal Management	1	$1.0
Luminaire Thermal Management Techniques	2	$4.1
LED Driver	1	$2.3
Total LED	**9**	**$17.0**
Organic Light-Emitting Diodes		
Substrate Materials	1	$2.1
Large Area OLED	1	$2.0
Panel Outcoupling	2	$1.8
Total OLED	**4**	**$5.9**
TOTAL	**13**	**$22.8**

Table 4.3: SSL R&D Portfolio: Current LED Research projects, April 2012[48]

Research Organization	Project Title
Cree, Inc.	High Efficiency Integrated Package
Cree, Inc.	Ultra-Compact High-Efficiency Luminaire for General Illumination
Eastman Kodak	High Efficiency Colloidal Quantum Dot Phosphors
General Electric	Optimized Phosphors for Warm-White LED Light Engines
National Renewable Energy Laboratory	Lattice Mismatched GalnP Alloys for Color Mixing White Light LEDs
Osram	High-Flux Commercial Illumination Solution with Intelligent Controls
Philips Lighting	High Efficiency Driving Electronics for General Illumination LED Luminaires
Philips Lumileds	High Power Warm White Hybrid LED Package for Illumination
Philips 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
Research Triangle Institute	System Reliability Model for SSL Luminaires
Sandia National Lab	Semi-Polar GaN Materials for High IQE Green LEDs
Soraa	Light Emitting Diodes on Semi-Polar Bulk GaN Substrate with IQE>80 percent at 150A/cm2 and 100°C
Soraa	Development of High Efficiency m-Planbe LEDs on Low Defect Density Bulk GaN Substrates
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

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

Table 4.4: SSL R&D Portfolio: Current OLED Research Projects, April 2012[48]

Research Organization	Project Title
Arizona State University	High Efficiency and Stable White OLED Using a Single Emitter
Cambrios	Solution-Processable Transparent Conductive Hole Injection Electrode for Organic Light-Emitting Diode (OLED) SSL
PNNL	Development of Stable Materials for High-Efficiency Blue OLEDs through Rational Design.
PPG Industries	Low Cost Integrated Substrate for OLED Lighting Development
University of Florida	High Triplet Energy Transporting Materials and Increased Extraction Efficiency for OLED Lighting
University of Rochester	Light Extraction from OLEDs Using Plasmonic Nanoparticle Layers to Suppress Total Internal Reflection
University of Rochester	Development and Utilization of Host Materials for White Phosphorescent OLEDs

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,* [49] 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 is 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. SSL sources are now available for the general illumination market, replacing some of today's lighting technologies in specific applications. In spite of a decline in sales for the overall lighting products market in 2011, sales of the LED lamps and luminaires grew 69 percent. According to Strategies Unlimited the LED lighting market's total revenue grew from $5.5 billion in 2010 to $9.4 billion in 2011.[50] Strategies Unlimited forecasts LED revenues to peak at $16.2 billion in 2014, dipping slightly to $15.3 billion in 2015.[51] The revenue decrease in 2015 is expected to be short-lived as lighting will be the primary driver for growth in the LED market after 2015.

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. 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 FY2012 began with a series of roundtable sessions convened in Washington, D.C. in November 2011. 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 Atlanta, Georgia at the beginning of February 2012. 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 2012. After subsequent review, and considering inputs received at the workshop, DOE has defined the task priorities for 2012 as listed in Sections 5.2 (LEDs) and 5.4 (OLEDs).

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[49] The *SSL Research and Development: Manufacturing Roadmap,* can be found at: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_manuf-roadmap_july2011.pdf

[50] LEDs Magazine, 2012 LED lighting experienced strong growth surge in 2011, http://www.ledsmagazine.com/news/9/2/9

[51] Strategies Unlimited, Strategies Unlimited Forecasts LED Revenue to Peak at $16.2B in 2014, http://www.strategies-u.com/articles/press-releases/forecasts-led-revenue-to-peak.html

5.1 Light Emitting-Diodes

Significant progress has continued to be made in the development of LED-based SSL over the past year. Many new replacement lamp and luminaire products have reached the market with improved efficiencies and reduced costs. Progress is especially pronounced in the price competitive consumer replacement lamp market where the retail price for a 60W A19 dropped from around $40 to $25 by the end of 2011. Sales volumes have continued to rise with Lighting Science Group reporting that it had surpassed the 4.5 million LED bulb manufacturing milestone in 2011 to become North America's largest producer of LED light bulbs. This represents a 450 percent increase compared with 2010. Improvements in LED package efficacy have been less prominent during the past year while the primary focus has been on implementation and cost reduction. 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[52] Addendum b, as updated and released in 2009.

Component level (no power source or driver)

- <u>LED</u> refers to a p-n junction semiconductor device (also referred to as chip) that emits incoherent UV, visible, or infrared radiation when forward biased.
- <u>LED Package</u> 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

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

standardized base are not incorporated into the device. The device cannot be connected directly to the branch circuit.

- LED Array or Module refers to an assembly of LED packages (components), or dies on a printed circuit board or substrate, possibly with optical elements and additional thermal, mechanical, and electrical interfaces that are intended to connect to the load side of a LED driver. Power source and ANSI standard base are not incorporated into the device. The device cannot be connected directly to the branch circuit.

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), Cree (Luminaire – Troffer 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 2011 for individual luminaire and LED packages to the 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 allocation of 2011 efficiency values among the various sources of loss together with the program goals 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.* In particular, in order to record and forecast progress, the tables and charts this chapter employ a specific set of assumptions about drive current density, operating temperature, and color metrics for "warm" versus "cool" white light as follows:

- Current drive: So as to achieve 35A/cm^2 (depends on current and chip size) some reported data has been re-normalized
- Color temperature: For "warm" white, 2580K to 3710K; for "cool" white, 4746K to 7040K.
- Color rendering index: For "warm" white, >80; for "cool" white, >70
- For the efficiency bar charts and efficacy asymptotes: CCT = 3000K; CRI = 85.

In part, these selections were made to allow tracking of historical data; where the parameters above are known, or if the data can be re-normalized to comply, then the data point is called "qualified". One consequence of these choices is that the charts may therefore not reflect the "best" reported results, which can lead to some confusion. To address this issue in part, a new chart has been added in Section 5.1.3 showing the anticipated effects over time of changing the assumption about the current drive.

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;[53]
- *Light Extraction efficiency* is the ratio of photons emitted from the semiconductor chip into the encapsulant to the total number of photons generated in the active region. This includes the effect of power reflected back into the chip because of index of refraction difference, but excludes losses related to phosphor conversion;
- *External quantum efficiency*, EQE, is the ratio of extracted photons to injected electrons.[54] 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

[53] 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).

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

controls needed to adjust for changes in conditions (e.g. temperature or age) so as to maintain brightness and color or for active control of the lighting system;

- *Additional EQE current droop* represents the ratio of EQE (at 25°C) at a current density of 100 A/cm^2 as compared with 35 A/cm^2. Packages are often operated at higher current densities in order to minimize the number of packages required to achieve a specific lumen output. Increasing the current density currently results in reduced efficiency due to additional EQE current droop. Reducing the droop sensitivity of the LED can reduce this additional loss;
- *Flux thermal stability* is the ratio of the lumens emitted by the LED package in thermal equilibrium under continuous operation in a luminaire to the lumens emitted by the package as typically measured and reported in production at 25°C.[55] 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 program goal. 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 35 A/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.

[55] 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.

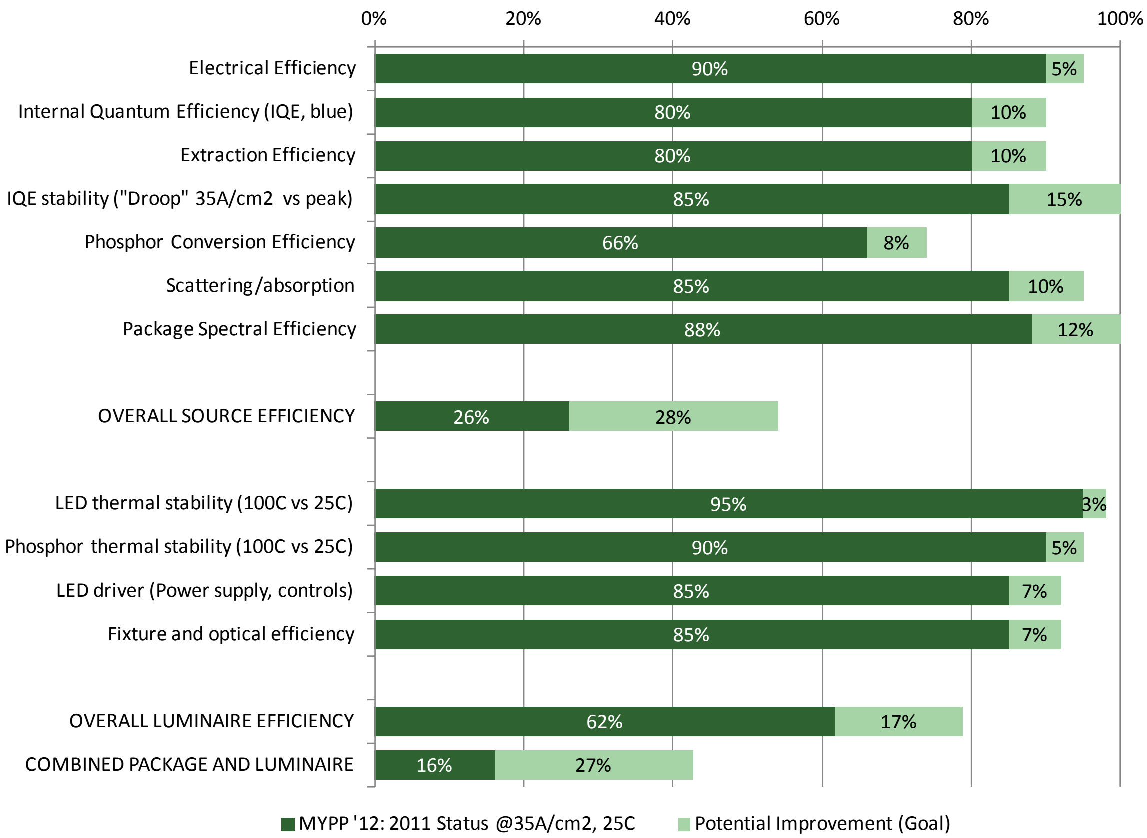

Figure 5.2: pc-LED Package and Luminaire Loss Channels and Efficiencies

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 percent 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 percent 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 of IQE 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 normalized 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. In addition, alternative design approaches offer an effective route to the elimination or amelioration of some of these loss components. For example, using lower operating currents would minimize the IQE stability loss although there would be a cost implication due to the need for additional LED packages to achieve the same lumen output.

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

Metric	2011 Status	Goal
Optical Power Conversion Efficiency	49%	77%
Phosphor Conversion/Scattering	56%	70%
Spectral Efficiency	88%	100%
LED Package Efficiency[56]	26%	54%
LED Package Nominal Efficacy (lm/W)	*98*	*199*
Luminaire Efficiency	62%	79%
Luminaire Efficacy (lm/W)	*61*	*157*
COMBINED SOURCE/LUMINAIRE	*16%*	*43%*

Note: Luminaire efficiency is calculated for normalized operating conditions and 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 seriously limits the capability color-mixed LEDs today.

