Solid-State Lighting Research and Development:

Multi-Year Program Plan

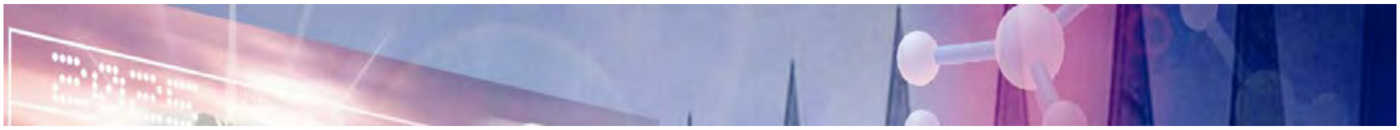
March 2010

Lighting Research and Development

Building Technologies Program

U.S. DEPARTMENT OF ENERGY

Energy Efficiency & Renewable Energy



Multi-Year Program Plan

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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DISCLAIMER

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COMMENTS

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1.0 Introduction

President Obama's energy and environment agenda calls for deployment of "the Cheapest, Cleanest, Fastest Energy Source – Energy Efficiency."[1] The Department of Energy's (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[2]

Lighting in the United States is projected to consume nearly 10 quads of primary energy by 2012.[3] A nation-wide move toward solid-state lighting (SSL) for general illumination could save a total of 16 quads of primary energy between 2010 and 2030. No other lighting technology offers the DOE and our nation so much potential to save energy and enhance the quality of our built environment. The 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.*

1.1 Significant SSL Program Accomplishments to Date

1.1.1 Recent Research Highlights

Researchers have made considerable progress in the advancement of SSL since the U.S. Department of Energy (DOE) initiated its work in SSL research and development (R&D) in 2000. In the course of their research, performers supported by the DOE SSL portfolio have won several prestigious national research awards and have achieved several significant accomplishments in the area of SSL. The following research highlights significant achievements funded by the DOE's SSL Program in the past year (FY 2009).

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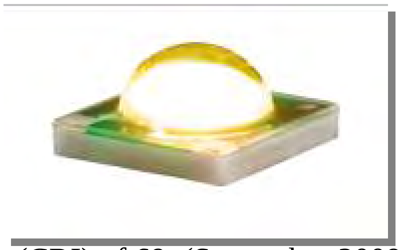
[1] The Agenda – Energy and Environment. Last Accessed February 26, 2009. Available at: http://www.whitehouse.gov/agenda/energy_and_environment/.
[2] Fleck, J. "Bingaman Thinks LEDs a Bright Idea." *Albuquerque Journal*. 10 November 2003.
[3] Energy Savings Potential of Solid State Lighting in General Illumination Applications 2010-2030. Prepared by Navigant Consulting, Inc. for the Department of Energy. Washington D.C. February 2010.

Cree, Inc. Develops Efficient Cool White LED

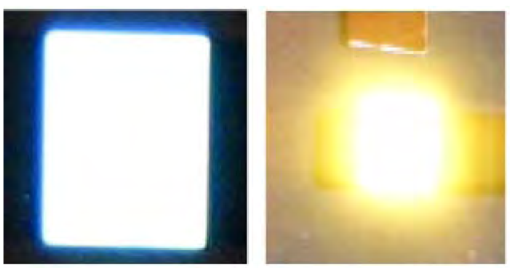


Cree successfully fabricated a cool white LED that delivers 117 lumens per Watt (lm/W) at 350mA. This achievement builds on the Cree EZBright® LED chip platform, developed in part with prior funding support from DOE. Based on a 1 mm^2 chip, the new prototype LED produces white light with a color correlated temperature (CCT) of 6,450 K and a color rendering index (CRI) of 69. (September 2009)

PhosphorTech Develops New Materials for Efficient SSL with Good Color Quality

PhosphorTech has developed new phosphor materials for use in SSL. These materials have tunable color spectra and have shown quantum yields as high as 88 percent. Certain compositions of these phosphors become even more efficient at higher temperatures—a property known as thermal anti-quenching. Typical phosphors used in SSL have limited color flexibility, and the efficiency quenches rapidly at higher temperature operation. With these new phosphors, LEDs will potentially operate more efficiently at higher temperature and experience less of a color shift due to the drop-off in phosphor efficiency. PhosphorTech is currently working to improve the chemical stability of these materials and to better understand the anti-quenching effect in order to implement it in other phosphor compositions. (September 2009)

University of North Texas Improves Emitters for OLEDs



The University of North Texas, in conjunction with the University of Texas at Dallas, has made significant improvements in electrophosphorescent emitters for OLEDs. Through the use of novel platinum-based phosphors that exhibit tunable emission colors, including white from a single material, researchers are seeking to replace the more commonly-used iridium-based phosphors in conventional OLEDs. Additional achievements include superior stability at lighting brightness and achievement of cool- and warm-white OLEDs with a color rendering index up to 82 from a single phosphor. (September 2009)

Philips Lumileds Demonstrates LED with 735 Lumens Light Output

The research team at Philips Lumileds Lighting Company has demonstrated a warm white LED with a light output of 735 lumens, an efficacy of 83 lm/W, and a CCT of 3343 K. The LED chip was 2x2 mm^2 and was driven at a current density of 70 A/cm^2. The goal of this project is to demonstrate a 100 lm/W warm white LED with a light output of 800 lumens. Smaller, more efficient light sources that have higher light outputs would give luminaire manufacturers more flexibility when designing lighting products. (September 2009)

RTI Develops Quantum Dot Technology for Efficient SSL Lighting

Research Triangle Institute (RTI) has developed red emitting quantum dots embedded in a nanofiber which can be used with a cool white LED to produce warm white lighting. This technology is about four times more efficient than an incandescent bulb with similar, excellent color quality, demonstrating a color correlated temperature of 2900 K and a color rendering index of 90. Limited color quality has been identified as a roadblock to the adoption of high-efficiency lighting with CFL- and LED-based technologies; with this approach, high efficiency and excellent color quality can be achieved simultaneously. Prototype downlight-type fixtures are being developed to further investigate and demonstrate this technology. (August 2009)

Rensselaer Polytechnic Institute Achieves Stable Green LEDs on GaN Substrates

Researchers at Rensselaer Polytechnic Institute (RPI) have grown a wavelength-stable green LED on a non-polar m-plane gallium nitride (GaN) substrate. Today's high-brightness LED efficiency is reduced as drive current is increased, and this efficiency roll-off is caused by the polarization of the GaN material. RPI is working on growing LEDs on non-polar GaN to eliminate polarization effects and thus eliminate the efficiency roll-off. Growing green LEDs on non-polar substrates is difficult due to poor indium incorporation, which is needed to produce green LEDs. Efficient green LEDs are important when using the color mixing approach to produce white light. (March 2009)

Eastman Kodak High Efficiency for Hybrid White OLED Device

The Eastman Kodak Company has demonstrated an efficacy of 62 lm/W with a hybrid OLED device, while achieving color coordinates that are well within the ENERGY STAR® color requirements for LED products. Their new device architecture delivered improvement in external extraction efficiency, achieving an estimated 56 percent, which impacts the device's lifetime and power efficiency. In addition, the company reduced forward voltage, which also impacts power efficiency, achieving a drive voltage below 3.0 volts at $5 mA/cm^2$. The team will continue their work in multiple parallel areas to further improve the power efficiency and lifetime of OLED devices. (March 2009)

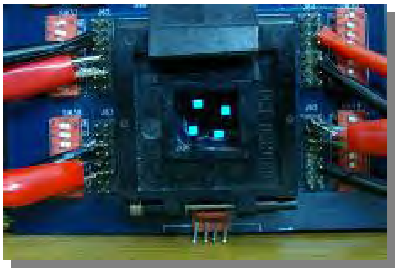
Osram Sylvania Demonstrates Efficient LED Light Engine

The research team at Osram Sylvania has demonstrated an efficient LED light engine with a 3500 K CCT and CRI greater than 80. The light engine consists of an array of blue LEDs on a circuit board covered by a phosphor-coated glass disk. The phosphor coating on the glass disk converts the blue light into a warm white light. The project results support Osram Sylvania's goal of developing a highly efficient LED downlight by improving the phosphor, optical, electronic, and thermal systems of the luminaire. This latest performance improvement was due to a new red phosphor that allowed both a higher efficacy and CRI to be achieved. (March 2009)

GE Global Research Progresses Toward Commercial OLED Luminaires

GE Global Research has demonstrated a large-area OLED luminaire constructed in a desk lamp configuration. The luminaire consists of eight 7.62 cm x 7.62 cm devices with a total active emissive area of ~240 cm^2 and a luminous output of 75 lumens. Although currently primarily only OLEDs used for display purposes are sold commercially, research is being conducted in white OLEDs so that commercial products can be sold in the future for general illumination purposes. This OLED luminaire deliverable demonstrates notable progress toward this commercialization goal. The team will continue its work to deliver an illumination-quality white light source with >75 lm/W, having a luminous output comparable to a standard 60-Watt incandescent lamp (900 lumens), with an area <0.35m^2. (March 2009)

University of Florida Continues to Advance Blue Efficiency for OLEDs



The University of Florida has achieved an efficacy of 59 lm/W for a blue phosphorescent OLED, exceeding its previous achieved efficacy of 50 lm/W. This accomplishment was reached by replacing the electron injection layer of lithium fluoride with cesium carbonate ($CsCO_3$) while incorporating microcavity structures. Currently, blue is the least-efficient color for OLEDs, affecting both color-mixing and down-converted approaches. Improvements to blue emission translate to higher-efficiency white devices for both approaches. Also conducted under the research, down-conversion phosphors were incorporated in the microcavity OLED to obtain a luminance enhancement of 1.71X and a CRI value of 87 with a combination of yellow and red phosphors. (March 2009)

Add-Vision Successfully Demonstrates High-Quality Flexible White OLED Device

Add-Vision, Inc. has demonstrated a flexible white OLED device with a CRI of 70 and a CCT of 5000 K. This important achievement supports Add-Vision's objective to develop an efficient, long-lived, low-cost, and flexible OLED. Advantages of OLED light sources are their small cross section and their flexibility, which make them easy to integrate into a variety of efficient lighting products. Development of efficient lighting products will significantly reduce energy consumption for lighting. (March 2009)

Universal Display Corporation Progresses Toward Commercially Available OLED Panels

Universal Display Corporation (UDC) has fabricated a white OLED device of 5 cm x 5 cm that achieves 68 lm/W, a lifetime of >10,000 hours, and a CRI of 80. This is a significant milestone that ties lifetime and color quality to efficiency while moving towards a commercially available OLED panel. The device was measured in an integrating sphere using an outcoupling lens, and results were met at lighting brightness at a color temperature of 3420 K. With this project, UDC will team with Armstrong World Industries to incorporate an OLED lighting panel into Armstrong's TechZone™ Ceiling System. (February 2009)

1.1.2 Recent SSL Program Highlights

February 2010 - DOE SSL R&D Workshop

The seventh annual Department of Energy (DOE) SSL R&D Workshop was held February 2-4 in Raleigh, NC. With 350 attendees and three days of formal and informal discussion, the workshop provided a unique opportunity to share updates and network among stakeholders from industry, academia, research institutions, and government. Both speakers and attendees offered insights on key issues impeding SSL technology advances, and ideas to move past the current limits of SSL efficacy and performance. Attendees also provided input to guide updates to the DOE SSL R&D Multi-Year Program Plan.

DOE Report Estimates Energy Savings Potential of SSL

The U.S. Department of Energy (DOE) has released analysis findings of the energy savings potential of SSL sources for general illumination applications compared to conventional light sources (e.g., incandescent and fluorescent). Using an econometric model of the U.S. lighting market, the February 2010 report estimates national energy savings if SSL technology achieves certain forecasted price and performance objectives. Over the analysis period, spanning 2010–2030, the cumulative energy savings are estimated to total approximately 1,488 terawatt-hours, representing $120 billion at today's energy prices. These savings would reduce greenhouse gas emissions by 246 million metric tons of carbon. To download a PDF of the report, go to http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_energy-savings-report_10-30.pdf

2009 Transformations in Lighting: Sixth Annual DOE SSL R&D Workshop

In February 2009, more than 400 attendees—lighting industry leaders, chip makers, fixture manufacturers, researchers, academia, lighting designers, architects, trade associations, energy efficiency organizations, and utilities—gathered in San Francisco to share insights and updates on technology advances and market developments. The annual DOE SSL workshop provides a forum for building partnerships and strategies to accelerate technology advances and to guide market introduction of high-efficiency,

high-performance SSL products. Attendees also had an opportunity to provide input to guide updates to the DOE SSL R&D Multi-Year Program Plan. A PDF copy of the workshop report is available at:
http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/workshop_report09.pdf.

DOE Launches New SSL Manufacturing R&D Initiative

As SSL technology advances, challenges emerge that require a fresh approach and a new focus on manufacturing issues. In FY09, DOE launched an SSL manufacturing R&D initiative, which has two primary objectives: to enhance product consistency and quality and to accelerate cost reductions through manufacturing improvements. A third objective is to encourage domestic U.S.-based manufacturing of SSL products.

To create a working roadmap for SSL manufacturing R&D, DOE hosted two workshops where chip makers, fixture and component manufacturers, and others could join DOE in exploring issues related to materials, equipment, process control, and other factors that influence SSL product quality and cost. The first workshop, held in April 2009 in Fairfax, Virginia, was attended by nearly 200 lighting technology leaders, who focused on identifying key barriers on the path to lower-cost, higher-quality SSL products and making recommendations as to what should be done, who should do it, when they should do it, and what DOE's role should be. Participants were also encouraged to submit white papers describing their views on how the goals would be achieved. Their insights and recommendations were used to draft a "strawman" manufacturing R&D roadmap for review at the second workshop.

In the second workshop, held in June in Vancouver, Washington, the "strawman" R&D roadmap was reviewed and discussed by well over 150 attendees. The feedback from the Vancouver workshop led to a published version of the roadmap, issued in September, that represents industry consensus on the expected evolution of SSL manufacturing, best practices, and opportunities for collaboration. This roadmap will be updated annually so that it can serve as a long-term tool to guide the development of SSL manufacturing R&D, with an eye to accelerating market introduction of SSL for maximum national energy savings. The hope is that, by identifying key goals, target metrics, and a timeline, it will provide a common industry focus, reduce risk, and foster cooperation where appropriate.