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

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

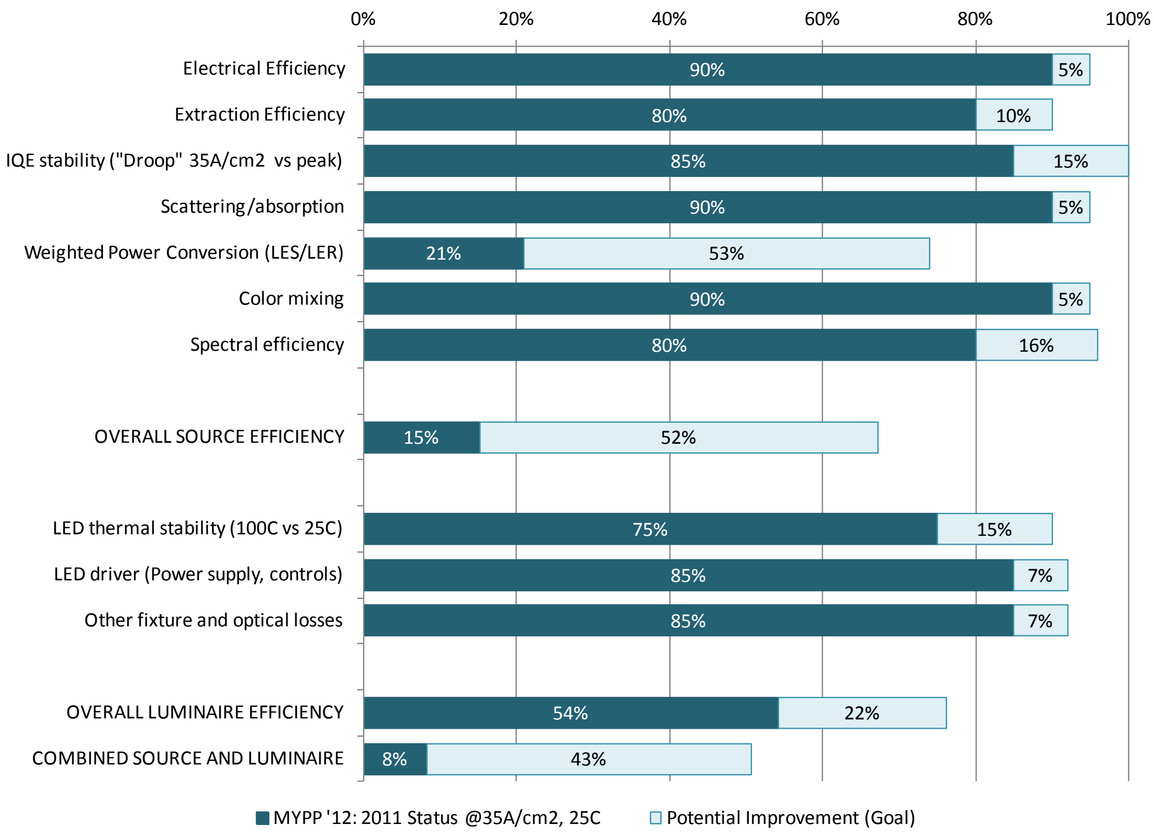

Figure 5.3: Color-mixed LED Package and Luminaire Loss Channels and Efficiencies

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 5.7, 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 percent across the visible spectrum, bringing the total package conversion efficiency to 67 percent. 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	2011 Status	Goal
Optical Power Conversion Efficiency	19%	69%
Spectral Efficiency	80%	96%
LED Package Efficiency	15%	67%
LED Package Nominal Efficacy (lm/W)	*97*	*266*
Luminaire Efficiency	54%	76%
Luminaire Efficacy (lm/W)	*52*	*202*
COMBINED SOURCE/LUMINAIRE	*8%*	*51%*

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

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 percent 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.

5.1.3 LED Package Efficacy Projections

This section explores the limits of LED package efficacy, assuming certain technological improvements in line with the assumptions in the previous section and provides some projections for improvement over time and eventual practical limits.

The performance of white light LED packages depends on both the CCT of the package and on the CRI objective. In this report the designation of color temperature ranges as cool, neutral and warm reflect the designations assigned to ANSI binning ranges.[57] As every case cannot be examined, efficacy projections and program targets have been grouped into two bands: one for cooler CCT (4746K to 7040K) with CRI=70-80, and the other for warmer CCT (2580K to 3710K) with CRI = 80-90. These groupings have been representative of lighting applications in the past where cooler color temperatures are typically used where color rendering is of lesser interest, while warmer temperatures have been used mainly for interior applications where color quality is more important. Many assumptions like this one may fairly be called into question as SSL products begin to enter the market in large numbers. However, the groupings do still provide an indication of the range of practical efficacies likely to be achieved as the technology evolves. As we will show below, however, ultimately we expect there will be no substantial difference in the efficacies of warm and cool LEDs as various barriers are overcome. In fact, although there are some substantial technology issues in the way, with

[57] ANSI C78.377-2008

improvements in spectral efficiencies as outlined in this report, it is possible that warm LED efficacies could be higher than for cool LEDs.

A bigger difference in efficiency performance is evident in the choice of phosphor-converted (pc) LEDs versus true color mixing. Because there is no efficient green LED available today, virtually all LEDs on the market use the pc approach. Recognizing that fact, we have provided this year an estimate of the maximum efficacy of a packaged pc-LED as well as the projection for the theoretically-highest efficacies achievable with color-mixing. In making these calculations, we simulated the phosphor using NIST's 4-color LED model, but assuming broad green and amber phosphor spectra and a narrower red line to improve spectral efficiency. The results, as detailed below, show that the pc-LED efficacy will top out around 199 lm/W for packaged LEDs (at standard current density), while color-mixing has the potential to approach an efficacy about 33 percent higher. The improvement in pc-LEDs from today's value for commercial product (around 144 lm/W) is essentially made possible by the narrower red phosphor and optimization of the resulting spectrum. Stokes' loss, however, remains as a fundamental limitation for pc-LEDs.

Maximizing luminous efficacy of radiation

A starting point is the theoretical maximum efficacies of an SSL product *given perfect conversion of electricity to light*. This "ideal" performance is characterized by the Luminous Efficacy of Radiation, or LER, which is the useful light in lumens obtained from a given spectrum per Watt. Work by Yoshi Ohno and Wendy Davis at NIST[58] 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. We have used NIST's model (v 7.5) to estimate efficacies for a number of CCT/CRI combinations, both for narrow-band monochromatic LEDs (color-mixed) and by simulating a phosphor using a combination of broadband "LEDs" and a narrow-band pump. Efficacies are optimized by varying the relative intensities and central wavelengths of the spectral components. Table 5.3 shows LER_{max} as computed with this model for a range of choices for CCT and CRI, and the resulting package efficacy for assumed overall package conversion efficiencies of 67 percent, the estimated potential maximum conversion efficiency for color mixing (Table 5.3). These figures assume a moderate (approximately 20nm) full width at half maximum (FWHM) of the LED emission in a RGBA configuration for all colors. Under these conditions, the analysis suggests that warm white LEDs could have higher efficacies than cooler ones. As noted in the footnotes to the tables and charts in the previous section, program targets assume a CCT of 3000K and a CRI of 85, for which the maximum LER is about 397 lm/W. For 67 percent conversion from electrical to optical

[58] Y. Ohno, Color Rendering and Luminous Efficacy of White LED Spectra, Proc., SPIE Fourth International Conference on Solid State lighting, Denver, CO, August 2004, 5530, 88-98 (2004).
Y. Ohno, Spectral Design Considerations for Color Rendering of White LED Light Sources, Opt. Eng. 44, 111302 (2005).
W. Davis and Y. Ohno, Toward an Improved Color Rendering Metric, Fifth International Conference on Solid State Lighting, edited by Ian T. Ferguson, John C. Carrano, Tsunemasa Taguchi, Ian E. Ashdown, Proc. SPIE Vol. 5941, 59411G (2005).

power, the luminous efficacy of the source is about 266 lm/W. That value serves as an "asymptote" in time for what we consider to be "reasonably" achievable for practical devices. However, it is worth noting that this limit could only be reached by both improving electrical to optical conversion as outlined in Section 5.1.2, *AND achieving efficient LED emission for all four colors*. It is worth noting that little progress has been made on the latter despite several years of effort.

Table 5.3: Estimated Efficacies as a Function of CCT and CRI - Color mixed LEDs (lm/W)

cm-LED	Maximum LER			Efficacy for 67% Conversion		
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

In the case of pc-LEDs, broad phosphor spectra emit a considerable amount of the long-wavelength energy outside the visible spectrum, resulting in spectral inefficiency. Additionally, Stokes' loss constitutes an additional and unavoidable loss channel.
In order to explore the potential benefit of a narrower red emission band, and to estimate the effects of otherwise optimizing the phosphors, we simulated a pc-LED spectrum again using the four-color LED NIST model,[59] this time assuming broader line widths (FWHM) as follows: blue - 15nm; green - 110 nm; amber - 140nm; red - 30nm. Current red phosphor line widths are typically around 150nm by comparison, limiting efficacy.

In addition to these assumptions about spectral width, we also estimated Stokes' efficiency at 82 percent by assuming that the mean phosphor emission is around 580nm for all solutions. In fact, this is a rather coarse assumption, since the emission generally has a two-peak characteristic in which the red peak intensity is about 1.5 to three times that of the green (Figure 5.4). The 30nm red phosphor emission decidedly reduces the spillover out of the visible spectrum and thus would considerably improve package efficacy beyond what we typically see today while still maintaining the simplicity of a phosphor solution.

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

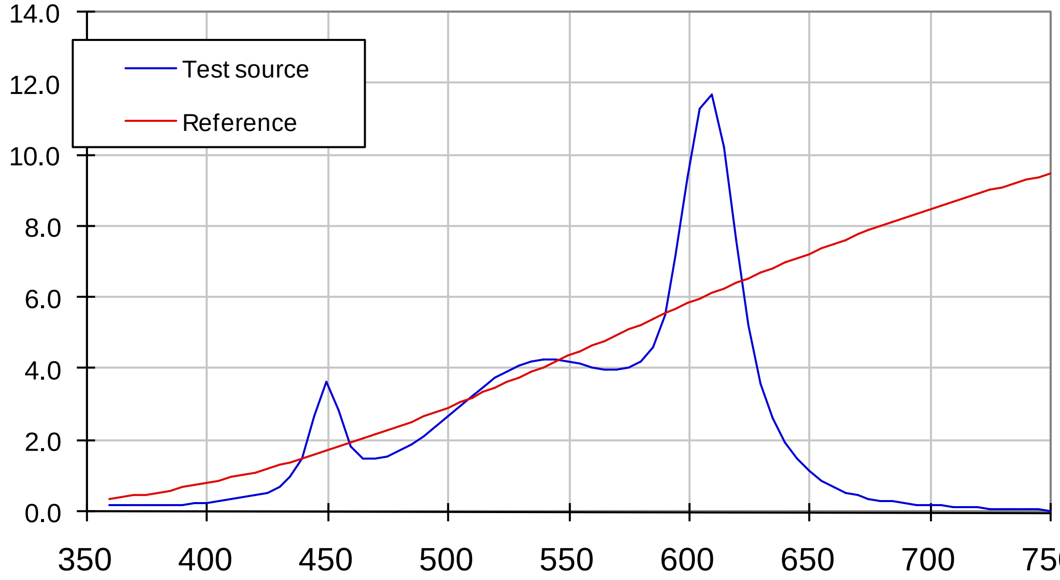

Figure 5.4: Simulated pc-LED spectrum compared to black body curve (3000K, 85 CRI)

Simulation results for several combinations of CCT and CRI are indicated in Table 5.4. The electrical-to-optical conversion efficiency assumed for this table is a uniform 54 percent across all combinations, arrived at by multiplying the 67 percent conversion assumed for color mixing by 82 percent, the estimated reduction due to Stokes' loss. This is an admittedly crude approximation. A detailed analysis would integrate the Stokes' contribution under the entire spectrum and would thus vary depending on peak wavelengths and relative intensities. The overall effect would be to reduce efficacy somewhat for high-CRI or low-CCT while increasing it for low-CRI or high-CCT packages, generally reducing the spreads. Again using the assumption of 3000K and 85 CRI as a typical central value for projections, we arrive at an "average" asymptote for projections of about 199 lm/W for the phosphor conversion case.

Table 5.4: Estimated efficacies - Phosphor-converted LEDs (lm/W)

pc-LED	**Maximum LER**			**Efficacy for 54% Conversion**		
CCT	**CRI 70**	**CRI 85**	**CRI 90**	**CRI 70**	**CRI 85**	**CRI 90**
5000	350	337	332	189	182	179
3800	369	352	350	199	190	189
2700	391	371	363	211	200	196

Projections of efficacy

Figure 5.5 shows anticipated package efficacy improvement (progress) over time based on experience to date. In contrast to versions of this figure shown in earlier editions of the MYPP, we no longer include "laboratory" data or a projection for it on this chart, but we have added projections for pc-LED solutions. 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. In the past, however, they have provided a useful preview of actual products appearing a few years later. But at this point they no longer provide very much insight. The data indicated, therefore, all represent commercial products.

Data points shown in this figure are all "qualified", i.e. within the parameters defined in the footnotes for "cool" or "warm" white. In prior years we have also shown data that is not qualified, meaning one or more parameters is either outside the indicated limits, or values are unknown. At this point we have sufficient qualified data that it is no longer necessary to show the others. To show anticipated progress over time, we use a logistic fit to the data points with an assumed upper asymptote derived as explained above. The curves have been fit using the "best in class" qualified data points, augmented by the best non-qualified points in years prior to 2009. All of the data points are for pc-LED solutions.

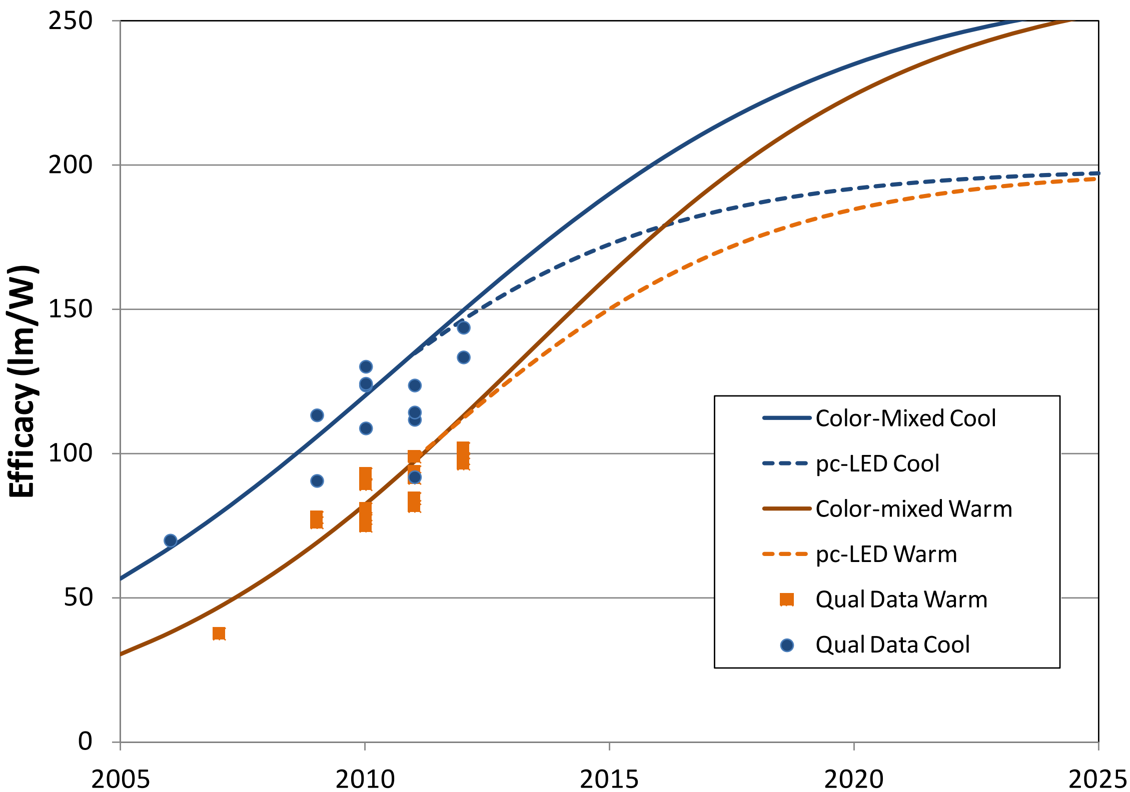

Figure 5.5: White Light LED Package Efficacy Projections for Commercial Product

Notes:

1. "Qualified" data points are confirmed to satisfy the following criteria or may have been normalized for current density if not reported at 35 A/cm^2:
2. Cool White: CRI 70-80; CCT 4746-7040K
3. Warm White: CRI 80-90; CCT 2580-3710K
4. Current density: 35A/cm^2
5. These results are at 25°C package temperature, not steady state operating temperature. Thermal sensitivity may reduce efficacies by as much as 24 percent or so in normal operation, depending on luminaire thermal management.

As noted in the discussions above, the "ultimate" pc-LED efficacy appears to be about 199 lm/W as compared to the color-mixed limit of about 266 lm/W, although up to now the fitted curves are very nearly identical. It is becoming apparent, though, that progress for best-in-class has been slowing for the past couple of years. There has been, however, an increase in the number of offerings approaching the best-in-class. Table 5.5 below provides a tabulation of the projections for selected years.

Table 5.5: Tabulated Progress Projections for LED Package Efficacy (lm/W)

Metric	2011	2013	2015	2020	Goal
Cool White (Color-mixed)	135	164	190	235	266
Cool White (Phosphor)	135	157	173	192	199
Warm White (Color- mixed)	97	129	162	224	266
Warm White (Phosphor)	98	126	150	185	199

Notes:

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. Asymptote for color mixed is 266 lm/W, and for phosphor-converted is 199 lm/W

It is worth noting again that the optimization was achieved by varying both the intensity of each color and its central wavelength. While reasonable solutions (which could have tunable color) can be achieved with a choice of fixed wavelengths and variable intensities, neither the efficacy nor the color rendering is necessarily optimal, and the color point may depart from the black body curve. By way of example and to emphasize this point, Figure 5.6, shows the variation of the red phosphor emission peak necessary to achieve optimal efficacy with CRI for a CCT of 3800K. This variation (different values) applies to some extent for all wavelengths to both color mixing and phosphor conversion, although in the latter case the variation for the green emission is much less.

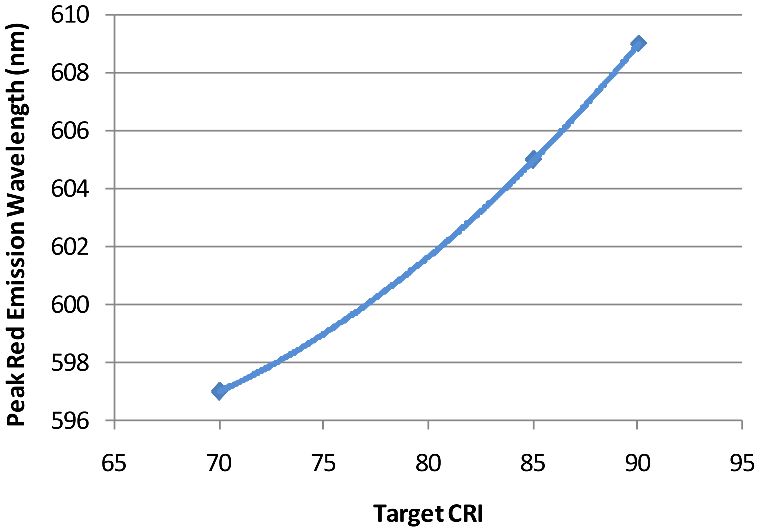

Figure 5.6: Variation in optimal red phosphor central wavelength for a CCT of 3800K

As progress on efficacy (when normalized to the 35 A/cm^2 current density) has been slowing in the last year or two, the latest projection shows a somewhat lower 2020 program target than did last year's report. That fact does not change what might eventually be achieved; of course, it is just a reflection of slower progress.

As noted earlier in this chapter, the normalization of current drive for purposes of comparison to present and historical data does not highlight recently reported results in which lower current drive or larger chip size has been used to reduce the effects of current droop by reducing the current density. Indeed, this is an excellent design solution for high efficacy which is in part made possible by the rapidly declining costs of the LEDs themselves. On the other hand, designs for some applications, particularly those requiring very high total light output, may drive the LEDs harder than the nominal density, resulting in lower efficacy. Figure 5.7 illustrates the anticipated effects of both low (so as to have negligible droop) and high (ca. 3x current densities) as compared to the base case using the assumptions shown in the bar charts about the current state of droop and its evolution. (This is assuming a steady rate of improvement, although we recognize that a more likely scenario might show a step-improvement resulting from some significant breakthrough at some point during the next few years.)

If, as assumed in the efficiency discussions above, current droop is essentially eliminated as a result of efforts between now and the end of the program, then the effect of changing the current density is greatly diminished. But the effect is very significant now and will be for the next several years, with the estimated efficacy in 2012 ranging from roughly 88 lm/W to 140 lm/W.