The roadmap is an extension of the DOE SSL R&D Multiyear Program Plan, which for years has guided DOE efforts to accelerate the development and market introduction of high efficiency, high performance SSL products. It will be used to inform and guide planning for the new manufacturing initiative, including solicitations for manufacturing R&D projects. A PDF copy of the roadmap is available at:
http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl-manufacturing-roadmap_09-09.pdf.

Voices for SSL Efficiency 2009: DOE and Midwest Energy Efficiency Alliance Host Market Introduction Workshop

More than 280 attendees gathered in Chicago, Illinois, to participate in the "Voices for

SSL Efficiency 2009" workshop in July. The workshop, hosted by DOE and the Midwest Energy Efficiency Alliance, was the fourth DOE meeting to explore strategies for successful market introduction of high-quality, high-efficiency SSL solutions. Representatives from industry, utilities, and efficiency organizations, plus federal, state, and local government shared tools and guidance for assessing LED products, strategies for implementing programs and incentives, the latest on LED product performance and reliability, and cost effectiveness trends and factors. Designers and specifiers shared their perspective on using today's LEDs, and retailers and distributors offered perspective on marketing LED products.

L Prize℠ Receives First Entrant

In September 2009, the Bright Tomorrow Lighting Prize (L Prize) competition received its first entrant, a product from Philips Electronics. Sponsored by DOE, the L Prize competition challenges industry to develop LED replacements for two of the most widely used and inefficient types of light bulb—the common 60-Watt bulb and the PAR-38 halogen reflector-lamp bulb. Philips' entry is intended to replace incandescent bulbs. Philips' entry will now begin a rigorous multiphase evaluation process. Performance testing conducted by independent laboratories will be followed by long-term lumen maintenance testing and field assessments conducted with utility and other partners. For more information, see: http://www.lightingprize.org/.

Lighting Facts Initiative Gains Traction

In FY09, DOE launched the SSL Quality Advocates initiative featuring the Lighting Facts label. LED luminaire manufacturers can participate in this voluntary pledge and labeling program and use the Lighting Facts label, similar to the familiar Nutrition Facts label, to demonstrate their commitment to accurate and consistent reporting of product performance claims. The Lighting Facts label provides a quick summary of product performance data in five areas—lumens, efficacy, input power, CCT, and CRI—as measured by the industry standard for testing photometric performance, IES LM-79. The Lighting Facts web site provides access to the program, including on-line pledge agreements, partner lists and products that have been registered to use the Lighting Facts label. In just one year, more than 290 manufacturers, 80 retailers, and another 95 lighting designers and energy efficiency organizations have all taken the Lighting Facts pledge. There is now a list of 500 LED products that have been approved to use the Lighting Facts Label. For more information, see: www.lightingfacts.com.

DOE Issues Six Competitive Solicitations Related to SSL

During FY09, DOE issued six competitive solicitations related to SSL:

- Core Technology Research, Round VI
- Core Technology Research Call for National Laboratories, Round VI
- Product Development, Round VI
- Manufacturing R&D, Round I
- Small Business Innovation Research, Phase I
- Small Business Innovation Research, Phase II

The Department reviewed 249 proposals in FY09 and then selected and initiated 25 projects. Selections for Round VI solicitations will be made in FY10.

Results from DOE-Funded Projects: Patents and Publications
As of August 2009, a total of twenty four SSL patents have been granted as a result of DOE-funded research projects. This demonstrates the value of DOE SSL projects to private companies and notable progress toward commercialization. Since DOE began funding SSL research projects in 2000, a total of 94 patents' applications have been applied for or awarded as follows: large businesses - 44, small businesses - 20, universities - 26, and national laboratories - 4. For the list of patents awarded for DOE funded SSL research, see Appendix A.

1.2 Legislative Directive

EPACT 2005, enacted on August 8th 2005, issued a directive to the Secretary of Energy to carry out a "Next Generation Lighting Initiative" (NGLI) to support the R&D of SSL:[4]

> ***"(a) IN GENERAL.—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.***
> ***(b) 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; more energy-efficient; and cost-competitive, and have less environmental impact…"***
>
> **Energy Policy Act of 2005**

The legislation directs the Secretary of Energy to support research, development, demonstration, and commercial application activities related to advanced SSL technologies. This law specifically directs the Secretary to:

- Develop SSL technologies based on white LEDs that are longer lasting, more energy-efficient, and cost-competitive compared to traditional lighting technologies.
- Competitively select an Industry Alliance to represent participants that are private, for-profit firms that, as a group, are broadly representative of United States SSL research, development, infrastructure, and manufacturing expertise.
- Carry out the research activities of the NGLIA through competitively awarded grants to researchers, including Industry Alliance participants, National Laboratories, and research institutions.
- Solicit comments to identify SSL research, needs, and progress. Develop roadmaps in consultation with the industry alliance.
- Manage an on-going development, demonstration, and commercial application program for the NGLIA through competitively selected awards.

The Secretary may give preference to participants of the Industry Alliance. Excerpts from EPACT 2005 describing the NGLIA can be found in Appendix B**.**

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[4] Section 911 of Energy Policy Act of 2005, Pub. L. 109-58, enacted on August 8, 2005, authorizes $50 million for each fiscal year 2007 through 2009 to the NGLI, with extended authorization for the Secretary to allocate $50 million for each of the fiscal years 2010 to 2013. In total, Congress proposed $350 million for R&D investment in SSL.

As a result of the next generation lighting initiative, DOE and the Next Generation Lighting Industry Alliance (NGLIA) signed a Memorandum of Agreement (MOA) detailing a strategy to enhance the manufacturing and commercialization focus of the DOE portfolio by utilizing the expertise of this organization of SSL manufacturers in February 2005. This document can be found in Appendix C.

In addition to signing an MOA with NGLIA, DOE also issued an Exceptional Circumstances Determination to the Bayh-Dole Act to facilitate more rapid commercialization of SSL technologies in June 2005. The determination places guidance on intellectual property generated under the Core Technology program area, which creates technology breakthroughs that can be widely applicable to future products. See Appendix A for a full version of the Exceptional Circumstances Determination.

Building on EPACT 2005 the Energy Independence and Security Act (EISA), Pub. L 110-140 was enacted on December 19, 2007.[5] EISA instituted the "Bright Tomorrow Lighting Prizes." The "Bright Tomorrow Lighting Prizes" establishes prizes for a SSL product with an efficacy of 90 lm/W to replace an incandescent 60W lamp, a SSL product with an efficacy of 123 lm/W to replace halogen PAR 38 lamps, and a SSL product with an efficacy of 150 lm/W. After the prizes are awarded, the Federal Government may purchase the lamps for its own facilities. More information on the "Bright Tomorrow" Lighting Prizes is at: http://www.lightingprize.org/.

EISA 2007 also mandated increases in the energy efficiency of general service incandescent lamps by 2012 and directs the Secretary of Energy to initiate a rulemaking for general service lamps (LEDs, OLEDs, general service incandescent lamps, and compact fluorescent lamps) by January 1, 2014. This rulemaking is to establish standards for general service lamps that are greater or equal to 45 lm/W by January 1, 2020. EISA 2007 also authorizes a lighting R&D program of $10 million per year for fiscal years 2008-2013, to terminate by September 30, 2015. The legislation specifically directs the Secretary 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
- Assist manufacturers of general service lamps in the manufacturing of general service lamps that, at a minimum, achieve the wattage requirements required by the legislation.

Accounting for the directives issued in EPACT 2005 and EISA 2007, the Energy and Water Development and Related Agencies Appropriations Act 2010, Pub. L 111-85, enacted on October 28, 2009, authorizes $27 million to the DOE for SSL R&D.

[5] EISA 2007 can be found in its entirety at: http://frwebgate.access.gpo.gov/cgi-bin/getdoc.cgi?dbname=110_cong_bills&docid=f:h6enr.txt.pdf

1.3 Global SSL Market

The global lighting fixtures market is expected to reach $94 billion by 2010, and SSL is expected to play a substantial role in the market by that time.[6] Sales of high-brightness LEDs (HB–LEDs), the technology associated with LEDs for lighting applications, were $5.3 billion in 2009.[7] Of these HB-LED revenues, approximately 12% (or $636 million) was attributable to general illumination applications.[8]

Foreign governments have recognized the importance of supporting the development of SSL technology among their industrial and academic institutions. For example, the German Federal Ministry of Education and Research (BMBF) has recently awarded 3-year grants to four teams developing OLED technology for lighting. The total investment in these four programs exceeds $80M. Many of the participants in these programs are also receiving support from the European Union.

DOE recognizes that steps taken to increase research funding could encourage the production of more energy efficient SSL, thus supporting the conservation goals embedded in the strategic direction of DOE. Through a proactive, collaborative approach, DOE anticipates that its cost-shared projects will deliver substantial energy savings and position U.S. companies as global leaders. SSL R&D investments can help secure our nation's energy future and technological leadership in products, systems and services.

1.4 Federal Role in Supporting the SSL Initiative

A part of the DOE's overarching mission is to advance the national, economic, and energy security of the United States and to promote scientific and technological innovation in support of that mission. DOE has five strategic themes toward achieving the mission. Of these five themes, the Science Discovery and Innovation Theme aligns best with the SSL portfolio[9]:

> *Strengthening U.S. scientific discovery, economic competitiveness, and improving quality of life through innovations in science and technology*

The SSL portfolio funds research, development, and demonstration activities linked to public-private partnerships. The government's current role is to concentrate funding on high-risk, pre-competitive research in the early phases of development. Currently, the majority of the SSL program's activities are in the area of applied technology R&D, which includes efforts that are in our national interest and have potentially significant public benefit, but are too risky or long-term to be conducted by the private sector alone. As SSL activities progress through the stages of developing technology to validating technical targets, the government's relative cost share, although perhaps not its absolute cost burden will diminish. The government will bring technologies to the point where the

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[6] "Lighting fixtures market to exceed $94 billion by 2010." August 2007. Available at: http://www.ledsmagazine.com/news/4/8/3
[7] Robert Steeles at the Strategies in Light Conference. Santa Clara, CA. February 10 – 12, 2010.
[8] Does not include signage, mobile appliances, signals, automotive, or electrical equipment.
[9] More information on Department of Energy strategic mission, vision, and themes available at: http://www.cfo.doe.gov/strategicplan/strategicplan.htm

private sector can successfully integrate SSL into buildings and then decide how best to commercialize technologies. And, as this technology advances, the federal role of the DOE will become even more important in order to keep the focus on saving energy.

1.5 DOE Goals and Solid-State Lighting

The SSL Portfolio falls under the Building Technologies Program (BT) in the Office of EERE. Listed below are the goals of EERE, BT, and the SSL Portfolio.

1.5.1 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;
- Lead by example through government's own actions; and
- Change the way EERE does business.

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.

David Garman, former Assistant Secretary for EERE, launched the November 2003 SSL Workshop with a keynote address highlighting the importance of SSL technology. Mr. Garman discussed creating a focused partnership between government and industry, to accelerate SSL technology with the potential to reduce energy consumption, to create affordable long-lasting general illumination technology, to strengthen U.S. leadership in this critical technology area, and to provide the necessary infrastructure (people and policy) to accelerate market adoption. Indicators of success would be two quads of energy per year displaced, a market price of $3 per kilolumen, and the creation of new forms of lighting systems that improve our quality of life.

Mr. Garman outlined the reasons why the United States needs a national research initiative in SSL:

- To maintain its leadership position in SSL, it must compete with other countries' government funding efforts.
- White-light sources represent a higher risk R&D investment that industry is unlikely to fund in the near term.
- The projected energy savings for the U.S. is significant.

1.5.2 Building Technologies Program

The Building Technologies Program is designed to reduce America's growing dependence on energy by developing technologies to increase the energy efficiency of buildings. This mission was chosen because of the benefits associated with reducing building energy consumption, potential energy security, reliability benefits and environmental benefits. Additionally, in support of the President's policies and initiatives, BT has embraced the program goal of developing Zero Energy Buildings (ZEB) to reduce national energy demand.

The mission of DOE's Building Technologies Program is:

> *To 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.*

1.5.3 Solid-State Lighting Portfolio Goal

The goal of DOE lighting R&D 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 lighting R&D activities, shaped by input from industry leaders, research institutions, universities, trade associations, and national laboratories. Through interactive workshops, DOE and its partners identified SSL as a high-priority research area.

The goal of the SSL portfolio is:[10]

> *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*

[10] The SSL goal has been slightly reworded in the 2010 MYPP to reflect that the SSL spectral output should resemble the "visible portions" of the sunlight spectrum and may deviate from that spectrum in the infrared and ultraviolet portions.

percent with lighting that closely reproduces the visible portions of the sunlight spectrum.

This goal of increasing the energy efficiency of lighting technologies directly supports BT's vision of ZEBs. Specifically, SSL sources will "*greatly reduce needs for energy through efficiency gains,*" which reduces the balance of energy consumption that must be supplied by renewable sources. The commercialized efficacy goal of SSL is to reach an order of magnitude increase in efficacy over incandescent luminaires and nearly a two-fold improvement over fluorescent luminaires. Advances in the efficiency of SSL will reduce the number of power plants being constructed and improve the reliability of the grid. This SSL portfolio goal also dovetails directly into EERE's strategic goal to "*increase the energy efficiency of buildings and appliances.*"

This Multi-Year Program Plan provides a description of the activities that the SSL R&D Portfolio will undertake over the next few years to implement this mission. This plan is a living document, updated periodically to incorporate new analyses and progress, and new research priorities, as science evolves.

1.5.4 Cross-Area Coordination

The DOE SSL program has coordinated with a variety of agencies and organizations. Below is a list of organizations in which some of this coordination has occurred. Chapter 5 provides further detail on the activities associated with each of these partnerships.