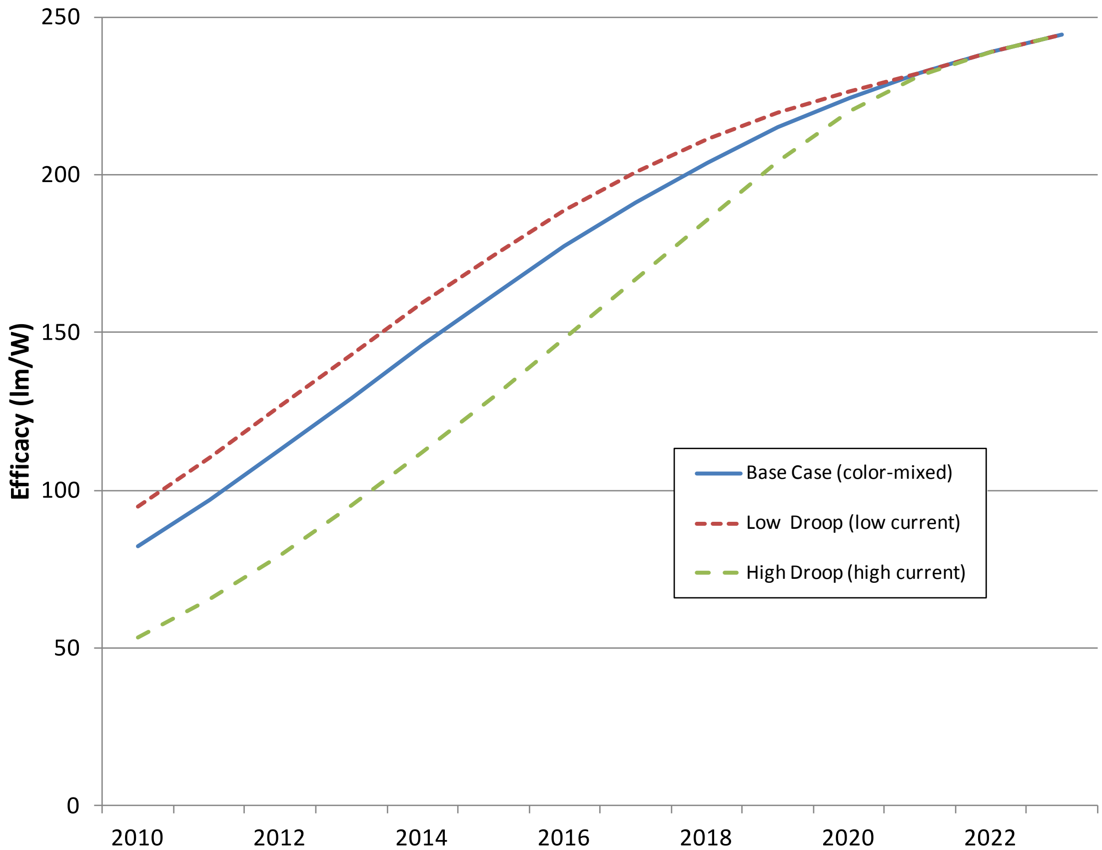

Figure 5.7: Estimated Range of Efficacies Resulting in Variation of Drive Current Densities

Hybrid solutions and other variations

The projections for pc-LEDs do assume ongoing phosphor improvements, especially narrowing the emission spectrum for red (but others too), along with other conversion efficiency improvements that are common to all solutions, especially reduction of droop. The promise of color-mixing has even greater efficiency rewards as the projections indicate, but realizing those depends critically on achieving practical high-efficiency monochromatic emitters at all wavelengths. Typically, too, at least four LEDs are needed for color mixing in order to achieve reasonable CRI particularly for warm white.

In between these two cases, however, lie hybrid solutions which may use pc-LEDs along with, usually, red monochromatic LEDs. This solution, for which there may be a number of variants, offers higher efficacy than a pure pc-LED by providing a narrow source near the edge of the visible band while also eliminating the Stokes' loss associated with conversion to red. These diodes could be packaged together in a conventional package, although it is more common to see them as separate packages on a printed circuit board or they may be even more closely integrated with the luminaire or light engine. Performance of light engines and luminaires using this approach have been excellent and begin to approach what is possible with the more "pure" solutions. Hybrid solutions, along with other developments to improve thermal management and simplify assembly may, in fact, bode the end of the "LED package" as we have come to understand it.

Another recent and now fairly common improvement is to use low drive current density to realize higher efficacy by reducing droop. The diodes may also operate at lower temperatures, easing thermal management and improving lifetimes as well. As a rule, this would require increasing the number of LEDs in a luminaire or using larger LEDs in order to achieve the same total light output. Both approaches are commercially available. The use of lower drive currents, somewhat the opposite of what had been expected a few years ago, has been made increasingly practical by the rapidly falling costs of the LEDs themselves. While efficacy improvement alone would justify a low current approach, prices have fallen fast enough that the cost per lumen may, at least in some cases, fall despite the larger number of diodes.

5.1.4 LED Package Lifetime

The LED package "useful life" has been commonly understood to mean the point at which the lumen output has declined by 30 percent, or "70 percent lumen maintenance", or "L_{70}". Performance in this regard has increased steadily since the program began, and several manufacturers claim that L_{70} is currently above its former target of 50,000 hours with some claiming 100,000 hours of operation or more. Lumen depreciation, in earlier years thought to be the dominant determinant of useful life of an LED package, may not, in fact, be so important. Especially when driven at lower drive currents or operated at lower temperatures, lumen depreciation can be so low as to be difficult to project to the eventual 30 percent point. Many researchers have put a great deal of effort into devising a way to project the time at which L_{70} will be reached,[60] but for the best products the results are questionable.

Useful life of a luminaire may be shorter, sometimes much shorter, than the LED package 70 percent lumen maintenance metric. There are many other potential failure mechanisms. Additional components and subsystems such as the drivers, optical lenses or reflectors can fail independently of the LED. There may also be assembly defects or optics that can lead to a failure. Moisture incursion can be an important determinant of life for an outdoor luminaire. Beyond such wear out mechanisms, poor luminaire design can shorten the life of an LED package dramatically through overheating. Inappropriate drivers may also limit the lifetime of an LED package, hastening lumen depreciation, by overstressing the LED. In the case of traditional commercial lighting products, an early failure rate of perhaps ten percent of product is probably the maximum acceptable value, but with the higher prices of LED products, customers will likely expect a much lower early failure rate.

Many such questions have been explored by an ongoing luminaire reliability study group sponsored by DOE. The most recent publication of that group, *LED LUMINAIRE*

[60] National Institute of Standards & Technology. IES TM-21-11 Overview, History and Q&A Session, http://www.energystar.gov/ia/partners/prod_development/new_specs/downloads/luminaires/TM-21%20Discussion.pdf

LIFETIME: Recommendations for Testing and Reporting (second edition)[61] identified what testing might be necessary to provide a useful estimate of life taking all failure mechanisms into consideration, and provided a working definition. However, the group also concluded that measuring full luminaires (required in principal) is in most cases prohibitively expensive and strongly recommended that the industry cooperate to develop accelerated tests, perhaps at the component or subsystem level, along with suitable means to simulate full system failure rates. This is an important area of work, and there is an identified task for it (research task B.6.3) described in Section 5.2.2. The DOE SSL program is already funding a core task to begin looking at software approaches to simulating failure rates. In parallel, a consortium of manufacturers in the industry, facilitated by DOE, has begun to explore means of gathering the necessary component and subsystem reliability data needed to drive the simulation effort.

5.1.5 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 5.6 are luminaire performance projections to complement the package and lamp performance projections.

Table 5.5 and Table 5.6 assume a more or less linear progression over time from the previous 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, a typical warm white luminaire at the reference drive current in 2011 was capable of achieving 61 lm/W (which is consistent with SSL products on the market). With the present rate of progress, 2020 warm white luminaire efficacies should reach a capability of 170 lm/W, with an end goal of 202 lm/W. Last year the final number for 2020 showed the asymptotic value; this year we show the projection for that year, reflecting actual progress. For the record, we added a column to show the end capability. In future years, we may maintain the projection and just record market results even if they depart from the curves. A purely pc-LED approach would have an end goal of about 151 lm/W. Hybrid approaches will lead to intermediate values between 151 and 170 lm/W and low current drive designs can raise efficacies by about ten percent or more. A hybrid, low current density product could approach the color mixed reference limit (although a low-current density color mixed solution would still be higher).

[61] NGLIA with the DOE. June 2011. Available at: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/led_luminaire-lifetime-guide_june2011.pdf

Table 5.6: Summary of Warm White LED Luminaire Performance Progress Targets

Metric	2011	2013	2015	2020	Goal
Package Efficacy (lm/W)	97	129	162	224	266
Thermal Efficiency	86%	87%	88%	90%	90%
Efficiency of Driver	85%	87%	89%	92%	92%
Efficiency of Fixture	86%	87%	89%	92%	92%
Resultant luminaire efficiency	63%	66%	69%	76%	76%
Luminaire Efficacy (lm/W)	61	85	112	170	202

Notes:

1. Package efficacy projections are for the color-mixed case, per Table 5.5
2. Warm white packages and luminaires have CCT=2580-3710K and CRI=80-90.
3. All projections assume a drive current density of 35 A/cm^2, reasonable package life and steady-state operating temperature.
4. Luminaire efficacies are obtained by multiplying the resultant luminaire efficiency by the package efficacy values.

5.1.6 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 has come down significantly over the past few years but still remains 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 packages 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 of LEDs can still improve. Progress in this area using a phosphor-converted LED approach has begun to slow down. While improvement of the phosphors, particularly narrow-emission red, would provide significant gains, alternative hybrid and color mixed approaches may also be necessary to maintain progress. 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 efficiency of the LED reduces the number of LEDs required for the lighting application as well as the thermal handling demands in the LED luminaire. This is particularly beneficial for high-lumen output products.

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. DOE has supported industry efforts to foster understanding, but much additional work remains to establish a full reliability database of components and subsystems to aid luminaire design.

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. Issues associated with the lack of dedicated equipment for LED manufacture are being addressed under DOE's manufacturing initiative for SSL.

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 2012 MYPP, DOE first held SSL roundtable sessions in Washington, D.C. in November of 2011 (see Appendix D for the entire task list). The tasks were further discussed and refined at the February 2012 "Transformations in Lighting" workshop in Atlanta, GA. Using these recommendations, and after further internal review, DOE defined a set of task priorities for 2012. The task priorities for 2012 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 improving IQE and 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 quantum yield and thermal stability, and targets down converters 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 luminaires, 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 LED Luminaire Systems) targets the development of truly novel luminaire system architectures and form factors that take advantage of the unique properties of LEDs such as form factor, optical distribution, and color control to save energy, and present a pathway to enhanced market adoption.

5.2.1 LED Priority Core Technology Tasks for 2012

The following sections summarize the conclusions and discussion points for each of the preliminary LED priority tasks proposed for prioritization in 2012. To be consistent among the tasks, the definitions in the table below for various colors and color temperatures are used throughout:

Table 5.7: LED emission wavelength and color definitions for this section

Color		Wavelength/CCT range	CRI
Blue		440-460 nm	-
Green		520-540 nm	-
Amber		580-595 nm	-
Red		610-620 nm	-
White	Warm	2580-3710K (ANSI 2700, 3000, 3500K)	80-90
	Neutral	3711-4745K (ANSI 4000, 4500K)	70-80
	Cool	4746-7040K (ANSI 5000, 5700, 6500K)	70-80

A.1.2 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, green, or amber LEDs which allow for optimization of spectral efficiency with high color quality over a range of CCT and which also exhibit color and efficiency stability with respect to operating temperature.

Metric(s)	2011 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) 52% (Red) 10% (Amber)	81% (Blue, Green, Red, Amber)
Power Conversion Efficiency[62] @ 35 A/cm^2	44% (Blue) 21% (Green) 33% (Red) 7% (Amber)	73% (Blue, Green, Red, Amber)
Droop – Relative EQE at 100 A/cm^2 vs. 35 A/cm^2	77%	100%
Thermal Stability – Relative Optical Flux at 100°C vs. 25°C	95% (Blue, Green) 50% (Red) 25% (Amber)[63]	98% (Blue, Green) 75% (Red, Amber)

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

A.1.3 Down Converters

Description: Explore new high-efficiency wavelength conversion materials for improved quantum yield and down 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. Non-REM (rare earth metal) and non-toxic down converter materials are encouraged.

Metric(s)	2011 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[64] (pc-LED)	66%	69%
Spectral Full Width Half Max. (FWHM)	150 nm (Red)	<30 nm all colors
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%
Max Flux Density @ 85°C (for zero flux dependent QY saturation)		

[64] 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.

5.2.2 LED Priority Product Development Tasks for 2012

See Table 5.7 for definitions that are used throughout this section for LED emission wavelength and white LED color point.

B.1.1 Substrate Development		
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.		
Metric(s)	**2011 Status(s)**	**2020 Target(s)**
Price of LED Package @ target efficacy	\$10/klm (cool) \$15/klm (warm)	\$0.70/klm
Though the following metrics are examples for a GaN substrate, this task is not meant to be exclusive to GaN substrates.		
GaN Substrate Price	>\$2,000 (25-50 mm)	<\$500 (>200 mm)
Droop - Relative EQE at $100A/cm^2$ vs. $35A/cm^2$	77%	100%
Thermal Stability – Relative Optical Flux at 100ºC vs. 25ºC	85% (Blue, Green)	95% (Blue, Green)
GaN Transparency (absorption coefficient)	2-10 cm^{-1}	<0.5 cm^{-1}

B.3.6 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, chip on heat sink, or other approaches to address these issues.		
Metric(s)	**2011 Status(s)**	**2020 Target(s)**
Change in Chromaticity over time	Delta u'v' @ 6khrs < 0.003	Delta u'v' < 0.002 over lifetime
Price of LED Package	$10/klm (cool) $15/klm (warm)	$0.70/klm
Luminaire Efficiency	68 lm/W (warm)	184 lm/W
Luminaire Price		

B.6.3 System Reliability and Lifetime		
Description: Collection and analysis of system reliability data for SSL luminaires and components to determine failure mechanisms and improve luminaire reliability and lifetime (including color stability). Develop and validate accelerated test methods taking into consideration component interactions. Develop an openly available and widely usable software tool to model SSL reliability and lifetime verified by experimental data and a reliability database for components, materials and subsystems. This task includes projects that focus on specific subsystems such as LED package, driver, and optical and mechanical components.		
Metric(s)	**2011 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

B.6.4 Novel LED 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 could be the integration of controls/sensors to enable utilization of the unique LED properties. 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)	**2011 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 through the roundtable and workshop discussions that will mark progress over the next ten years. These milestones are updated annually, but are not exclusive of the progress graphs shown earlier. Rather, they are highlighted targets that reflect significant gains in performance. Where only one metric is 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 community 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.

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, ongoing, is to further improve efficiency while decreasing price in order to realize the best possible energy savings. The availability of LED packages with efficacies 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. Finally, the fourth phase is to significantly reduce the cost of LED lighting to the point where it is competitive across the board. This phase, currently underway, is further supported through the R&D Manufacturing Program.

The LED package and luminaire milestones in Table 5.6 were revised in 2011 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.

Table 5.8: 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; 3500K; 80 CRI; 50,000 hrs
Milestone 3	FY15	LED package: ~$2/klm (cool white); ~$2.2/klm (warm white)
Milestone 4	FY17	Luminaire: >3500 lumens (neutral white); <$100; >150 lm/W
Milestone 5	FY20	200 lm/W luminaire

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

5.4 Organic Light Emitting-Diodes

During the last twelve months, significant improvement was achieved in the efficacy of commercially available panels, with the maximum value rising from 28 lm/W to 60 lm/W. Advancements in lifetime and luminance have also been made with lifetime being reported more frequently in terms of L_{70}, rather than L_{50} (time to 50 percent initial luminance). For general lighting applications, L_{70} should be considered the minimum acceptable level. In 2010, L_{50} of around 5,000 - 30,000 hours at initial luminance of 1,000 cd/m^2 was observed. In 2011, operating lifetimes L_{70} at 3,000 cd/m^2 of 10,000 hours is now the norm. CRI values are simultaneously improving with most prototype panels achieving values of at least 80, though CRI over 90 has been attained and including a deep red component in the spectrum has not proven to be difficult. The broad angular distribution of the light is ideal for simultaneous illumination of vertical and horizontal surfaces, but efficient methods to tailor the angular distribution are not yet available. The difficulty in controlling the angular distribution of light from OLEDs may be a deterrent to market adoption. Internal structures, light shaping optics, transparent panels, and panel profile/placement are being explored to vary light distribution profiles.

Though performance enhancements have been observed, OLED panel characteristics have not changed much since last year. The majority of devices are bottom-emitting devices built on display-grade glass substrates with indium tin oxide (ITO) as a transparent, bottom anode. The cost of these substrates is high, so groups are exploring polymeric, metallic, and residential glass substrates as alternatives. Much research has gone into developing integrated substrates comprising alternative substrates, transparent conductor materials and extraction layers. With DOE support, Arkema and PPG have been exploring the use of alternative transparent conducting oxides on residential glass substrates to reduce the cost of OLED substrates. Also with DOE support, Cambrios is developing transparent conducting/hole injection structures using silver (Ag) nanorods in a polymeric matrix which is planarized with a Plextronics hole injection layer. Though these techniques have been successful in achieving performance similar to ITO on glass, they have not yet been adopted by OLED manufacturers.

Regardless of the transparent conductor used, it is unlikely that any transparent conductor film will be developed with sheet resistance low enough to allow effective transport of current across a large panel using only a thin, homogenous sheet. However auxiliary structures, such as metallic grids can be used to facilitate current distribution. Thus, more flexibility is allowed for choice of transparent conducting material and there appears to be no theoretical impediment to the construction of very large panels. However, due to low yields and the high capital cost associated with large area fabrication lines, panel sizes in 2011 have remained small, though with continued development and greater demand, the panel area is expected to rise. Most current production is restricted to panels of area below 100 cm^2. These panels rarely produce more than 100 lumens, so that they need to be tiled together for most applications in general illumination. This practice places a premium on panel-to-panel reproducibility of color and intensity, as well as stability over time of the same.

Since panel sizes have not yet scaled to very large areas, encapsulation schemes have not been required to change considerably. Current encapsulation technique typically consists of a glass cover epoxy sealed with desiccant to the glass substrate. As device areas increase, the weight and cost of the glass encapsulation will present issues and alternatives are needed. Multilayer barrier structures as well as single layer barrier structures have been developed that may provide adequate protection for OLEDs on flexible substrates, but it has yet to be demonstrated that defect-free coatings can be fabricated at acceptable costs for lighting applications.

Another area in need of intensive research is in light extraction approaches. Adequate external extraction techniques are in place to extract light typically trapped in substrate modes and such external extraction surfaces are found in OLED products. The major obstacle to achieving efficacy targets is the trapping of light inside the OLED device. Many internal light extraction techniques have been demonstrated to enhance light extraction in small laboratory devices, such as ordered microstructures, but no approach has yet proven to be suitable for high volume production of thin, large area panels, and no OLED products currently comprise internal extraction layers. Extraction enhancement remains the principle obstacle to high efficacy and long operating lifetime.

Advancements have been made in OLED materials, but stable white OLED devices have not been realized. As current density is increased to obtain the necessary luminance levels, a drop in efficacy is observed. The need for a highly efficient, stable blue emitter remains. 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. Novaled has demonstrated a 60 lm/W (at 3,000 lm/m^2) device with a lifetime of 100,000 hours and CRI of 87 using fluorescent blue and phosphorescent red and green emitters.

Exploration into the use of solution-processed small molecule or polymeric emitters has been an area of interest due to the potential cost reductions associated with solution deposition (including high materials utilization and reduced equipment costs). 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. Efficient printed OLED devices have been realized with 52 lm/W efficacy and lifetime L_{50} of 20,000 hours at 1,000 cd/m^2. Polymeric emitters have not yet demonstrated the efficacy necessary for general illumination applications, but advances are being made. White polymer sources currently have efficacy of about 25 lm/W without extraction enhancement. Using technology developed by Cambridge Display Technologies, Sumitomo plans to mass produce polymer-based OLED devices in 2012. The performance of solution-processed materials can be highly dependent on the deposition method used. For example, spin coating, inkjet printing, contact printing, and slot-die coating can each yield different performance and reliability. Further material research is needed into the interaction between active organics, solvents, and interfaces. It is hoped that the success of OLED displays will lead to materials advancements that can be leveraged by OLED lighting manufacturers.

The success of OLED displays in the past year has confirmed that the broader color gamut, higher contrast and faster video response can give OLED panels a distinct advantage over the traditional LCD screens. This has prompted Samsung to shift the bulk of its capital investment for displays from LCD to OLED. This has provided a major boost for suppliers of OLED materials and equipment so that, for example, Universal Display Corporation has recorded its first profitable year and DuPont has licensed its solution-processable materials to a major Asian manufacturer.

In 2011, the state of the OLED lighting industry has made significant progress, but performance issues are still a concern. It is anticipated that, in the first half of 2012, luminaires will become available commercially that have performance levels close to those required for general illumination. It is promising that the lag-time between laboratory demonstrations and commercial production is shortening. Nevertheless, low manufacturing volumes and consequent high cost will likely deter widespread adoption. The performance and form factor of an OLED luminaire can be mimicked with thin, large area, diffuse LED-based light sources. However, the cost of the LED-based luminaire is significantly lower. The emergence of these highly efficient LED luminaires using conformable edge-lit light guides has emphasized the need to define the special characteristics of OLEDs such flexibility or conformability. In order to justify the manufacture of large volumes to drive down the enormous costs, a breakthrough OLED luminaire concept is desired to create market demand and to differentiate OLEDs from competing lighting technologies.

5.4.1 Components of OLED Luminaires

This section of the MYPP 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 around 100 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 one 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 $50cm^2$. OLED panels require current conducting structures to ensure uniform emission of light across the panel. Precise control of layer thicknesses within the OLED device is required for color uniformity. Panels may also incorporate packaging, thermal management, and elements to enhance light extraction.