American Lighting Association (ALA)
American National Standards Institute (ANSI)
Canadian Standards Association (CSA)
Consortium for Energy Efficiency (CEE)
Defense Advanced Research Projects Agency (DARPA)
DOE Federal Energy Management Program (FEMP)
ENERGY STAR®
Federal Trade Commission (FTC)
Illuminating Engineering Society of North America (IESNA)
Institute of Electrical and Electronics Engineers (IEEE)
International Association of Lighting Designers (IALD)
International Commission on Illumination (CIE)
International Electrotechnical Commission (IEC)
Midwest Energy Efficiency Alliance (MEEA)
National Electrical Manufacturers Association (NEMA)
National Institutes of Standards and Technology (NIST)
National Science Foundation (NSF)
Next Generation Lighting Industry Alliance (NGLIA)
Northeast Energy Efficiency Partnerships (NEEP)
Underwriters Laboratories (UL)

2.0 SSL Technology Status

2.1 Brief History of Lighting Technologies[11]

The last century of lighting has been dominated by incandescent, fluorescent and high-intensity discharge (HID) light sources.

In 1879, Joseph Swan and Thomas Edison independently developed the first electric lamp based on principles of a blackbody radiator. In the United States, Thomas Edison developed the first incandescent lamp using a carbonized sewing thread taken from his wife's sewing box. His first commercial product, using carbonized bamboo fibers, operated at about 60 Watts for about 100 hours and had an efficacy of approximately 1.4 lm/W. Further improvements over time have raised the efficacy of the current 120-volt, 60-Watt incandescent lamp to about 15 lm/W for products with an average lifetime of 1,000 hours.

In 1901, Peter Cooper Hewitt, an American inventor, patented the first low-pressure mercury vapor (MV) discharge lamp. It was the first prototype of today's modern fluorescent lamp. George Inman, working for General Electric, improved upon this original design and created the first practical fluorescent lamp, introduced at the New York and San Francisco World's Fairs in 1939. Since that time, the efficacy of fluorescent lighting has reached a range of approximately 65-100 lm/W, depending on lamp type and wattage.

In 1801 Sir Humphry Davy, an English chemist, caused platinum strips to glow by passing an electric current through them. In 1810, he demonstrated a discharge lamp to the Royal Institution of Great Britain by creating a small arc between two charcoal rods connected to a battery. This led to the development of high-intensity discharge lighting, but the first high-pressure mercury vapor lamp was not sold until 1932. In 1961, Gilbert Reiling patented the first metal halide (MH) lamp. This lamp demonstrated an increase of lamp efficacy and color properties over MV, which made it more suitable for commercial, street and industrial lighting. The MH lamp was introduced at the 1964 World's Fair. The first high-pressure sodium (HPS) lamp was introduced soon after in 1965. Since that time, the efficacy of HID lighting has reached a range of approximately 45-150 lm/W, a value which again is dependent on lamp type and wattage.

In the 1950s, British scientists conducted experiments on the semiconductor gallium arsenide (GaAs), which exhibited electroluminescence or the emission of a low level of infrared light, leading to the creation of the first "modern" light-emitting diode (LED). In 1962, the first practical visible-spectrum light-emitting diode (LED) was invented at General Electric's Advanced Semiconductor Laboratory.[12] After subsequent improvements in this technology, the first commercial visible (red) light LEDs were fabricated in the late 1960s using gallium arsenide phosphide (GaAsP). In the mid 1970s, green LEDs were produced using gallium phosphide (GaP). The first blue LEDs

[11] *Lighting a Revolution*. National Museum of American History. Smithsonian Institute.
[12] Holonyak and Bevaqcua, Applied Physics Letter, Volume 1, pp.82-83 (1962).

emerged in the 1990s using gallium nitride (GaN). Combining the red, green, and blue LEDs or coating the blue LEDs with a yellow phosphor led to the creation of white LEDs, a promising, high-efficiency technology for general illumination. Parallel to efforts to create white LEDs, researchers have been working to improve the efficacy of the technology. Present day LED commercial packages have reached efficacies of 132 lm/W, while commercial luminaires have reached efficacies of 62 lm/W exceeding the efficacies of many fluorescent and certain HID systems[13, 14]

In the late 1970s, Dr. Ching Tang at Eastman Kodak discovered that sending an electrical impulse through a carbon compound caused such materials to glow. Continuing research in this vein, Dr. Ching Tang developed the first organic light-emitting diode (OLED). A paper on his research was published in 1987.[15] Since then researchers have developed white OLED devices that have reached efficacies up to 90 lm/W in the laboratory. Companies have only recently begun to offer white OLED products commercially. These OLED panels are primarily prototype products and offer efficacies as high as 23 lm/W.

The traditional three light sources – incandescent, fluorescent (which includes compact fluorescent and linear fluorescent) and HID – have evolved to their present performance levels over the last 60 to 120 years of R&D. Industry researchers have studied all aspects of improving the efficiency of these sources, and while marginal incremental improvements are possible, there is little room for significant, paradigm-shifting efficacy improvements. SSL technology, such as LEDs and OLEDs, on the other hand, has potential to achieve a near two-fold improvement over some of today's most efficacious white-light sources. Figure 2.1, developed from historical lighting catalogues and the SSL projections discussed in chapter 4, depicts this potential.

[13] Efficacies of incandescent, fluorescent, and HID lamps from Audin, L., Houghton, D., et al. *Lighting Technology Atlas.* E Source, Inc., Boulder, CO (1997). (p 2.2.5)
[14] For a definition of "LED Package," see Section 4.2.1.
[15] C. W. Tang, S. A. VanSlyke, Organic electroluminescent diodes, Appl. Phys. Lett. 1987, 51, 913

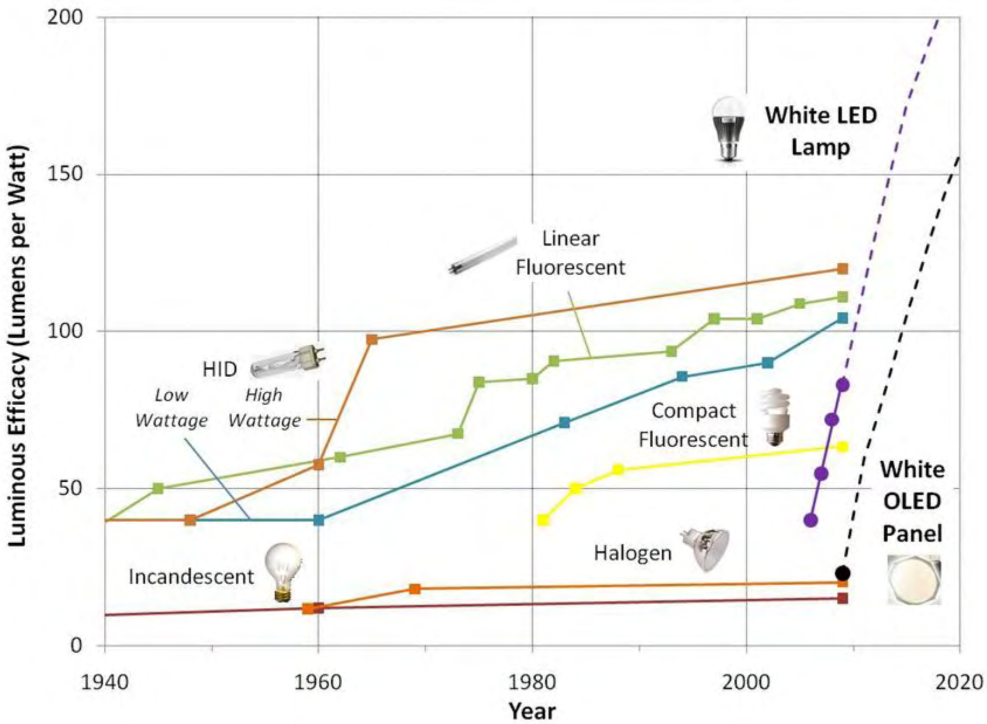

Figure 2.1: Historical and Predicted Efficacy of Light Sources[16]
Source: Navigant Consulting, Inc - Updated Lumiled's chart with data from product catalogues and press releases

2.2 Current National Lighting Needs

Lighting is the second largest end-use of energy in buildings.[17] New lighting technologies offer one of the greatest opportunities for energy savings potential within the building sector.

2.2.1 Lighting Energy Use in Buildings

The Energy Information Administration estimates total U.S. electricity consumption to be 39.0 quads in 2009.[18] The DOE estimated that lighting technologies across all sectors

[16] LED Luminaire and OLED panel projections based on Chapter 4. SSL data points have not been tested by independent sources. Luminous efficacies depicted are for lamps with lumen output similar to following technologies:

60 Watt incandescent lamp;
75 Watt halogen lamp;
100 Watt HID lamp (low Wattage);
400 Watt HID lamp (high Wattage);
15 Watt CFL; and
4-foot MBP 32 Watt T8 lamp.

[17] 2009 Building Energy Data Book, U.S. Department of Energy, Office of Planning, Budget and Analysis, Energy Efficiency and Renewable Energy. Prepared by D&R International, Ltd., October 2009. Available at: http://buildingsdatabook.eren.doe.gov/

[18] Annual Energy Outlook 2010 Early Release. U.S. Energy Information Administration. Available at: http://www.eia.doe.gov/oiaf/aeo/index.html

were responsible for 9.84 quads of electricity in 2009, or 25% of the U.S. total.[19] Lighting constitutes approximately 12 percent of residential building energy consumption and 25 percent of commercial building energy consumption.[17] This electricity consumption figure does not include the additional loads due to the heat generated by lighting, which is estimated to be up to 40 percent in a typical "stock" building. Improving the efficiency and decreasing the cost of SSL will have a large contribution toward DOE's goal of a net-zero energy building.

In 2002 an in-depth study of lighting energy consumption in the U.S. during 2001 was performed by the DOE.[20] Figure 2.2 provides the break-down by end-use sector of the energy consumption for lighting our homes, offices and other metered applications around the country as reported in this study.

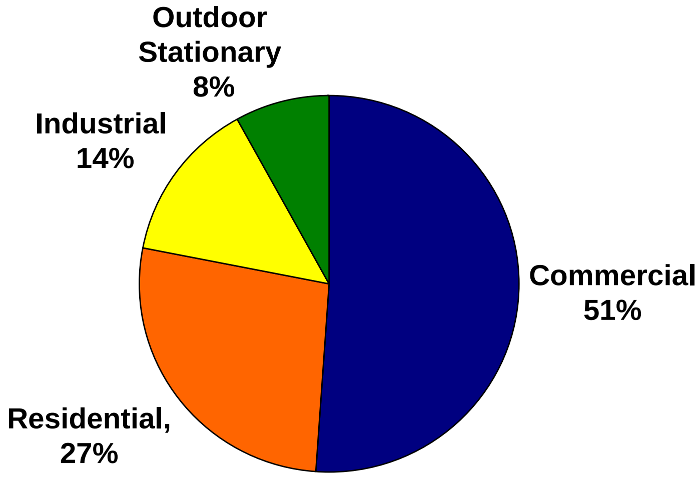

Figure 2.2: Total U.S. Primary Energy Consumption for Lighting by Sector, 2001

Figure 2.2 shows that more than half of energy consumed by lighting in 2001 was for the commercial sector, the largest energy user for lighting. This is one of the principal markets the DOE has targeted to develop more efficient technologies.

2.2.2 Description of Competing Technologies

While Figure 2.2 presented the end-use energy for lighting in terms of primary energy consumption (quads) in 2001, Figure 2.3 presents the same data, disaggregated by sources, in terms of terawatt-hours per year (TWh/yr). These units represent the electrical energy measured by the site meters for lighting throughout the United States. Figure 2.3 illustrates the end-use electricity consumed by incandescent, fluorescent and high-intensity discharge lamps.

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[19] Energy Savings Potential of Solid State Lighting in General Illumination Applications 2010-2030. Prepared by Navigant Consulting, Inc. for the Department of Energy. Washington D.C. February 2010. Available at: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_energy-savings-report_10-30.pdf

[20] U.S. Lighting Market Characterization Volume I: National Lighting Inventory and Energy Consumption Estimate. Prepared by Navigant Consulting, Inc. for the Department of Energy. Washington D.C. September 2002.

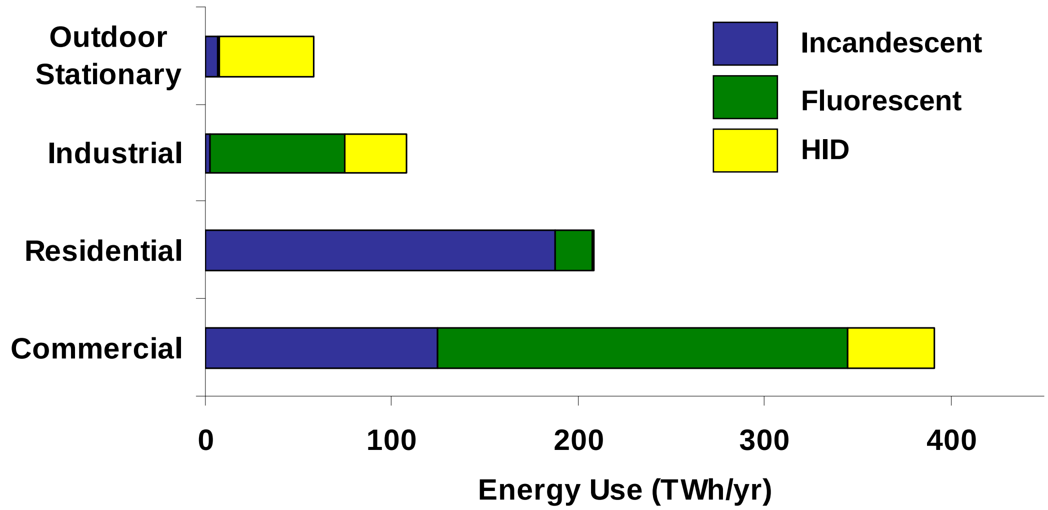


Figure 2.3: Lighting Energy Consumption by Sector & Source
Source: *U.S. Lighting Market Characterization Volume I: National Lighting Inventory and Energy Consumption Estimate.* Prepared by Navigant Consulting, Inc. for the Department of Energy. Washington D.C. September 2002.

The lighting end-use energy consumption chart in Figure 2.3 shows that fluorescent sources in the commercial sector were the single largest energy-consuming segment in the U.S. in 2001, slightly greater than incandescent sources in the residential sector. However, across all sectors, incandescent lighting was the leading energy consumer in the U.S., consuming 321 TWh/yr. Fluorescent lighting was second with about 313 TWh/yr and HID was third with approximately 130 TWh/yr.

Figure 2.3 shows that outdoor stationary energy consumption was primarily from HID sources in 2001, which accounted for 87% of its 58 TWh/yr of electricity use. The industrial sector had sizable energy shares of both fluorescent and HID sources, 67% and 31% respectively, of this sector's 108 TWh/yr consumption. The commercial sector was the largest energy user overall, having large quantities of energy used by all three light sources. Fluorescent and incandescent sources were the two largest commercial lighting energy users, accounting for 56% and 32% of its annual 391 TWh/yr of electricity use in 2001. In the residential sector, energy use for lighting was primarily driven by incandescent technologies; 90% of the lighting energy was consumed by this light source.

In September 2005, the DOE published U.S. Lighting Market Characterization Volume II: Energy Efficient Lighting Technology Options.[21] This report looks broadly at energy-efficient options in lighting and identifies leading opportunities. Volume II presents fifty-two technology options that promise to save energy or demonstrate energy savings potential. The options encompass both conventional technologies such as incandescent, fluorescent, and HID, as well as SSL.

[21] U.S. Lighting Market Characterization Volume II: Energy Efficient Lighting Technology Options. Prepared by Navigant Consulting, Inc. for the Department of Energy. Washington D.C. September 2005.

Since 2001, lighting energy consumption has been affected by a general trend towards more efficient technologies. For example, in the commercial and industrial sectors, highly efficient T5 fluorescent lamps were introduced in the beginning of the decade and have steadily gained market share, achieving 2% of sales in 2005.[22] In addition, HID lamps have seen significant efficacy improvements as ceramic metal halide lamps have replaced mercury vapor lamps in high bay commercial, industrial, and outdoor applications. Also, since 2001, CFLs have taken market share away from incandescent lamps, accounting for over 25% of all residential lamp sales in 2009.[23]

2.3 Current Technology Status

2.3.1 Performance of Light Sources

Table 2.1 presents the performance of 2009 SSL products on the market[24] 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.. However, persistent market barriers, such as high prices and color consistency issues (discussed in Section 4.4), prevent LEDs from gaining a competitive advantage.

[22] Technical Support Document for Energy Conservation Standards for General Service Fluorescent Lamps and Incandescent Reflector Lamps. Department of Energy. July 2009.
[23] "CFL Market Share Rises During Second Quarter", Association of Electrical and Medical Imaging Equipment Manufacturers, August 2009
[24] It should be noted that LED laboratory prototypes reach much higher efficacies than those listed in Table 2.1.

Table 2.1: Performance of Solid State Lighting Compared to Conventional Lamp Technologies in 2009

Lamp Type	Luminous Efficacy	Luminous Output	Wattage	CCT (Typical)/ Dominant Wavelength	CRI	Lifetime
LED White Package (Cool)	132 lm/W	139 lm	1.05 W	6500 K	75	50k hours
LED White Package (Warm)	78 lm/W	87.4 lm	1.12W	3150 K	80	50k hours
LED Lamp (Warm)	62 lm/W	650 lm	10.5 W	3000 K	92	50k hours
OLED Panel[25]	23 lm/W	15 lm	0.65W	2800 K	75	5k hours
HID (High Watt) Lamp System	120 lm/W 111 lm/W	37800 lm	315W 341W	3000 K	90	20k hours
Linear Fluorescent Lamp System	111 lm/W 97 lm/W	2890 lm 5220 lm	26W 54W	4100 K	85	25k hours
HID (Low Watt) Lamp System	104 lm/W 97 lm/W	7300 lm	70W 75W	3000 K	90	12k hours
CFL	63 lm/W	950 lm	15W	2700 K	82	12k hours
Halogen	20 lm/W	970 lm	48W	2750 K	N/A	4k hours
Incandescent	15 lm/W	900 lm	60W	3300 K	100	1k hours

Notes: For LED packages (defined in Section 4.2.1) - drive current density = 35 A/cm^2, T_j=25°C., batwing distribution, lifetime measured at 70% lumen maintenance. Sodium lamps are not included in this table. Source: GE 2009, Cree 2009, Philips Lighting 2009, OSRAM Sylvania 2009 product catalogs, LED lamp based on CALiPER testing.

[25] The Orbeus product referenced here is commercially available but is not large enough to meet the strict definition of a panel described in Section 4.2.2.

2.3.2 First Cost of Light Sources

The prices of light sources are typically compared on a price per kilolumen basis. The first costs for today's principal lamps indicate the degree of the challenge facing SSL in the marketplace in 2009:

Incandescent Lamp (A19 60W)	$0.30	per kilolumen
Compact Fluorescent Lamp (13W)	$2	per kilolumen
Fluorescent Lamp-and-Ballast System (F32T8)	$4	per kilolumen[26]
LED Lamp	$128	per kilolumen[27]
OLED Panel[25,28]	$25,000	per kilolumen[29]

Although on a normalized light output basis LEDs are more than 430 times the cost of the incandescent light bulb and more than 50 times the cost of a CFL,[30] the price of the LED has significantly dropped over the years and will continue to drop. Over the next several years, as performance improves and price drops, LED light sources are projected to become competitive on a first-cost basis.

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

The following chart shows how the light output of LEDs has increased 20 fold each decade for the last 40 years, while the cost ($/lumen) has decreased ten-fold each decade over that same time period. Figure 2.4 also shows predictions for price and light output over the next decade.

[26] 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 2009 prices.

[27] LED lamp price from SSL Research and Development Manufacturing Roadmap available at: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl-manufacturing-roadmap_09-09.pdf

[28] "LED lamp" and "OLED panel" are defined in Sections 4.2.1 and 4.2.2.

[29] OLED panel price for low volume purchase of Osram ORBEOS product.

[30] Because LEDs can be more directional than conventional technologies, comparing them on a lumen per lumen basis based on the lamp may not be entirely accurate. For example, if a CFL and LED lamp emitted the same lumens, there could be more light from the LED luminaire reaching a specific surface than the light from the CFL luminaire.

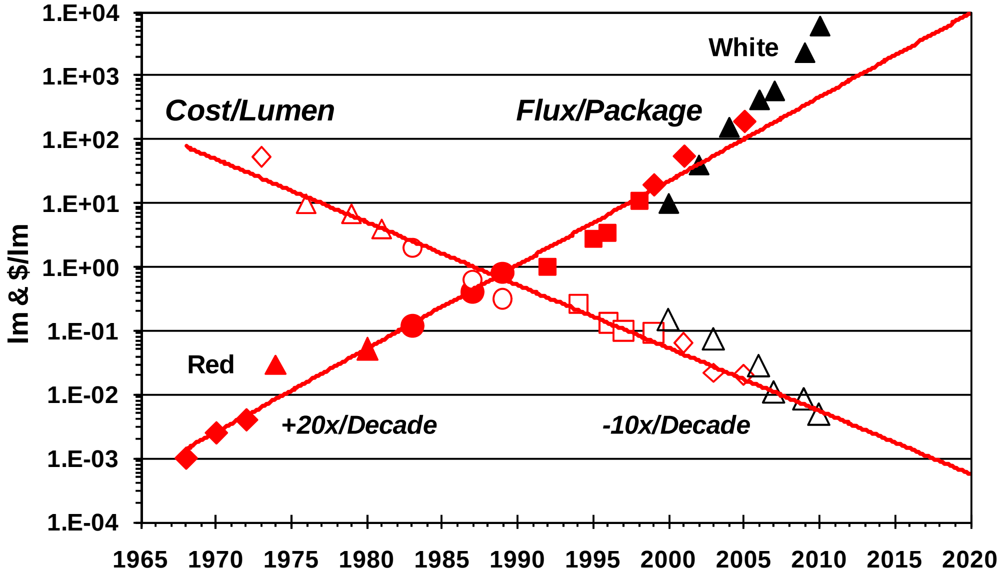


Figure 2.4: Haitz's Law: LED Light Output Increasing / Cost Decreasing
Source: Roland Haitz 2010
Note: Both lines are on the same numerical scale (with different units)

2.3.3 The Cost of Light

Considering the value of energy savings and lifetime may allow a modest premium over the initial cost of traditional technologies. Life-cycle cost, the effective "cost of light," can be estimated by including lamp cost, energy consumption and maintenance over a lighting service period. The unit used for this lighting service period is dollars per kilolumen-hour ($/klm-hr): [31]

$$CostOfLight = \left(\frac{1}{LampLumens}\right) \times \left(\frac{LampCost + LaborCost}{Lifetime} + EnergyUse \times EnergyCost\right)$$

Where:

LampLumens = the light output of the lamp measured in lumens

LampCost = the initial cost (first cost) of the lamp in dollars

LaborCost = the labor cost necessary to replace a lamp in dollars

Lifetime = the useful operating life of the lamp, expressed in 1000 hours

EnergyUse = the power consumption of the lamp, expressed in Watts

EnergyCost = the cost of the electricity necessary to operate lamp in $/kWh

By this measure, it can be argued that LED-based illumination is already a viable economic alternative for many applications. For instance, although incandescent lamps have a very low cost and high lumen output compared with LEDs, the LED source has a much longer lifetime and consumes far less power. In fact, using the equation above and

[31] IES Lighting Handbook, 9th Edition. Lighting Economics, p25-1.

looking at a finite quantity of light emission (one million lumen-hours), typical LEDs already have a slightly lower "cost of light" than incandescent and halogen sources today (Figure 2.5). While consumers may not always acknowledge the full lifetime benefit of LED technologies, many will be willing to pay some portion of this energy savings as a first-cost premium.

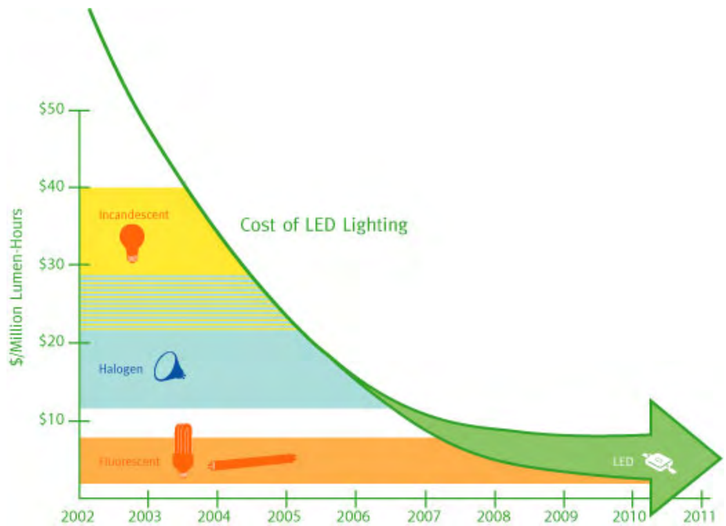


Figure 2.5: Cost of Light

Note/Source: To see how these values were calculated, please see the complete paper: "Cost of Light – When does Solid-state Lighting make Cents?" by Kevin Dowling, Color Kinetics, September 12, 2003 Available at: http://www.colorkinetics.com/support/whitepapers/CostofLight.pdf and http://www.colorkinetics.com/energy/cost/

In the case of conventional technologies, the price and performance are not projected to change drastically, and the cost of light will remain relatively constant. However, as LED efficacy improves and the first cost decreases, the "cost of light" for LED lighting will continue to decrease, and eventually reach the point where it is more cost effective on a life-cycle basis than fluorescent lighting (Figure 2.5).

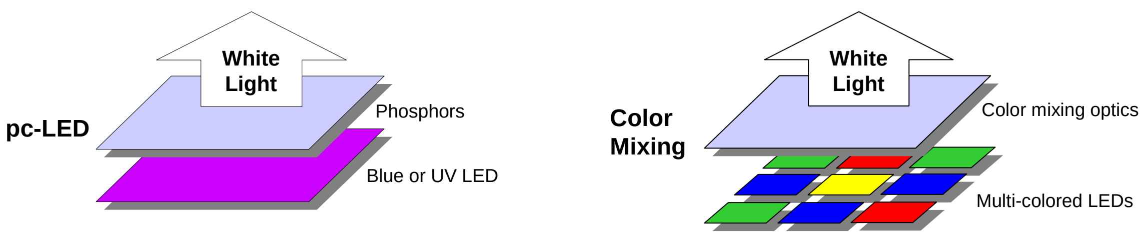
The combination of a low lifetime cost and several unique technical attributes (such as color quality and robustness) gives LEDs a competitive advantage in many real world installations. The DOE GATEWAY program has showcased several of these installations, and provided data on the cost effectiveness. In a GATEWAY demonstration completed in 2009 in an Oregon grocery store, freezer case lighting was retrofitted with LED luminaires. Annual cost savings from reduced electricity consumption was found to be approximately $220 which equates to a simple payback from energy savings alone of 6.3 years. Maintenance savings were estimated to further reduce the payback to approximately 5.4 years.[32]

[32] Additional examples of the real world cost of LED light can be found at: http://www1.eere.energy.gov/buildings/ssl/gatewaydemos.html

2.3.4 Technology Status: Inorganic Light-Emitting Diodes

In 1962, the first practical visible-spectrum LED was invented at General Electric's Advanced Semiconductor Laboratory.[33] This LED consisted of a GaAsP alloy with a p-n homojunction. The performance of this technology improved over the next few years, culminating in the commercial release of red LEDs in the late 1960s. While the efficacy of these first LEDs was extremely low (~ 0.1 lm/W), researchers continued to improve the technology over the next three decades, achieving higher efficiencies and expanding the range of emission wavelengths through the engineering of new III-V alloy systems, thus providing the wide array of high-brightness LEDs on today's market.

LEDs are discrete semiconductor devices with a narrow-band 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, the narrow spectral band of an LED's emission must be converted into white light or two (or more) discrete emissions must be mixed. White-light LED luminaires are typically based on one of three common approaches: (a) phosphor-conversion, (b) discrete color-mixing, and (c) a hybrid consisting of phosphor (white) and monochromatic packages (or different LEDs in a single package). Figure 2.6 shows two of these approaches to white-light production.