- When panels are fabricated on a glass or plastic substrate, the usual procedure is to employ a transparent anode next to the substrate through which the light escapes, as the cathode can then be made from opaque metal and a foil, glass, or multilayer barrier cover can be used to encapsulate the device. It is also possible to manufacture an OLED with a highly transparent top electrode (typically with up to 80 percent transmission across the visible spectral region). These structures can make use of robust, low cost, flexible metal foil substrates, or can be built on transparent substrates to make transparent devices. Figure 5.8 displays a transparent OLED panel employing a transparent substrate and transparent electrodes;

Figure 5.8: Photo 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 5.9: Prototype luminaire 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 2011 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. Note that the program goals are not predictions, but are cost and performance goals suggested to accelerate the adoption of OLED lighting as an energy saving, general illumination technology.

In the tables that follow, certain assumptions are made to enable the comparison of devices. 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 2013 performance targets will assume an OLED panel with a luminous emittance of 10,000 lm/m^2. Though in last year's MYPP we assumed 2013 targets would be reported at 6,000 lm/m^2, it has been shown that most companies are reporting at either 3,000 cd/m^2 or 10,000 lm/m^2. For ease of performance comparison and to demonstrate technology advancements, we will look to 10,000 lm/m^2 as this seems to be an appropriate target illuminance for many general lighting applications. However, it is not the intention here to dictate OLED product operating conditions and products should be designed to operate at their own best brightness level.

Figure 5.10 shows the efficiency of an OLED panel and luminaire and compares values achieved for the individual system elements in prototype luminaires to a set of suggested program targets.[65] The breakdown of loss mechanisms may differ with alternative OLED architectures, but regardless of architecture the drive voltage and light extraction enhancement show the most room for 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

[65] 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.

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;[66]
- *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.

Figure 5.10: OLED Panel and Luminaire Loss Channels and Efficiencies

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

If all the improvements shown in Figure 5.10 are achieved, the efficiency of the OLED panel would rise from the current typical value of 18 to 51 percent. The corresponding panel efficacy would rise from 66 lm/W to as much as 190 lm/W. The following

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

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 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 four percent). 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 percent) and target (95 percent) 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 percent 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 percent of the efficiency of all phosphorescent devices.[67]

Opportunities for gains in light extraction efficiency:

It is clear from Figure 5.10 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 50-100 percent 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. Such structures are incorporated to deflect the light towards the normal direction. Gains of over 100 percent have been reported;
- Transfer of energy to the metal cathode (surface plasmon excitation) – 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.).

Much effort was expended on increasing light extraction through the use of internal extraction layers during 2011. Approaches that require the formation of ordered structures – such as low-index grids and nano-pillars are proving to be difficult to scale from small pixel devices to large area panels. More attention is now being focused upon random light scatterers or roughened surfaces. Even these approaches lead to manufacturing challenges. For example, metal-oxide particles of a size around 500nm are effective scatterers of light, but their roughness can lead to electrical breakdown. Embedding the particles in a smooth layer of polymer binder helps, but such layers can

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

be damaged by subsequent deposition steps during fabrication. Further, the density of particles required for adequate scattering can lead to excessive optical absorption in the scattering film. The advancement of light extraction technology remains a key challenge for OLED lighting. Suitable techniques must be low-cost, homogenously scalable to large area panels, robust, and compatible with OLED device designs and fabrication. In determining the performance of a light extraction enhancement technique, both the device efficacy as well as the enhancement factor are important considerations.

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 desiccant 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.

Perhaps the greatest conflict will be between performance and cost. For example, the use of a triple-stacked structure leads to significant improvement in electrical efficiency and to longer lifetime. However, many proponents of solution processing believe that the manufacturing of triple-stack architecture will be prohibitively expensive.

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 128 lm/W (Panasonic). 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.

Figure 5.11 shows a projection of future progress on the efficacy of OLED panels, based upon past performance panel data and an assumed asymptote of 190 lm/W. The data on panels is rather sparse, limited to a few recent years, and shows a lot of variation, so there is considerable uncertainty in the curve. The average of "qualified" data for each year was used to fit the data.

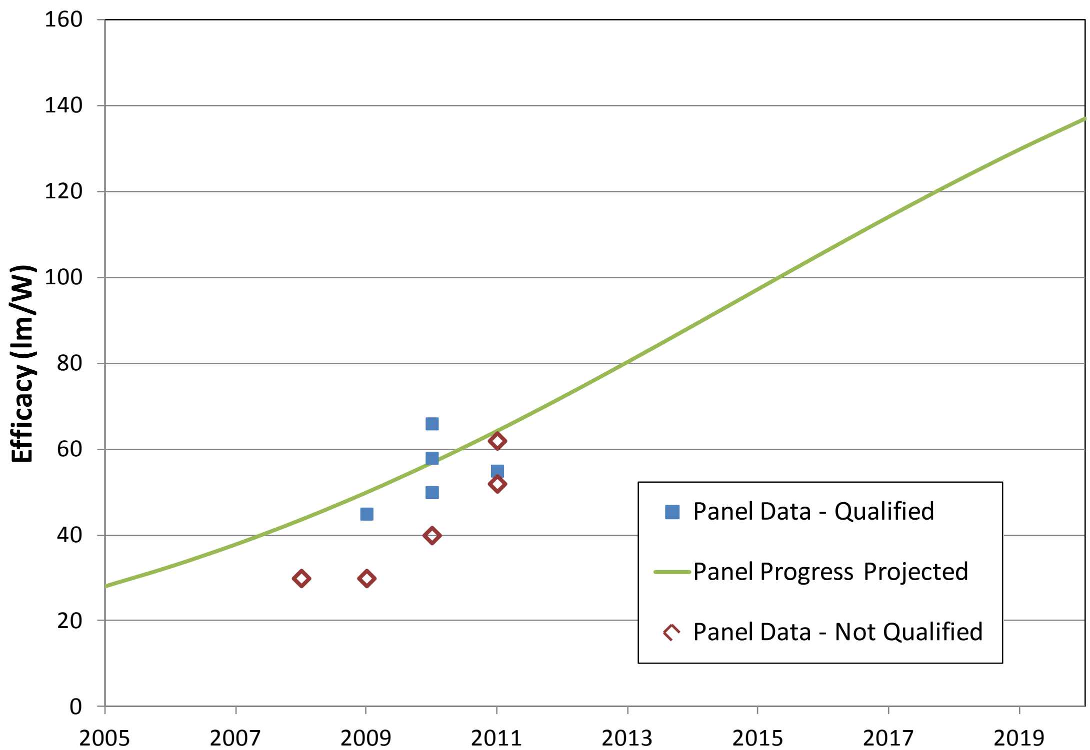

Figure 5.11: White Light OLED Panel Efficacy Projections

Performance targets for future years are shown in Table 5.9. These take into consideration the demands of the market as well as the anticipated technological improvements.

Table 5.9: Summary of OLED Panel Performance Targets

Metric	2011	2013	2015	2020	Goal
Panel Efficacy (lm/W)	58	80	100	140	190
Lumen Maintenance (to L_{70} in thousands of hours)	10	25	50	50	50

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

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 the increase in luminous emittance from 3,000 lm/m^2 to 10,000 lm/m^2 reduces the lifetime of the OLED by as much as 80 percent. 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.

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.

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 5.10 below, details a summary of the performance targets for OLED luminaires. The column for 2011 is based upon a prototype luminaire developed by UDC in collaboration with Armstrong Industries. The efficiency of the driver is 88 percent 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 5.10: Summary of OLED Luminaire Performance Targets

Metric	2011	2013	2015	2020	Goal
Panel Efficacy (lm/W)	58	80	100	140	190
Optical Efficiency of Luminaire[2]	100%	100%	90%	95%	95%
Efficiency of Driver	91%	92%	93%	93%	93%
Total Efficiency from Device to Luminaire	91%	92%	84%	88%	88%
Resulting Luminaire Efficacy (lm/W)	53	74	84	123	167

Notes:

1. Efficacy projections assume CRI > 80, CCT 2580-3710
2. The values of optical efficiency quoted for 2011 and 2013 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: OLEDs are at least as successful as LEDs in creating warm white light, but less than half of this light emerges from large area panels, as the majority of light is trapped within the device. 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. The use of tandem structures helps in this respect.

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 5.1.6 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.[68] However, this is rarely optimal 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. Research into the design of external films that will control the angular distribution as well as enhance extraction could be valuable.

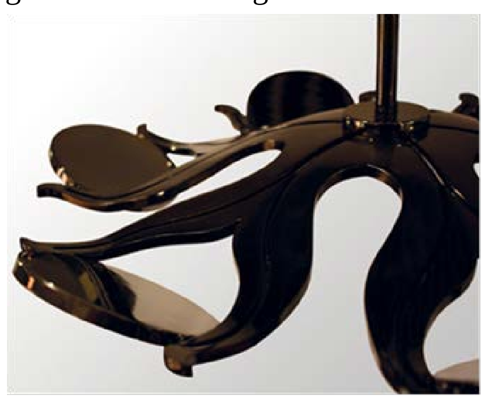

Figure 5.12 Luminaire using multiple panels with varying orientation
Source: WAC Lighting

8. Investment in Manufacturing: Manufacturing costs are high, and outside of Korea, companies appear unwilling to invest the necessary capital costs required for high-volume manufacturing. Asian manufacturers of OLED displays may be able to adapt their fabrication lines to produce OLED light

[68] 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

sources, but the lower cost constraints will require important modifications. 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.

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. Compelling product differentiators are required to drive customers to pay the premium prices that OLEDs will initially demand.

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, including manufacturability and low cost. 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 2012 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 2011 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 2012 “Transformations in Lighting” workshop in Atlanta, Georgia. Using these recommendations, and after further internal review, the DOE defined the task priorities for 2012. It should be noted that the title of task C.1.2 has been changed from “Novel Materials and Structures” to “Stable White Devices”. The task priorities for 2012 are as follows:

For OLED Core Technology:

- Subtask C.1.2 (Stable White Devices) promotes the development of efficient, stable white light OLED materials and structures to improve color quality, EQE, and lifetime while offering the potential for large scale, low-cost production and processing. Novel materials and structures should be demonstrated in OLED devices and exhibit significant improvements in stability while preserving or advancing other performance metrics; and
- Subtask C.6.3 (Light Extraction Approaches) supports the development of new optical and device designs to improve light extraction while preserving the performance and thin profile of OLED panels. Proposed methods should be supported quantitative analysis, demonstrated in a device at least $1cm^2$ in size and provide potential for low cost and large area scalability.

For OLED Product Development:

- Subtask D.4.2 (Breakthrough OLED Luminaire) emphasizes the need to employ the unique properties of OLEDs through new luminaires and form factors. Designs should capture the value proposition features of OLEDs; 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 methods should allow some control of the angular distribution of intensity but minimize the variation of color with angle.