(a) Phosphor-Conversion LED (pc-LED) **(b) Color-Mixing LED**

Figure 2.6: General Types of White-Light LED Packages

The phosphor-converting LEDs primarily create white light by blending a portion of the blue light emitted directly from the die with light emission down-converted by a phosphor. Discrete color-mixing packages, on the other hand, utilize color mixing optics to blend together the light output from discrete colored sources, creating white light. In the phosphor-converting blue LED approach, an LED die emits blue light, generally around 460nm. Some of this light is emitted directly, and some of it is down-converted by a phosphor from the 460nm wavelength (blue) to longer wavelengths (e.g., green, yellow, red) with wide-band emissions that blend with the blue to produce white light. Nichia was the first manufacturer to use this method to produce white-light LED packages on a commercial scale in 1997. It has since been adopted by numerous other manufacturers as a method for generating white light. Some manufacturers have successfully lowered the color correlated temperature and increased the color rendering index by adding a second phosphor to the package, but at a cost to package efficacy. These "warm-white" packages are currently available with an efficacy of 88 lm/W and a CCT of 3000 K at a current density of 35 A/cm^2.

[33] Holonyak and Bevaqcua, Applied Physics Letter, Volume 1, pp.82-83 (1962).

One of the problems confronting manufacturers of pc-LED devices is the difficulty of maintaining consistent-quality white light due to natural variations in the LED pump wavelength and in the deposition of the phosphors. The white light produced by pc-LEDs is susceptible to variations in LED optical power, peak emission wavelength, and operating temperature, in addition variations in phosphor thickness and thermal quenching of the phosphor at different operating conditions can lead to color shift. Thus, noticeable variations in color appearance can occur from one pc-LED to another, a potentially serious problem for many lighting applications.

Stokes loss, the energy difference between the LED pump wavelength and the phosphor emission wavelength, is a fundamental limitation to the efficiency of phosphor converted LEDs. In addition, some phosphors have relatively low quantum efficiencies, most phosphors lead to optical scattering losses, and phosphor emission spectra are, generally, very broad which can reduce the luminous efficacy of radiation which reduces the maximum potential efficacy of the LED. For these reasons, discrete color-mixed LEDs are thought to promise the highest-theoretical efficacy LED devices. In color-mixing, LED packages mix direct emissions from two or more LED dies to generate white light. This approach is accompanied by its own challenges for improving the LED efficiency for emission of green wavelengths, maintaining color stability as the different LEDs respond differently to temperature variations, and blending the discrete colors. Analysis has shown that with the color-mixing approach a high luminous efficacy of radiation can be achieved for good color quality white light. The principal advantage of the color-mixing method is that it does not involve phosphors, thereby eliminating phosphor conversion and scattering losses in the production of white light. The largest challenge is the absence of efficient emitters of green light, which significantly limits achievable efficacy. Another drawback is increased complexity. Blending discrete colors potentially requires multi-die mounting and potentially sophisticated optics. It may also require color control feedback circuitry to address the different degradation and thermal characteristics of the discrete LED dies.

2.3.5 Technology Status: Organic Light-Emitting Diodes

OLEDs are thin-film multi-layer devices based on organic molecules or polymers. They consist of: 1) a substrate foil, film or plate (rigid or flexible), 2) an electrode layer, 3) layers of active materials, 4) a counter electrode layer, and 5) a protective barrier layer.[34] At least one of the electrodes must be transparent to light. For a diagram of an OLED, see Figure 4.3.

Materials used in OLED devices have broad emission spectra. This gives OLEDs an advantage over LEDs in that minor changes in the chemical composition of the emissive structure can tune the emission peak of the device. Therefore, getting good-quality white light from OLEDs is easier and it is anticipated that the quality of the white light will improve as OLED technology continues to develop.

[34] Organic Light Emitting Diodes (OLEDs) for General Illumination: An OIDA Technology Roadmap Update 2002. Optoelectronics Industry Development Association. November 2002. Available at: http://lighting.sandia.gov/lightingdocs/OIDA_SSL_OLED_Roadmap_Full.pdf.

OLED technology for general illumination applications is in a critical stage of development. Although OLEDs are currently being used for display applications, experts agree that without ongoing research leading to technical breakthroughs, competitive OLED technologies developed for general illumination applications may not become commercially viable. Currently, only a handful of niche OLED luminaires and panels exist. These products are produced at a high price and in very limited quantities with significant performance limitations (see Section 4.2). With continued government R&D support it is expected that OLED based general illumination products will become commercially viable and that mass marketed OLED lighting products will be available within the next year.

Although much of the work for this technology is still exploratory, research is being conducted in industry as well as at research institutions and academia. For example, SSL divisions of General Electric, Osram Sylvania, and Philips are participating in the research, positioning themselves to participate in this market when white-light OLEDs become a reality.[35] Currently, the best laboratory OLED panels have efficacies of approximately 45 lm/W.

2.3.6 Technology Trends

As LED and OLED research progresses, competing energy efficient lighting technologies are also steadily improving in efficacy and cost through the efforts of the major manufacturers, further raising the bar for market penetration of SSL. This section outlines the research directions for conventional and SSL technologies and the potential for higher efficacy lamps from this research.

Current incandescent light sources range in efficacy from 3 to 20 lm/W.[36] Research is being conducted on higher efficiency incandescent light sources and has the potential to raise the efficacy of these lamps. Basic and applied research is being conducted on advanced infrared reflectors and selective radiators that tailor the spectrum of incandescent emissions to maximize emission in the visible spectrum. Some researchers claim that these technologies may allow incandescent sources to achieve efficacies of 80 lm/W.[37]

Fluorescent lamps are typically more efficient than incandescent lamps. Efficacies for

[35] For the display industry, more than 70 companies--ranging from the OLED pioneer, Eastman Kodak, to DuPont and eMagin, a small microdisplay company based in New York--are ready to bring OLED displays to market. In March 2003, Kodak launched the first digital camera incorporating a full color OLED display. In December 2007, Sony started production on an 11" OLED TV called the XEL-1. In 2009, the first general illumination OLED panels were brought to market, Osram's ORBEOS and Philips Lumiblade.

[36] U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy. Final Report: U.S. Lighting Market Characterization, Volume I: National Lighting Inventory and Energy Consumption Estimate. 2002. Washington, D.C. Available at: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/lmc_vol1_final.pdf

[37] U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy. Final Report: U.S. Lighting Market Characterization Volume II: Energy Efficient Lighting Technology Options. 2005. Washington D.C. Available at: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ee_lighting_vol2.pdf

this technology range from 25 to 111 lm/W.[36] Linear and compact fluorescent lamp technology can improve in efficacy through a variety of research efforts. For example, researchers estimate that basic and applied research on multi-photon phosphors has the potential to raise efficacies of this light source to 200 lm/W.[37]

High-intensity discharge lamps are the most efficacious lamps currently on the market, with efficacies ranging from 25 to 150 lm/W.[36] Efforts are underway to improve the energy efficiency of high-intensity discharge lamps (which includes mercury vapor, metal halide and high-pressure sodium lamps).

Commercial LED devices have the potential to surpass the efficacy of the most efficient conventional light sources. Although the range in efficacy for commercial LEDs is currently 76 to 132 lm/W,[38] research in a variety of areas, as outlined in this report, can raise the efficacy of LEDs to approximately 230 lm/W. Laboratory efficacies for OLEDs are beginning to surpass efficacies of conventional technologies. The best laboratory efficacy for an OLED device is currently around 90 lm/W. Ongoing research needs to continue to be supported to fully realize the potential of this technology for creating efficient white light.

2.4 Current Solid State Lighting Market

2.4.1 Market Status

Presently, BT's SSL R&D portfolio is investing in activities to improve efficiency, lifetime, and quality of light all while decreasing the cost of the light sources. While SSL sources are just starting to compete for market share in general illumination applications, recent technical advances have made LEDs cost-effective in a cost of light basis for certain sizable applications in outdoor lighting and interior lighting. LED technology is capturing these new applications because it offers a better quality, cost-effective lighting service compared to less efficient conventional light sources such as incandescent or neon. In addition to energy savings, LEDs offer longer operating life (>50,000 hours), lower operating costs, improved durability, compact size and shorter startup time. Applications for white-light LED products include LED task lights, downlights, under-cabinet lighting, and outdoor lights. At the 2009 Solar Decathlon,[39] many of the universities' solar homes featured these products.

Figure 2.7 shows photographs from this event of integrated LED lighting products that the university teams chose to incorporate into their designs.

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[38] Philips Lumileds, 2009. CREE, 2009. Product Catalogs.
[39] For more information on this event, see http://www.solardecathlon.org/.

Figure 2.7: LED Technologies Employed during 2009 Solar Decathlon

In addition to the applications listed above, LEDs currently are beginning to compete with HID lamps in street lighting applications. Several cities including Raleigh, NC, Austin, TX, and Ann Arbor, MI have begun installing LED street and area lights to save both on energy and maintenance costs.[40] DOE's SSL GATEWAY program has demonstrated installations of outdoor SSL systems in several other areas across the country.[41] LEDs also have the potential to compete in many other applications. As discussed in Section 1.1.2, DOE cosponsored two design competitions called "Next Generation Luminaires" and "Lighting for Tomorrow" to encourage the use of LEDs in a variety of applications in the residential and commercial sector, respectively.[42] The Memorandum of Understanding between DOE and the Illuminating Engineering Society of North America (IESNA) is located in Appendix E, and the Memorandum of Understanding between DOE and the International Association of Lighting Designers (IALD) is located in Appendix F.

A 2008 study[43] analyzed the energy savings potential of LEDs in twelve niche markets. Figure 2.8 summarizes the on-site electricity savings and coal power plants avoided from the six of the twelve niche markets. As shown, LEDs are achieving high levels of market penetration for some niche applications. Since the 2008 study, there have been rapid changes in many of the niche markets analyzed. Thus, DOE is currently working on an update to the 2008 study.

[40] Details about the LED city program are available at: http://www.ledcity.org/.
[41] DOE's Solid-State Lighting GATEWAY program is at: http://www1.eere.energy.gov/buildings/ssl/gatewaydemos.html
[42] Details about the "Next Generation Luminaires" competition is available at: http://www.ngldc.org/. Details about "Lighting for Tomorrow" competition is available at: http://www.lightingfortomorrow.org/
[43] To review the complete analysis, please refer to the report- "Energy Savings Estimates of Light Emitting Diodes in Niche Lighting Applications," which can be found at: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/nichefinalreport_october2008.pdf.

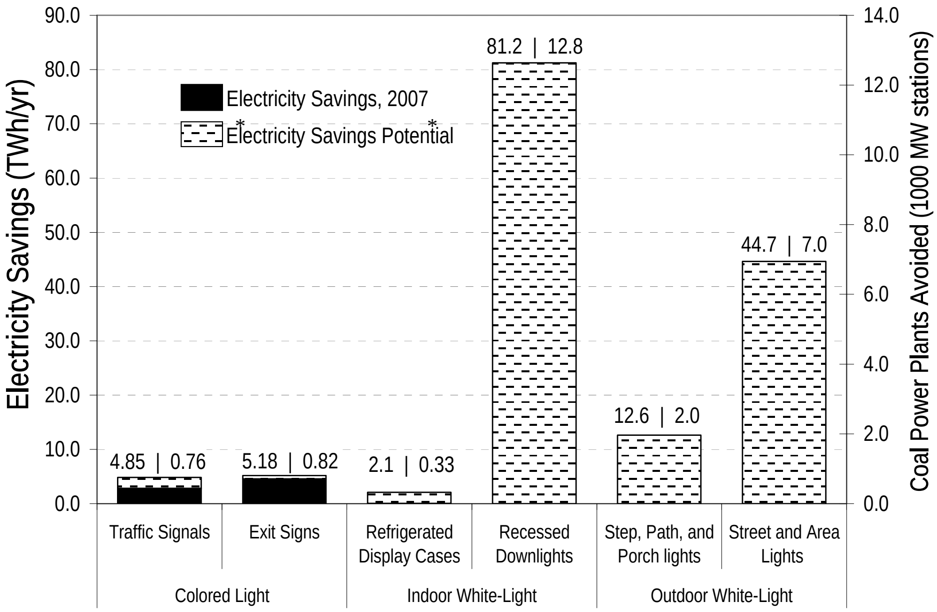


Figure 2.8: Electricity Saved, Coal Plants Avoided, and Potential Savings of Selected Niche Applications

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. October 2008.

Considering only those applications that are grid-connected, approximately 8.7 TWh of electricity consumption was saved in 2007, more than the equivalent output of one large (1,000 MW) electric power station. The following summarizes the findings for three of those niche applications:

Recessed Downlights**.** In 2007, there were approximately 829 million recessed downlights installed in commercial and residential buildings in the United States. These lamps used 103.1 TWh of energy. About 17% of the downlights were CFLs. Currently, the penetration of LEDs into the recessed downlight market is almost negligible. A complete conversion of the installed base of recessed downlights to LED technologies could save the nation about 81.2 TWh, or 876.6 TBtu of primary energy.

Step, Path, and Porch Lights**.** The penetration of LEDs into the residential outdoor step, path, and porch light market has also been negligible. Though 17% of the approximately 265 million step, path, and porch lights were CFLs in 2007, the majority of outdoor lights in these areas (82%) are particularly power-intensive incandescent and halogen systems. A complete conversion of residential step, path, and porch lights over to LED technologies would save the nation 12.6 TWh, or 136.3 TBtu of primary energy.

Street and Area Lights**.** In 2007, the majority of the 131 million street and area lights in the United States were high pressure sodium lamps, with metal halide and mercury vapor technologies comprising additional large portions of the installed base. LED lamps currently have a negligible penetration in this market. 44.7 TWh of energy (about 482.0 TBtu of primary energy) could be saved with a complete conversion of street and area lights to LED technologies. This is about 24% of the maximum energy that could be saved if all of the lamps in the twelve niche markets analyzed by this study were converted to LEDs.

A 2010 study[44] examined the national energy savings that could be realized through the market penetration of energy-efficient SSL if the technology achieves the DOE forecasted price and performance objective (Table 2.2).

Table 2.2: Energy Savings of Continued Adoption of SSL Products

SSL Performance Scenarios	**Low Improvement Conventional Technology**	**Medium Improvement Conventional Technology**	**High Improvement Conventional Technology**
Reference (Quads for lighting in 2030)	8.70 Quads	8.26 Quads	8.10 Quads
LED Scenario (Quads ***saved*** in 2030)	2.42 Quads	2.05 Quads	1.89 Quads
OLED Scenario (Quads ***saved*** in 2030)	1.77 Quads	1.51 Quads	1.39 Quads

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

Though currently SSL products have relatively low penetration in the general illumination market, with continued development of SSL technologies (both reduction in cost and improved efficacy) the energy savings is expected to reach 2.05 quads a year starting in 2030, or a 25% reduction in lighting energy use. That represents enough electricity to illuminate more than 95 million homes in the U.S. today.