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 2012

C1.2 Stable White Devices		
Description: Develop novel materials and structures that can help create a highly efficient, stable white device. The devices should have good color, long lifetime and high efficiency even at high brightness. Color shift over time should be minimal. The approach may include the development of highly efficient, blue emitter materials and hosts or may comprise a device architecture leading to longer lifetime. Any proposed solutions should keep cost, complexity and feasibility of scale-up in mind. Materials/structures should be demonstrated in OLED devices which are characterized to ascertain the performance as compared to the metrics below. Novel materials/structures should demonstrate a significant improvement in stability, while maintaining or improving other metrics.		
Metric(s)	**2011 Status(s)**	**2020 Target(s)**
Lumen Maintenance (L_{70}) from 10,000 lm/m^2	10,000 hrs	>50,000 hrs
Voltage Rise		<15%
Color Shift (delta u'v')	<0.004	<0.002
EQE without external extraction enhancement	~22%	25-30%
Voltage @ 2mA/cm^2	~3.4V	<3V
CRI	84	>90

C.6.3 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. Applicants should consider how their approach affects the energy loss due to waveguided and plasmon modes and should include any modeling or quantitative analysis that supports the proposed method. The approach should provide potential for low cost and should be demonstrated in a device of at least 1 cm^2 in size to demonstrate applicability and scalability to large area (panel size) devices.		
Metric(s)	**2011 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 2012

D.4.2 Breakthrough OLED Luminaire		
Description: Develop novel luminaire system architectures and form factors that take advantage of the unique OLED energy saving properties and represent a pathway toward greater market adoption. It is important that the novel luminaire capture the unique aspects offered by OLEDs, such as lightweight, thin profile, or flexibility of form factor. Proposals should provide quantitative targets for distinctive performance and assess the potential customer appeal.		
Metric(s)	**2011 Status(s)**	**2020 Target(s)**
Lumen Output	75 lm	>500 lm
Color stability		2 step MacAdam ellipse
Lumen maintenance (L_{70}) from 10,000 lm/m^2	10,000 hrs	50,000 hrs

D.6.3 Panel Light Extraction

Description: Demonstrate manufacturable approaches to improve light extraction efficiency for OLED panels while providing some control over the angular distribution of the intensity of the emitted light. The approach should retain the thin profile and state of the art performance of OLED panels (for example, extraction layers should not lead to voltage increases, reduction in device efficacy, angular dependence of color). The proposed solution could involve modifications within the OLED stack, within or adjacent to the transparent electrode, and/or external to the device. The approach should be demonstrated over large areas (> 25cm^2) and must be amenable to low-cost manufacture.

Metric(s)	2011 Status(s)	2020 Target(s)
Extraction Efficiency	40%	70%
Incremental Cost		<$10/$m^2$

5.6 OLED Interim Product Goals

Table 5.11 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 5.11: 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	200 lm/panel ; >70-80 lm/W ; >10,000-20,000 hrs LT_{70} (laboratory panel)
Milestone 4	FY15	<$25/klm (cost); >100 lm/W panel @ 10,000 lm/m^2 (commercial panel)
Milestone 5	FY18	50,000 hour lifetime; >10,000 lm/m^2 panel

Assumptions: CRI > 85, CCT < 2580-3710K. 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 1,000 cd/m^2, CRI greater than 80, CCT between 2700K and 4100K 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 (L_{70}) over 10,000 hours. When operated at the nominal luminance of 1,000 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 (L_{70}) 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.

In 2012, panels delivering 60 lm/W at 3,000cd/m^2 with a CRI >85, CCT of 3500K and lifetime (L_{70}) of 15,000 hours are available from LG Chem. These are the same panels to be found in the Acuity Brand Kindred and Revel luminaires. Already in 2011, small OLED devices (1in x 1in) developed by Osram have demonstrated 87 lm/W at 1,000 cd/m^2 and 75 lm/W at 5,000 cd/m^2, making good headway towards the 2012 milestones.

Since large volume manufacturing has still not been established, it seems unlikely that the 2015 cost target of $25/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.

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 one 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 2012 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 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**
- **B.6.4 Novel LED luminaire systems**

B.7.0 Electronic Components
- B.7.1 Color maintenance
- B.7.2 Color tuning
- B.7.3 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 Stable white devices**
- C.1.3 Material and device architecture modeling
- C.1.4 Material degradation
- C.1.5 Thermal characterization of materials and devices

C.2.0 Substrate and Electrode
- C.2.2 Electrode research

C.3.0 Fabrication
- C.3.1 Fabrication technology research

C.4.0 Luminaire Integration
- C.4.3 Optimizing system reliability

C.5.0 Electronic Components

C.6.0 Panel Architecture
- **C.6.3 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 Breakthrough OLED luminaire**
- D.4.3 System reliability methods
- D.4.4 Luminaire thermal management
- D.4.5 Electrical interconnects

D.5.0 Electronic Components
- D.5.1 Color maintenance
- D.5.2 Smart controls
- D.5.3 Driver electronics

D.6.0 Panel Architecture
- D.6.1 Large area OLEDs
- D.6.2 Panel packaging
- **D.6.3 Panel light extraction**
- D.6.4 Panel reliability
- D.6.5 Panel mechanical design

Task Work Structure

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.1.2	Emitter materials research	Address 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 improving IQE and reducing the thermal sensitivity of LEDs, especially those in the red and amber spectral regions.
A.1.3	Down converters	Emphasize 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.
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	Devise novel emitter geometries and mechanisms that show a clear pathway to efficiency improvement. Demonstrate a pathway to increased chip-level functionality offering luminaire or system efficiency improvements over existing approaches. Explore novel architectures for improved efficiency, color stability, and emission directionality including combined LED/converter structures.
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.1.1	Substrate development	Investigate 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.
B.1.2	Semiconductor materials	Reduce the operating voltage of LED chips or arrays by increasing lateral conductivity or architectural improvements or package design, etc.
B.1.3	Phosphors	
B.2.3	Electrical	Reduce the operating voltage of LED chips or arrays by increasing lateral conductivity or architectural improvements or package design, etc.
B.3.1	LED package optics	Beam-shaping or color-mixed at the LED package or array level.
B.3.2	Encapsulation	Develop a thermal/photo-resistant encapsulant that exhibits long life and has a high refractive index.
B.3.4	Emitter thermal control	Demonstrate an LED or LED array that maximizes heat transfer to the package so as to improve chip lifetime and reliability.
B.3.5	Environmental sensitivity	Develop and extensively characterize a packaged LED with significant improvements in lifetime associated with the design methods or materials.
B.3.6	Package architecture	Support the development of novel LED package and module architectures that can be readily integrated into luminaires, and address issues such as efficacy, thermal management, cost color, optical distribution, electrical integration, sensing and reliability.
B.4.1	Yield and manufacturability	Devise methods to improve epitaxial growth uniformity of wavelength and other parameters so as to reduce binning yield losses. Solutions may include in-situ monitoring and should be scalable to high volume manufacture.
B.4.2	Epitaxial growth	Develop and demonstrate growth reactors and monitoring tools or other methods capable of growing state of the art LED materials at low-cost and high reproducibility and uniformity with improved materials-use efficiency.
B.4.3	Manufacturing tools	Develop improved tools and methods for die separation, chip shaping, and wafer bonding, and testing equipment for manufacturability at lower cost.
B.5.1	Light utilization	Maximize the ratio of useful light exiting the luminaire to total light from the LED source. This includes all optical losses in the luminaire; including luminaire housing as well as optical losses from diffusing, beam shaping, and color mixing optics. Minimize artifacts such as multi-shadowing or color rings.
B.5.2	Color maintenance	Ensure luminaire maintains the initial color point and color quality over the life of the luminaire. 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.

LED Product Development Tasks (Cont'd)		
	Task	**Description**
B.6.3	System reliability and lifetime	Encourage 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.
B.6.4	Novel LED luminaire systems	Target the development of truly novel luminaire system architectures and form factors that take advantage of the unique properties of LEDs such as form factor, optical distribution, and color control to save energy, and present a pathway to enhanced market adoption.
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.1.2	Stable white devices	Promotes the development of efficient, stable white light OLED materials and structures to improve color quality, EQE, and lifetime while offering the potential for large scale, low-cost production and processing. Novel materials and structures should be demonstrated in OLED devices and exhibit significant improvements in stability while preserving or advancing other performance metrics.
C.1.3	Material and device architecture modeling	Developing software simulation tools to model the performance of OLED devices using detailed material characteristics.
C.1.4	Material degradation	Understand and evaluate the degradation of materials during device operation.
C.1.5	Thermal characterization of materials and devices	Involves modeling and/or optimizing the thermal characteristics of OLED materials and device architectures with the goal of developing less thermally sensitive and hydrolytically more stable materials and devices.
C.2.2	Electrode research	Develop a novel electrode system for uniform current distribution across a (>200 cm^2) panel. Solutions must have potential for substantial cost reduction with long life while maintaining high OLED performance. Work could include more complex architectures such as grids or patterned structures, p-type and n-type degenerate electrodes, two-material electrodes, electrodes that reduce I*R loss, flexible electrodes, or other low-voltage electrodes.

OLED Core Technology Tasks (Cont'd)

	Task	Description
C.3.1	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.
C.6.3	Light extraction approaches	Supports the development of new optical and device designs to improve light extraction while preserving the performance and thin profile of OLED panels. Proposed methods should be supported quantitative analysis, demonstrated in a device at least $1 cm^2$ in size and provide potential for low cost and large area scalability.

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.
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	Supports maximizing the ratio of useful light exiting the luminaire to total light from the OLED sources. This includes optical losses in the luminaire as well as from beam distribution and color mixing optics.
D.4.2	Breakthrough OLED luminaire	Emphasizes the need to employ the unique properties of OLEDs through new luminaires and form factors. Designs should capture the value proposition features of OLEDs.
D.4.3	System reliability methods	Develop models, methodology, and experimentation to determine the lifetime of the integrated OLED luminaire and all of the components.

OLED Product Development Tasks (Cont'd)		
	Task	**Description**
D.4.4	Luminaire thermal management	Design integrated thermal management techniques to extract heat from the luminaire in a variety of environments and operating conditions. Thermal management should maintain the OLED source temperature as well as enhance the luminaire color and efficiency performance.
D.4.5	Electrical interconnects	Develop standard connections for integration of OLED panels into the luminaire.
D.5.1	Color maintenance	Develop OLED driver electronics that maintain a color setpoint over the life of the luminaire by compensating for changes in OLED output over time and temperature, and degradation of luminaire components.
D.5.2	Smart controls	Develop integrated lighting controls and sensors that save energy over the life of the luminaire.
D.5.3	Driver electronics	Develop efficient, long-life OLED driver electronics and power converters that efficiently convert line power to acceptable input power of the OLED source(s) and maintain their performance over the life of the fixture. These can include energy-saving functionality such as daylight and occupancy sensors and communication protocols for external lighting control systems.
D.6.1	Large area OLEDs	Demonstrate a high efficiency OLED panel, with a white light output of at least 200 lm and an area of at least 200 cm^2. The OLED panel should have high brightness and color uniformity as well as a long operating lifetime. The panel should employ low cost designs, processes, and materials and demonstrate a potential for high-volume manufacturing.
D.6.2	Panel packaging	Demonstrate manufacturable approaches to improve light extraction efficiency for OLED panels while providing some control over the angular distribution of the intensity of the emitted light. The approach should retain the thin profile and state of the art performance of OLED panels (for example, extraction layers should not lead to voltage increases, reduction in device efficacy, angular dependence of color). The proposed solution could involve modifications within the OLED stack, within or adjacent to the transparent electrode, and/or external to the device. The approach should be demonstrated over large areas (> $25cm^2$) and must be amenable to low-cost manufacture.
D.6.3	Panel light extraction	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.
D.6.4	Panel reliability	Analyze and understand failure mechanisms of OLED panels and demonstrate a packaged OLED panel with significant improvements in operating lifetime. Specific issues may include enhanced thermal management to support operation at higher luminance levels, or the dependence of shorting on layer thickness and uniformity.
D.6.5	Panel mechanical design	Integrate all aspects of OLED-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 2012, a total of forty five 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 139 patent applications have been submitted by different groups as follows: large businesses - 40, small businesses - 56, universities - 36, and national laboratories - 7.