2.4.2 Market Share

The market share of lighting technologies such as incandescent lamps, compact and linear fluorescent lamps, high-intensity discharge lamps, and solid-state lamps varies by market sector. Table 2.3 illustrates the average number of lamps that existed in residential, commercial, and industrial buildings in 2001, disaggregated by technology type. Close to 63% of all lamps in the market were incandescent lamps while almost 35% of these lamps were fluorescent.

[44] Energy Savings Potential of Solid State Lighting in General Illumination Applications 2010-2030. Prepared by Navigant Consulting, Inc. for the Department of Energy. Washington D.C. February 2010. Available at: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_energy-savings-report_10-30.pdf

Table 2.3: Average Number of Lamps per Building and Total Lamps, 2001

Technologies	Residential	Commercial	Industrial	Total Lamps in U.S. (millions)	Percent of Lamps
Incandescent	39	91	33	4,397	63%
Fluorescent	6	324	1,340	2,473	35%
HID	0.04	7	67	105	2%
Solid State	0	0.4	0.3	2	0.03%
Total	45	422	1,440	6,977	100%
Number of Buildings (millions)	106.9	4.6	0.2	n/a	n/a

Source: *U.S. Lighting Market Characterization Volume I: National Lighting Inventory and Energy Consumption Estimate*. Prepared by Navigant Consulting, Inc. for the Department of Energy. Washington D.C. September 2002.

Although incandescent lamps accounted for the largest number of installations in 2001, they provided only 12% of the total amount of light delivered in the United States. Fluorescent lamps, on the other hand, provided the majority of light at 62% while HID sources provided around 26% of light delivered in the country.[45] Note that the data in Table 2.3 represents the lighting market share for the year 2001. LEDs for general illumination have since increased substantially in efficacy and become less expensive such that they are beginning to enter the market, as described in Section 2.4.3. In addition other lighting trends, such as the emergence of CFLs as discussed in Section 2.2.2, have altered the market.

2.4.3 Market Views

The lighting market faces major challenges in shifting to more energy-efficient technologies because the people who decide which lighting system to purchase (typically building contractors) 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 that would cost the consumer less over the long term. Therefore, the federal government must take a leading role in supporting investments in energy-efficient lighting. This section outlines the view of industry and academic partners of the market prospects of the major lighting technologies in the market: incandescents, fluorescents, HID lamps, LEDs, and OLEDs.

After more than a century of dominance, incandescent lamps are facing serious competition in the form of energy-efficient linear and compact fluorescent lamps. The UNDP-UNEP-GEF[46] has a global initiative to support the phase-out of incandescent

[45] U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy. Energy Conservation Program for Consumer Products: Final Report: U.S. Lighting Market Characterization, Volume I: National Lighting Inventory and Energy Consumption Estimate. 2002. Washington, D.C. Available at: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/lmc_vol1_final.pdf

[46] UNDP-UNEP-GEF is a partnership among the United Nations Development Programme (UNDP), United Nations Environment Programme (UNEP), and Global Environment Facility (GEF).

lamps in non-OECD[47] countries.[48] On April 25, 2007, the Canadian Government announced its commitment to phase out the use of inefficient incandescent lamps.[49] In addition, lamp manufacturers have made voluntary commitments to improve the efficacy of incandescent lamps. For example, in June 2007, European lighting manufacturers proposed standards for incandescent lamps. In addition, EISA 2007 established efficiency standards for incandescent lamps in the U.S. These standards will require the average efficacy of incandescent lamps to increase to at least 18 lm/W by 2014. In 2020, the efficacies of general service lamps must be at least 45 lm/W. This standard is expected to lead to a complete phase-out incandescent lamps.

Compact fluorescent lamps (CFLs), on the other hand, are becoming more popular as lighting energy efficiency standards are being increased and commercial, industrial, and municipal consumers are making energy efficiency retrofits. However, there is still some resistance to switching to CFLs in the residential market because of consumer familiarity with the warm-white light produced by incandescent lamps and the low initial cost of these lamps. In addition performance issues such as slow turn-on time and dimmability associated with CFLs contributes to residential consumer hesitance to adopting this technology. In the commercial and industrial sector, the market is moving toward the use of more energy efficient fluorescent lamps with electronic ballasts.

In addition, high-intensity discharge lamps such as mercury vapor, metal halide, and high-pressure sodium lamps have been the most common lighting technologies in use for outdoor area lighting. The less-efficient mercury vapor lamps are currently being replaced by the more-efficient metal halide lamps. Conventional HID lamps are also beginning to face some competition from LEDs for certain niche applications.

High-brightness LEDs are expanding from use as indicator lights in traffic signals and exit signs to usage for general illumination purposes. Sales of HB-LEDs were $5.3 billion in 2009, and are estimated to grow to $8.2 billion in 2010. Of the HB-LED revenues, approximately $636 million, or 12%, was attributable to general illumination applications (Figure 2.9).[7] LEDs form a small but rapidly growing segment of the global

[47] OECD stands for the Organisation for Economic Cooperation and Development. OECD member countries include Australia, Austria, Belgium, Canada, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungry, Iceland, Ireland, Italy, Japan, Korea, Luxembourg, Mexico, Netherlands, New Zealand, Norway, Poland, Portugal, the Slovak Republic, Spain, Sweden, Switzerland, Turkey, the United Kingdom, and the United States.

[48] International Energy Agency Energy Efficiency and Environment Division. European Policy Developments Concerning Incandescent Lighting. 2007. Available at: http://www.energy.ca.gov/2007_energypolicy/documents/2007-06-19_workshop/presentations/PowerPoint/Paul%20Waide%20-%20Policy%20developments%20in%20Europe%20CEC%2019th%20June%202007%20v2.ppt

[49] Greentech Media. "The Lighting Market by the Numbers, Courtesy of Philips Chairman." October 2008. Available at: http://greenlight.greentechmedia.com/2008/10/22/the-lighting-market-by-the-numbers-courtesy-of-philips-chairman-676/

lighting market, estimated at $75 billion a year in 2008.[50] The U.S accounted for approximately 20% of the market ($15 billion).

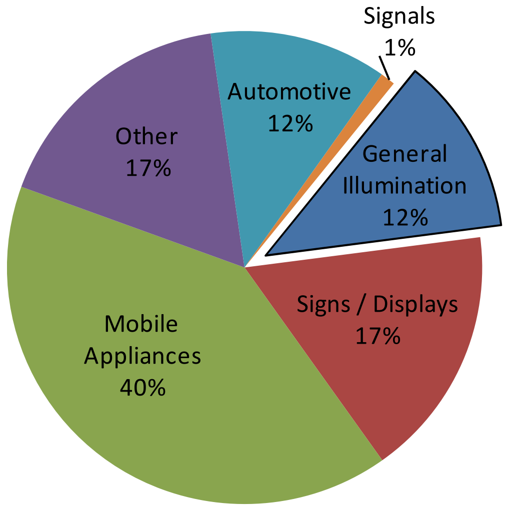


Figure 2.9: 2009 LED Market by Segment

OLEDs are still being improved in the lab, with a best reported efficacy for a white OLED device at 90 lm/W and OLED panel at 45 lm/W. Significant sales will not be achieved until progress in the laboratory is incorporated in reliable luminaires and high-volume manufacturing is established.

[50] Lighting Market size from "Building a better, greener light bulb." http://money.cnn.com/2007/02/13/magazines/fortune/gunther_pluggedin_lightbulb.fortune/index.htm?section=magazines_fortune. (2007).

3.0 Current Solid State Lighting Portfolio

This chapter offers a description of the SSL 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 concerning how the SSL project portfolio is determined is contained in Chapter 5.

3.1 Current SSL Project Portfolio

This section provides an overview of the current projects in the SSL portfolio (as of February 2010). The SSL Project Portfolio is grouped into six topic areas[51]:

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, DOE's SSL R&D agenda is further divided into tasks, which are further divided into subtasks. At the consultative workshops, participants discuss each of the tasks, and provide recommendations for prioritizing R&D activities over the next 1-2 years. The overall structure of the tasks is outlined in Appendix G. Details on the current funded tasks are presented in the tables and charts in this section, while details on the newly prioritized subtasks are presented in Chapter 4.0. Under each subtask there are a number of metrics to guide specific efforts by researchers in addressing the goals of the task.

3.2 Congressional Appropriation and Current Portfolio (March 2010)[52]

Figure 3.1 presents the congressional appropriation for the SSL portfolio from FY2003 through FY2010. The funding request for the current fiscal year (FY2010, which began in October 2009) totals $27 million. In FY 2009 an additional, one time, funding of $50 million was provided through the American Recovery and Reinvestment Act of 2009 to be used to accelerate the SSL R&D program and jumpstart the manufacturing R&D initiative.

[51] The definitions of Core Technology Research, Product Development, and Manufacturing R&D are provided in Appendix I. 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.

[52] Figures and charts in this section may not add up to stated cumulative values due to rounding.

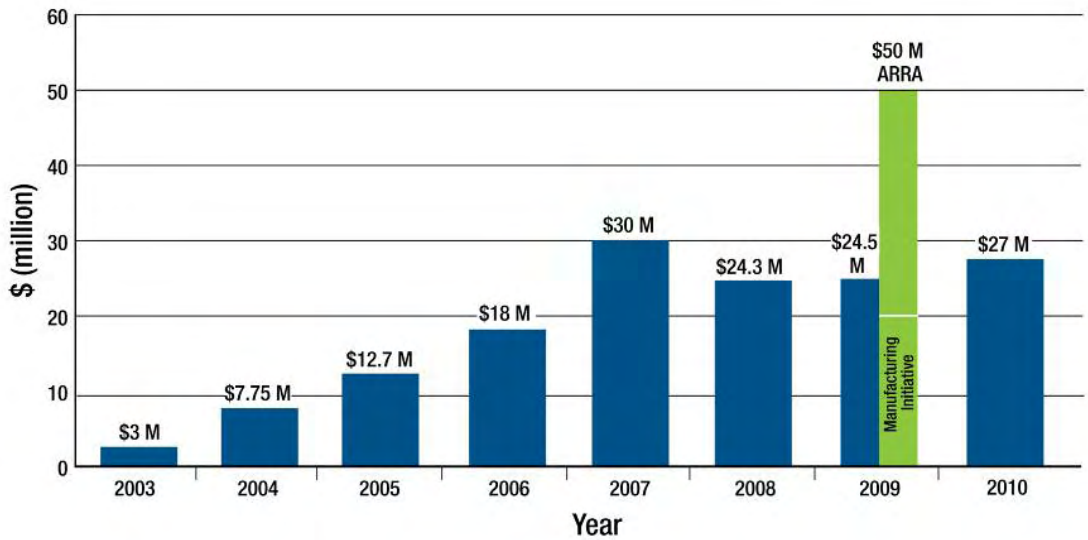


Figure 3.1: Congressional Appropriation for SSL Portfolio, 2003-2010

The current SSL DOE research portfolio as of February 2010 (not including completed projects) includes 67 projects, which address LEDs and OLEDs. Projects balance long-term and short-term activities, as well as large and small business and university participation. The portfolio totals approximately $150.7 million in government and industry investment.

Figure 3.2 provides a graphical breakdown of the funding for the current SSL project portfolio; this value represents funding levels for all active projects as of February 2010. DOE is currently providing $103.6 million in funding for the projects, and the remaining $47.0 million is cost-shared by project awardees. Of the 67 projects active in the SSL R&D portfolio, 38 were associated with LEDs and 29 were focused on OLEDs. The OLED project partners had a lower cost-share contribution ($15.6 million) than the LED project partners ($31.4 million).

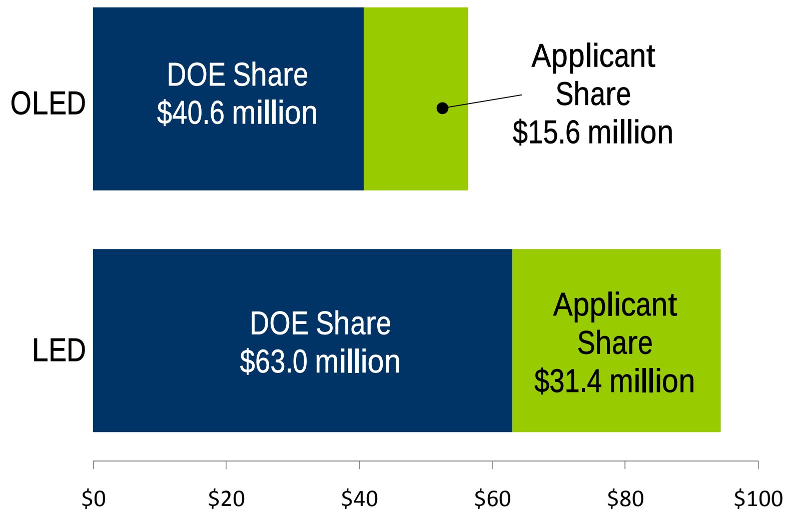


Figure 3.2: Funding of SSL R&D Project Portfolio by Funder, February 2010

Figure 3.3 shows the DOE funding sources and level of support contributing to the SSL project portfolio. The Building Technologies Program in the Office of EERE provided the majority of the funding; 57 projects receive $147.1 million (including the cost share portion) in funding from this source through the National Energy Technology Laboratory. The Small Business Innovation Research (SBIR) program in the Office of Science funded the remaining ten projects for a total of $3.6 million.

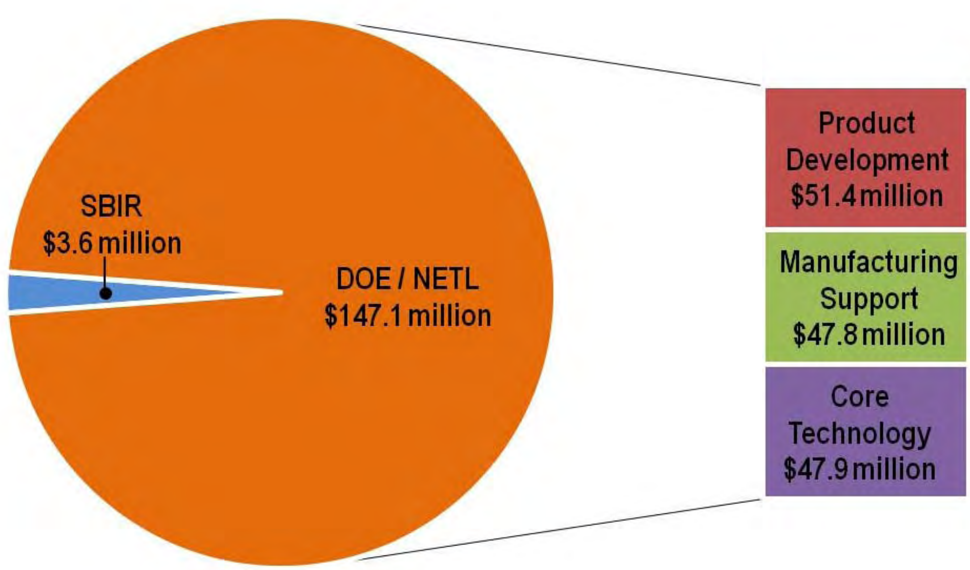


Figure 3.3: Cumulative SSL R&D Portfolio: Funding Sources, February 2010

The DOE supports SSL R&D in partnership with industry, small business, academia, and national laboratories. Figure 3.4 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 58% of portfolio funding, with $87.9 million in R&D activities. Small businesses comprise the next largest category and receive 20%, or $30.0 million, in research funds. Finally, universities and national laboratories comprise 12% and 10% of the R&D portfolio, respectively, and receive $18.3 million and $14.6 million, respectively.

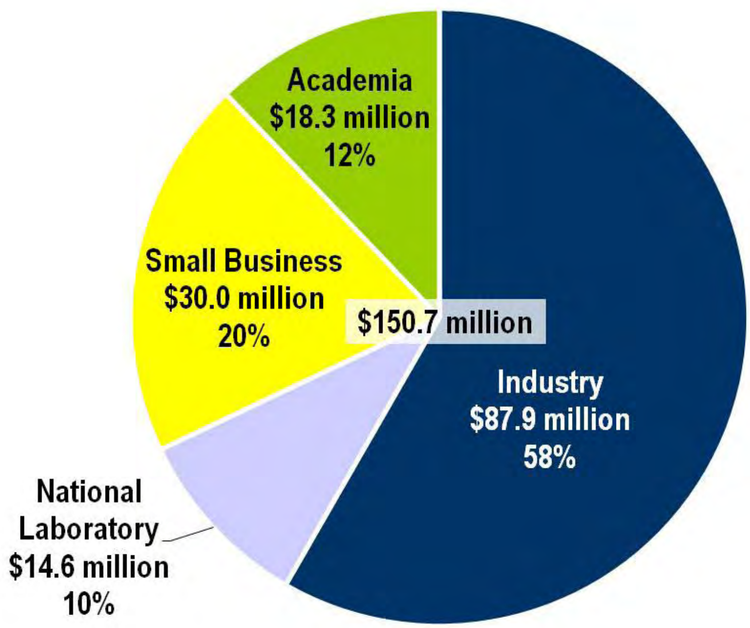


Figure 3.4: Funding Recipients of Projects in DOE's SSL R&D Project Portfolio, February 2010

Table 3.1, Table 3.2, and Table 3.3 show the total number of projects and total-project funding in the SSL portfolio by subtask. Table 3.1 shows the active projects that DOE funded or has selected for funding, keeping with the evolving priorities, under the Core Technology solicitations. Table 3.2 shows the projects that are currently funded in Product Development. Table 3.3 shows the projects that have been selected for funding in the Manufacturing R&D Initiative.

Table 3.1: SSL R&D Portfolio: Core Technology, February 2010

	Number of Projects	**$ Funding (Million)**
Light-Emitting Diodes		
Alternative Substrates	1	$1.3
Emitter Materials Research	9	$15.6
Down-converters	4	$7.3
Device Light Extraction	1	$2.5
Novel Emitter Materials and Architectures	1	$1.1
Optical Component Materials	1	$2.0
Total LED	**17**	**$29.5**
Organic Light-Emitting Diodes		
Novel Device Architecture	3	$4.0
Novel Materials	6	$9.9
Material Degradation	1	$0.8
Electrode Research	2	$3.5
Total OLED	**12**	**$18.3**
TOTAL	**29**	**$47.8**

Table 3.2: SSL R&D Portfolio: Product Development, February 2010

	Number of Projects	**$ Funding (Million)**
Light-Emitting Diodes		
Semiconductor Materials	4	$10.3
Phosphors	4	$8.7
Luminaire Mechanical Design	1	$1.1
Luminaire Thermal Management Techniques	4	$8.6
Electronic Components Research	2	$4.7
Total LED	**15**	**$33.4**
Organic Light-Emitting Diodes		
Practical Implementation of materials and device architectures	5	$7.1
OLED Device Failure	1	$0.7
Substrate Materials	2	$4.8
OLED Panel Manufacturing Technology	1	$0.1
Luminaire Mechanical Design	1	$2.4
Large Area OLED	3	$5.7
OLED Panel Packaging	1	$0.1
OLED Panel Outcoupling	1	$0.8
Total OLED	**15**	**$21.6**
TOTAL	**30**	**$55.0**

Table 3.3: SSL R&D Portfolio: Manufacturing Initiative, February 2010

	Number of Projects	**$ Funding (Million)**
Light-Emitting Diodes		
Epitaxial Growth Tools and Processing	3	$20.5
LED Chip Manufacturing	2	$9.3
Automated LED Packaging	1	$1.5
Total LED	**6**	**$31.4**
Organic Light-Emitting Diodes		
Production of OLED Lighting Prototypes	1	$8.4
Paths to High Volume Manufacturing of OLED Devices	1	$8.0
Total OLED	**2**	**$16.4**
TOTAL	**8**	**$47.8**

4.0 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. DOE's SSL R&D Portfolio focuses on meeting specific technological goals, as outlined in this document, that will ultimately result in commercial products that are significantly more energy-efficient than conventional light sources.

A part of DOE's mission, working through a government-industry partnership, is to facilitate new markets for high-efficiency general-illumination products that will enhance the quality of the illuminated environment as well as save energy. SSL sources have begun to enter the general illumination market, replacing some of today's lighting technologies in specific applications. DOE's R&D activities will work to ensure that U.S. companies remain competitive suppliers of the next generation of lighting technology in this new paradigm.

This chapter describes the objectives and work plan for future Core Research and Product Development activities under the SSL program for the next few years, and some specific targets for 2020. A separate Manufacturing Roadmap provides similar guidance for manufacturing-related R&D. Actual accomplishments will result in changes to the plan over time which will be reflected in future revisions. The process of updating the content of this chapter for FY10 began with a series of roundtable sessions convened in Washington, D.C. in November of 2009. The industry experts invited to these sessions presented short talks on current topics of interest for LED and OLED technologies and then discussed research tasks. The outcome of this meeting was a preliminary prioritization of the R&D tasks. In February, a workshop in Raleigh, North Carolina, gave representatives of various sectors of the lighting industry an opportunity to review and comment on the proposed high priority R&D tasks for 2010. After subsequent review, and considering inputs received at the workshop, DOE has defined the task priorities for 2010 as listed in Section 4.5.

4.1 Current Technology Status and Areas of Improvement

Significant progress has been made in LEDs over the past year, and several viable and efficient luminaire products have reached the market. Some of these products are beginning to establish significant sales volumes including the Cree LR6 downlight, which has now sold in excess of 350,000 units. LED package technology successfully met the first milestone set by DOE's multi-year plan and appears to be ahead of schedule for the next one. As a result, LED luminaires are now routinely more efficient than incandescent sources and can exceed the efficacy of CFLs in certain applications.[53] More work will be necessary to assure that luminaires and power conditioners do not excessively degrade the performance or lifetime of the packages. Further innovation will be necessary both to

[53] *DOE Solid-State Lighting CALiPER Program: Summary of Results: Round 3 of Product Testing.* http://www1.eere.energy.gov/buildings/ssl/caliper.html

reach efficiencies that can compete with linear fluorescent lamps, and to achieve high-efficiency packages with a warmer light (i.e., lower correlated color temperature).

Rapid progress has been made in the laboratory performance of OLED pixels and panels and the performance of OLED based lighting has the potential for higher efficacy than many of the available luminaires on the market today. OLED panels from pilot lines in Europe and Japan have become available over the last two years. For example, the Orbeus prototype panel from Osram shown in Figure 4.1 has a diameter of 79mm, luminous output of ~3000 lm/m^2, color temperature of 2800K, CRI of 80, efficacy of 23 lm/W, and lifetime of 5000 hours.[54] The total light output of this panel is still very low, but the design appears to be scalable to larger areas. In order for OLEDs to become competitive, brighter emission and the ability to scale up in size, while keeping a uniform light output across the entire panel, are needed.

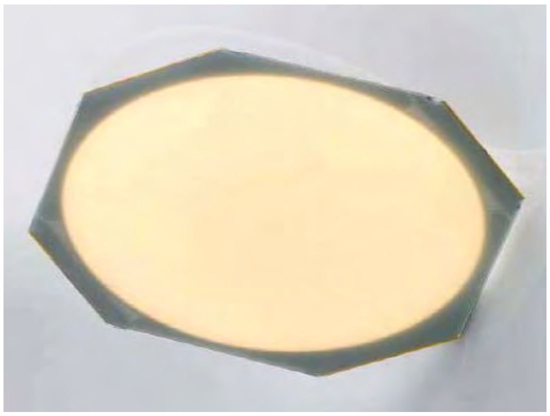


Figure 4.1: Orbeus Prototype OLED Panel
Photo source: OSRAM Opto-Semiconductor

The next section sets forth working definitions of the various components of a SSL luminaire in order to provide a common language for describing and reporting on the R&D progress.

4.2 Components of the SSL Luminaire

Subsequent sections of this multiyear plan describe both LED and OLED 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.

4.2.1 Components of LED Luminaires

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, Addendum a, as updated and released in 2008 and as further amended in 2009, still pending final approval.

[54] The area of this prototype is approximately 50 cm^2 and is not large enough to meet the DOE SSL strict definition of an "OLED panel."

Component level (no power source or driver)

- LED refers to a pn junction semiconductor device (also referred to as "chip") that emits incoherent optical radiation when forward biased. The optical emission may be in the ultraviolet, visible, or infrared wavelength regions.

- LED Package refers to an assembly of one or more LEDs, including the mounting substrate, encapsulant, phosphor if applicable, electrical connections, and possibly optical components along with thermal and mechanical interfaces.

- LED Array or Module. Several LED packages may be assembled on a common substrate or wiring board (possibly with additional optical components and mechanical, thermal, or electrical interfaces) to be connected to the LED driver.

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 assembly that is integrated with an LED driver and has an ANSI standardized base for connection directly to an electrical branch circuit.

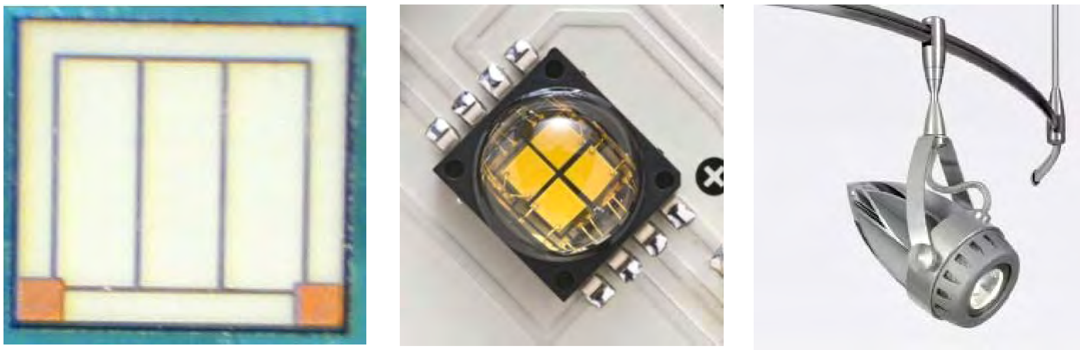
    - Non-Integrated LED Lamp refers to an assembly with an ANSI standardized base but *without* a built-in LED driver. Non-integrated LED lamps are designed for connection to LED luminaires.

- LED Light Engine (proposed definition) consists of LED packages or modules together with a driver, optical, mechanical, and thermal components intended to be directly connected to a branch circuit through a custom connector (not an ANSI-standard base).

- LED Driver refers to a power source with integral control circuitry designed to operate an LED package or module or lamp. Note that this definition includes the power source for conversion to DC from the electrical branch circuit, not just the controlling electronics. This is sometimes a point of confusion.

- LED Luminaire refers to the complete lighting unit, intended to be directly connected to an electrical branch circuit. It consists of a light source and driver along with parts to distribute the light and to connect, position, and protect the light source.

Figure 4.2, below, illustrates a few of these definitions.



LED **Package** **Luminaire**

Figure 4.2: Photos of LED Components
Photo sources: Cree, Journée

4.2.2 Components of OLED Luminaires

The core of a typical OLED light source is a stack of thin films with a total thickness of 100-200 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, a mechanism must be provided to distribute the current uniformly over the lamp and to protect the active layers from environmental damage.

- OLED Pixel is a small-area device (usually less than 1 cm^2) used for R&D that is roughly analogous to an LED. 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 light or light of a single color.

- OLED Panel refers to an OLED with a minimum area of 200cm^2. At a luminous emittance of 3,000 lm/m^2, a 200 cm^2 panel will emit 60 lumens, but this will increase as higher emittances are achieved. The OLED panel approximately corresponds to an LED array or module. It may be made up of a stack of continuous layers or an array of discrete pixels and generally contains elements to enhance the current spreading over the entire area of the panel. The OLED panel may also incorporate packaging, thermal management, and components to enhance light extraction. It is expected that the OLED will serve as a building block component for OLED luminaires.

- 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.

- The OLED Driver converts line voltage to appropriate power and current for the device and includes any necessary electronic controls.

Geometries that emit downward through a transparent substrate or upward from a reflective substrate are currently being considered for OLEDs. The simple planar structure shown in Figure 4.3 below displays an OLED which emits downward through a transparent substrate. These structures typically employ a reflective, metal cathode.