Primary Research Organization	Title of Patent Application (Bolded titles indicates granted patents)
Agiltron, Inc.	**Optoelectronic Device With Nanoparticle Embedded Hole Injection/Transport Layer** Air-Stable, Cross-Linkable Hole Transport Materials for Organic Light Emitting Devices
Arkema, Inc.	OLED Substrate Consisting of Transparent Conductive Oxide (TCO) and Anti-Iridescent Undercoat Chemical Vapor Deposition Using N,O Polydentate Ligand Complexes of Metals
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** **LED Package Element with Internal Meniscus for Bubble-Free Hallow Floating Lens Placement** **Light Emitting Diode with High Aspect Ratio Sub-Micron Roughness for Light Extraction and Methods of Forming** **Expandable LED Array Interconnect** Ultra-Thin Ohmic Contacts for P-type Nitride Light Emitting Devices
Crystal IS, Inc.	Growth of Large Aluminum Nitride Single Crystals with Thermal-Gradient Control Growth of Large Aluminum Nitride Single Crystals with Thermal-Gradient Control
Dow Corning	Method of Forming Three-Dimensional Silicon-Containing Structures Three other patent applications filed
Eastman Kodak	**Ex-Situ Doped Semiconductor Transport Layer** **Doped Nanoparticle-Based Semiconductor Junction** **Device Containing Non-Blinking Quantum Dots** Light-Emitting Nanocomposite Particles Making Colloidal Ternary Nanocrystals
Fairfield Crystal Technology	Method and Apparatus for Aluminum Nitride Monocrystal Boule Growth

Primary Research Organization	Title of Patent Application (Bolded titles indicates granted patents)
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 Lighting System with Thermal Management System Lighting System with Thermal Management System Having Point Contact Synthetic Jets Lighting System with Heat Distribution Face Plate Eight other patent applications filed
General Electric Lighting Solutions	Two patent applications filed
Georgia Tech Research Corporation	One patent application filed
International Technology Exchange	One patent application filed
Lawrence Berkeley National Laboratory	**Carbon Nanotube Polymer Composition and Devices** Organic Light Emitting Diodes with Structured Electrodes
Lehigh University	**Gallium Nitride-Based Device and Method** Staggered Composition Quantum Well Method and Device Staggered Composition Quantum Well Method and Device
Light Prescriptions Innovators	**Optical Manifold for Light-Emitting Diodes** **Optical Manifold for Light-Emitting Diodes** **Optical Manifold** **Wide Band Dichroic-Filter Design for LED-Phosphor Beam Combining** Optical Device for LED-Based Lamp Three other patent applications filed
Lightscape Materials Inc.	Oxycarbonitride Phosphors and Light Emitting Devices Using the Same Oxynitride-Based Phosphors and Light Emitting Devices Using the Same Carbonnitride Based Phosphors and Light Emitting Devices Using the Same Carbonitride-Based Phosphors Nitride and Oxynitride Based Phosphors and LED Devices Using the Same Two other patent applications filed
Maxdem Incorporated	Polymer Matrix Electroluminescent Materials and Devices
Nanosys	**Nanocrystal Doped Matrices**

Primary Research Organization	Title of Patent Application (Bolded titles indicates granted patents)
OSRAM Opto Semiconductors, Inc.	**Integrated Fuses for OLED Lighting Device** **Novel Method to Generate High Efficient Devices, Which Emit High Quality Light for Illumination** **Polymer and Small Molecule Based Hybrid Light Source** OLED with Phosphors Thermal Trim for a Luminaire Novel Method to Generate High Efficient Devices, Which Emit High Quality Light for Illumination Polymer Small Molecule Based Hybrid Light Source One other patent application filed
Pacific Northwest National Laboratory	**OLED Devices** 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	Zener Diode Protection Network in Submount for LEDs Connected in Series LED Module with High Index Lens
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	Metallized Silicon Substrate for Indium Gallium Nitride Light-Emitting Diode Process for Fabricating III-Nitride Based Nanopyramid LEDs Directly on a Metallized Silicon Substrate
RTI	Long-Pass Optical Filter Made from Nanofibers Stimulated Lighting Devices Reflective Nanofiber Lighting Devices Three other patent applications filed
Sandia National Laboratory	**Cantilever Epitaxial Process** **Nanowire-Templated Lateral Epitaxial Growth of Non-Polar Group III Nitrides**
Sinmat, Inc.	**High Light Extraction Efficiency Solid State Light Sources** Chemical Mechanical Fabrication (CMF) for Forming Tilted Surface Features
Universal Display Corporation	**Binuclear Compounds** **Organic Light Emitting Device Structure for Obtaining Chromaticity Stability** **Organic Light Emitting Device Structure for Obtaining Chromaticity Stability** **Organic Light Emitting Device Architecture for Reducing the Number of Organic Materials** Stacked OLEDs with a Reflective Conductive Layer Intermediate Connector for Stacked Organic Light Emitting Devices White Phosphorescent Organic Light Emitting Devices Organic Light Emitting Device with Conducting Cover One other patent application filed
University of California, San Diego	Rare-Earth Activated Nitrides for Solid State Lighting Applications Two other patent applications filed

Primary Research Organization	Title of Patent Application (Bolded titles indicates granted patents)
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	Organic Light-Emitting Diodes from Homoleptic Square Planar Complexes Two other patent applications filed
University of Southern California	**Fluorescent Filtered Electrophosphorescence** **Fluorescent Filtered Electrophosphorescence** **OLEDs Utilizing Macrocyclic Ligand Systems** **Organic Vapor Jet Deposition using an Exhaust** **Phenyl and Fluorenyl Substituted Phenyl-Pyrazole Complexes of Ir** Materials and Architectures for Efficient Harvesting of Singlet and Triplet Excitons for White Light Emitting OLEDs Stable Blue Phosphorescent Organic Light Emitting Devices Organic Light Emitting Device Having Multiple Separate Emissive Layers Low Index Grids (LIG) to Increase Outcoupled Light from Top or Transparent OLED One other patent application filed
Yale University	Conductivity Based Selective Etch for GaN Devices and Applications Thereof

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]

Department of Energy
Washington, DC 20585

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. Under the Declaration of Exceptional Circumstances for Inventions Arising Under the Solid State Lighting (SSL) Program, any entity having the right to use or sell any subject invention made under its DOE agreement in the United States and/or any other country, and any SSL Partnership member obtaining a license to such subject invention, 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 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: 3/14/12

Roland J. Risser
Program Manager
Building Technologies Program
Energy Efficiency And Renewable Energy

By: Keith R Cook Date: APRIL 2, 2012

Keith Cook
Chair
Next Generation Lighting Industry Alliance

Appendix H Memorandum of Understanding between the U.S. Department of Energy and the Illuminating Engineering Society of North America

[APPENDIX STARTS ON NEXT PAGE]

The United States Department of Energy
and
The Illuminating Engineering Society
of North America

MEMORANDUM OF UNDERSTANDING

This Memorandum of Understanding (MOU or Agreement) is entered into this 18th day of OCTOBER 2011, by and between the U.S. Department of Energy (DOE) and the Illuminating Engineering Society of North America (IES) (collectively, the "Parties").

I. Purpose and Authority.

The purpose of this MOU is to allow DOE and IESNA to work cooperatively to improve the efficient use of energy and to minimize the impact of energy use on the environment. The Department of Energy Organization Act (Pub. L. 95-91, as amended; 42 U.S.C. §7256).

II. Background.

The Illuminating Engineering Society was founded in 1906 with the purpose of bringing engineers, architects, designers and end users of lighting into an organization devoted to research, application and education. This non-profit, volunteer membership organization has since provided research/consensus based documents such as recommended practices, design guides, research technical memoranda, and educational materials. The Department invests resources to further the energy efficiency, and lighting quality, with programs in lighting research, product development, commercialization, and standards. Both parties seek to improve the quality and efficiency of lighting through science and engineering; and have, over the past five years, performed a number of joint activities. As one example, IES, with support from DOE, produced LM-79 and LM-80, two very pivotal test methods for LED lamps.

III. Responsibilities of the Parties.

DOE and IES agree to work together toward the following goals:

1) Promoting and supporting the DOE Building Technologies Program and the DOE Efficiency Standards development by means of input from technical experts, and development of appropriate IES standards and procedures.

2) Developing and maintaining guides and procedures to assist the lighting measurement and application community in the photometric measurement of solid state lighting devices and other technologies to (i) support DOE programs, and (ii) provide consistency and uniformity in photometric reports.

3) Developing and maintaining standards that include a focus on energy conservation strategies to benefit design professionals and users.

4) Encourage the participation of DOE personnel in IES technical committee activities and provide the opportunity for dissemination/publication of related research.

5) Develop and maintain appropriate educational modules for inclusion in IES course materials for use by the Society's Sections and other organizations.

IV. Points of Contact.

The points of contact responsible for administration of this Agreement are:

DOE:

James R. Brodrick
Solid State Lighting Portfolio Manager
Department of Energy, EE-2J
1000 Independence Avenue, SW
Washington, D.C. 20585-0121
T 202-586-1856
F 202-586-4617
james.brodrick@ee.doe.gov

IES:

Rita M. Harrold
Director of Technology
Illuminating Engineering Society of North America
120 Wall Street, 17th floor
New York, NY 10005
T 212-248-5000 x 115
F 212-248-5017
rharrold@ies.org

V. Terms and Termination.

This MOU shall remain in effect for five (5) years from the date on which it becomes effective, or until terminated by either party upon 90 days written notice to the other party.

This MOU in no way restricts either of the Parties from participating in any activity with other public or private agencies, organizations or individuals.

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

This MOU is not legally enforceable and does not create any legal obligation on the part of either party, nor does it create a private right or cause of action for or by any person or entity.

VI. Modifications.

This MOU may be modified by mutually acceptable written amendment duly executed by authorized officials of DOE and IES. Its provisions will be reviewed annually and amended/supplemented if mutually agreed upon in writing.

VII. Entire Agreement.

This MOU constitutes the full and final understanding of both Parties on all subjects contained within it. All prior negotiations, understandings, and agreements are merged into this Agreement.

VIII. Execution.

The Parties have caused this MOU to be executed in duplicate originals by their duly authorized representatives and is effective on the date of the last signature below.

For DOE:

Roland J. Risser 10-13-11

Roland J. Risser   Date
Program Manager – Building Technologies Program
US Department of Energy

For IES:

William Hanley August 4, 2011

William Hanley   Date
Executive Vice President
Illuminating Engineering Society of North America