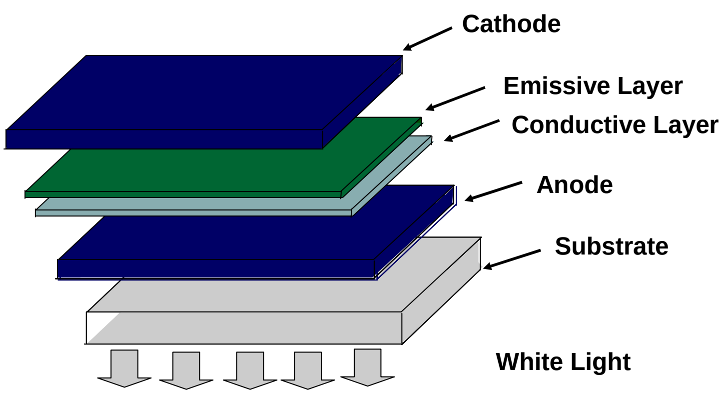


Figure 4.3: Diagram of OLED Device Structure and Photo of OLED Panel
Photo source: General Electric

It is also possible to manufacture an OLED with a highly transparent cathode (typically with up to 80% transmission across the visible spectral region). These structures can emit upward from a reflective substrate, such as a reflective metal foil, or can be entirely transparent devices. Figure 4.4 displays an entirely transparent OLED panel employing a transparent substrate and cathode.

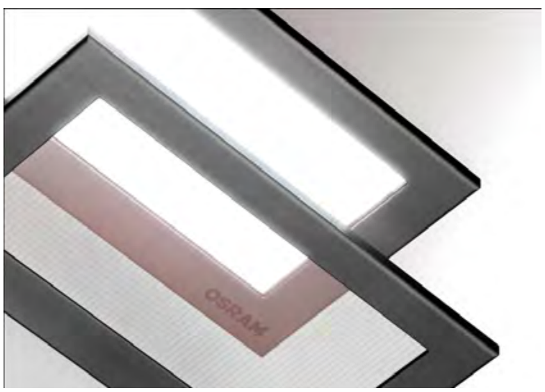


Figure 4.4: Photo of a Transparent OLED Lighting Panel
Photo source: OSRAM Opto-Semiconductor

Factors Affecting Luminaire Efficacy

To further define the relationship among the components of luminaires and to highlight relative opportunities for efficiency improvements, one can identify various elements of power efficiency, both electrical and optical, within the LED Package or OLED Panel (either is an “SSL Device” in the discussion which follows) and for the luminaire as a whole. Generally, the losses identified result from the conversion of electrical or optical energy into heat. In addition the efficiency of converting optical radiated power into useful light (lumens) 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 color temperature and color rendering index (or color quality scale) and the spectrum generated by the SSL devices.

The *luminaire efficacy*, a key metric for the DOE SSL program, is the ratio of *useful* light power radiated (visible lumens) to the electrical power (Watts) applied to the *luminaire*. The *SSL device* efficacy refers to the ratio of lumens out of the *SSL device* to the power applied to the SSL device at room temperature, thus not including the driver, luminaire optical, or thermal efficiencies. This technology plan forecasts both SSL device efficacy and luminaire efficacy improvements. It is important to keep in mind that it is the luminaire efficacy that determines the actual energy savings.

Opportunities for improvement of the SSL device include: reducing electrical and optical 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. Tailoring of the spectrum to the eye response is constrained by the need to provide light of appropriate color quality (correlated color temperature and color rendering index).

The following sections compare efficiencies achieved by 2009 for individual luminaire and SSL devices to set program goals for LED and OLED technologies to be achieved by 2020. These consensus goals were developed in consultation with the LED and OLED Roundtable groups and further refined by individual follow-up with industry experts and contributions from the R&D Workshop. It is important to realize there may be significantly different allocations of loss for any specific design, which may also result in an overall efficient luminaire. The allocation of example 2009 efficiency values and 2020 targets used in the sections to follow, however, serves as a guide for identifying the opportunities for improvement. It is not, however, the program’s intention to impede novel developments that use a different allocation of losses that may result in a better overall luminaire performance.

4.2.3 Light-Emitting Diode-Based Luminaries

As described in section 2.3.4, white-light LED luminaires are typically based on one of three approaches:

a) phosphor-converted LEDs (pc-LEDs)
b) discrete color-mixing LEDs
c) a hybrid consisting of phosphor (white) and monochromatic packages (or different LEDs in a single package)

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 ohmic losses within the package and the loss of any charge carriers that do not arrive at the active region of the package. When resistive losses are low, the voltage is essentially the breakdown voltage which is approximately the bandgap energy divided by the electronic charge. Ohmic losses in the LED material and electrode injection barriers add to the forward voltage. This efficiency also includes the injection efficiency, which reflects any loss of charge carriers that occurs away from the active region of the package.
- *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.[55]
- *Light Extraction efficiency* is the ratio of photons emitted from the encapsulated chip into air to the 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.[56] It is the product of the IQE and the extraction efficiency.
- *Current Droop* represents the difference in IQE (at 25C) between the peak, very low current density, value and that reported as nominal, commonly 35A/cm^2. Luminaires may operate at an ever higher current density resulting in additional current droop, defined below.
- *Phosphor conversion efficiency* 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. *Color-mixing efficiency* refers to losses incurred while mixing the discrete colors in order to create white light (not the spectral efficacy, but just optical losses).
- *Scattering efficiency* is the ratio of the photons emitted from the LED package to the number of photons emitted from the semiconductor chip. This efficiency, relevant only to the phosphor-converting LED in Figure 4.5 accounts for scattering losses in the phosphor and encapsulant of the package.
- *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

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[55] 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).

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

CCT, the CRI (or CQS), and the intrinsic spectral properties of the source. 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 120V 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.

- *Additional current droop* results when the package is operated at a higher than the nominal 35A/cm^2 current density. This is often done in practice since it can dramatically reduce the overall cost by requiring fewer LED packages to realize a given total lumen output. Reducing the droop sensitivity of the LED can reduce this additional loss.

- *Flux thermal sensitivity* is the ratio of the lumens emitted by the 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.[57] The thermal efficiency can be improved by minimizing temperature rise through innovative thermal management strategies or perhaps by reducing the thermal sensitivity of the LED package itself

- *Phosphor thermal sensitivity* is an additional cause of efficiency loss as the phosphor temperature increases at the operating temperature of the luminaire.

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

Phosphor-Converted LED

Figure 4.5 summarizes an analysis of the various sources of efficiency loss, as defined above, in a PC-LED. 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

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[57] 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.

improvement, that is, the difference between today's efficiency and the MYPP 2020 "target". These efficiencies are independent of spectrum of the emitted light to first order; they represent simply the conversion of electricity to light without regard to the usefulness of that light as measured against the human eye visual sensitivity to color. The table 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 $35 A/cm^2$. Target efficiencies represent DOE's goals for the SSL program for 2020.

The estimates in this chart, and the similar figures following, are based on a correlated color temperature (CCT) of 3100 K and a color rendering index (CRI, R_a) of at 85.[58] Different solutions for varying applications, color temperatures, or color rendering may have a different breakdown of loss than this specific example, but the variations are not large.

The overall electrical to optical power conversion efficiency is the product of these separate channel efficiencies. The LED package efficacy is then the product of the electrical-to-optical conversion, the spectral efficiency, and LER_{max}, which is about 411 lm/W for this specific example.

[58] There have been ongoing studies led by NIST to devise a more accurate metric for measuring color accuracy of a light source. The resulting new Color Quality Scale (CQS) is likely to be accepted as a standard in the coming year. Until then, we will continue to use CRI as a measure of color quality, recognizing that the optimum spectrum as measured with that metric may differ somewhat from that determined by CRI. These changes are not likely to materially change the overall targets or status, however.

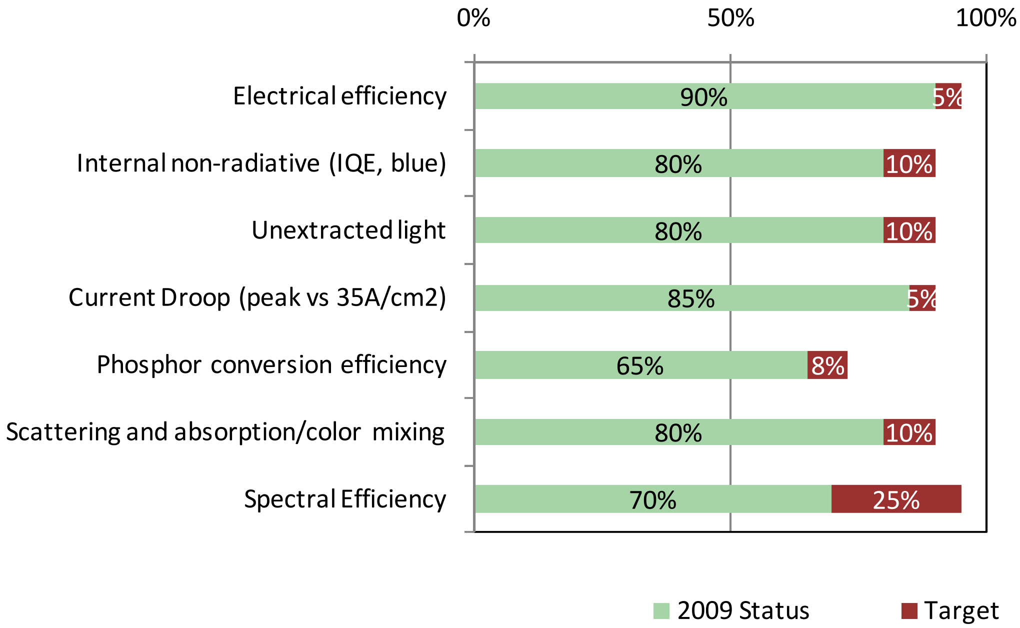

Figure 4.5: Phosphor-Converting LED Package Loss Channels and Efficiencies

Notes:

1. Efficiencies are as typically reported at 25°C and 35 A/cm^2.
2. The analysis assumes a CCT of 3100K 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 includes the loss due to the Stokes shift (90% quantum yield times the ratio of the average pumped wavelength and the average wavelength emitted). The value here is typical of a blue diode/yellow phosphor system, and different phosphor formulations will differ.
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 about a 5% gain in efficiency to be had by eliminating this loss.

While the above spells out the efficiency of the LED package, the ultimate usefulness of SSL depends on than luminaire design that effectively uses the LEDs. In this case, that means minimizing the additional losses associated with operating the LED in steady state at temperature and at a current density that makes sense from an economic and lifetime perspective. Figure 4.6 delineates luminaire loss channels and, like the LED package figure above, shows current status and the MYPP 2020 targets. Reducing the sensitivity to current density comes up as a significant opportunity for higher efficacies at lower costs, 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. For the case of the PC-LED this is summarized in Table 4.1. 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 of about a factor of five over today's luminaire performance.

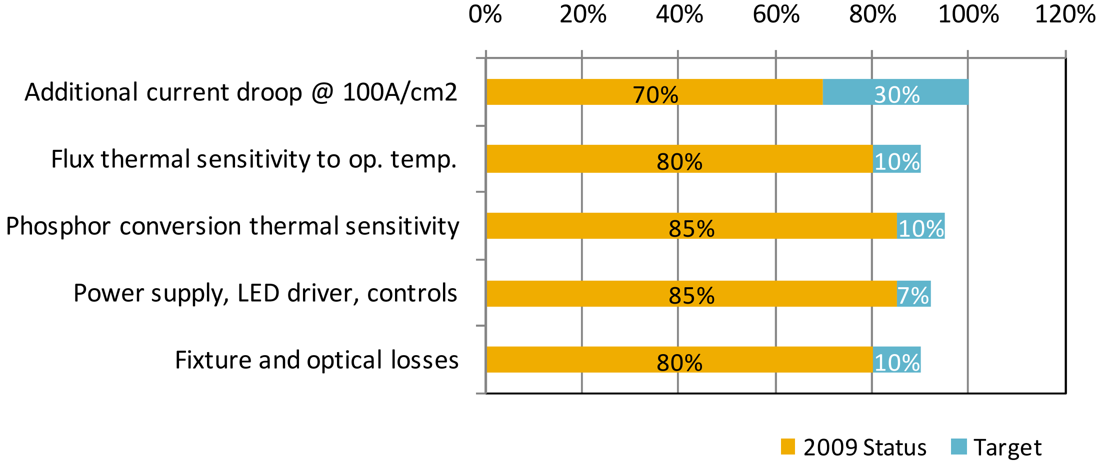

Figure 4.6: Sources of Loss in a PC-LED Luminaire
Notes: Refer to Figure 4.5.

Table 4.1: Summary of PC-LED Luminaire Efficiencies and Efficacies

Metric	2009 Status	2020 Target
LED Package Conversion Efficiency	25%	46%
Spectral Efficiency	70%	95%
LED Efficiency including spectrum	18%	43%
LED Efficacy (LER_{max} = 411 lm/W)	73	178
Overall Luminaire Efficiency (at 100C, 100A/cm^2)	5.8%	31%
Luminaire Efficacy	24	126

Note: Overall luminaire efficiency includes both LED and effects in Fig 1.6, i.e., all sources of loss in the product.

Color-Mixed LED

Figure 4.7 provides a similar analysis to the above for a color-mixed LED package. For simplicity, three colors are used, although a fourth color, e.g. amber, or even more colors could be used to improve the spectrum. The definitions for the various efficiencies are the same as listed for Figure 4.5. 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 really an estimate of what could be done today. Significantly, the lack of a green LED of reasonable efficiency shows up as a very large gap in capability today.

Because there is no Stokes loss, the color-mixing LED is theoretically capable of slightly higher efficacies than the pc-LED although the benefit is somewhat offset by the additional need for color mixing optics. Also, there are design issues of color-mixing luminaires that must be taken into account, such as additional driver complexity and cost. Other options are possible for obtaining different color temperatures or color rendition indices using a hybrid approach. For example, a warm white color can be achieved by mixing phosphor-converted white LEDs with monochromatic red or amber LEDs. In fact, several very successful high efficacy warm-white luminaires employing this hybrid approach have recently appeared on the market.

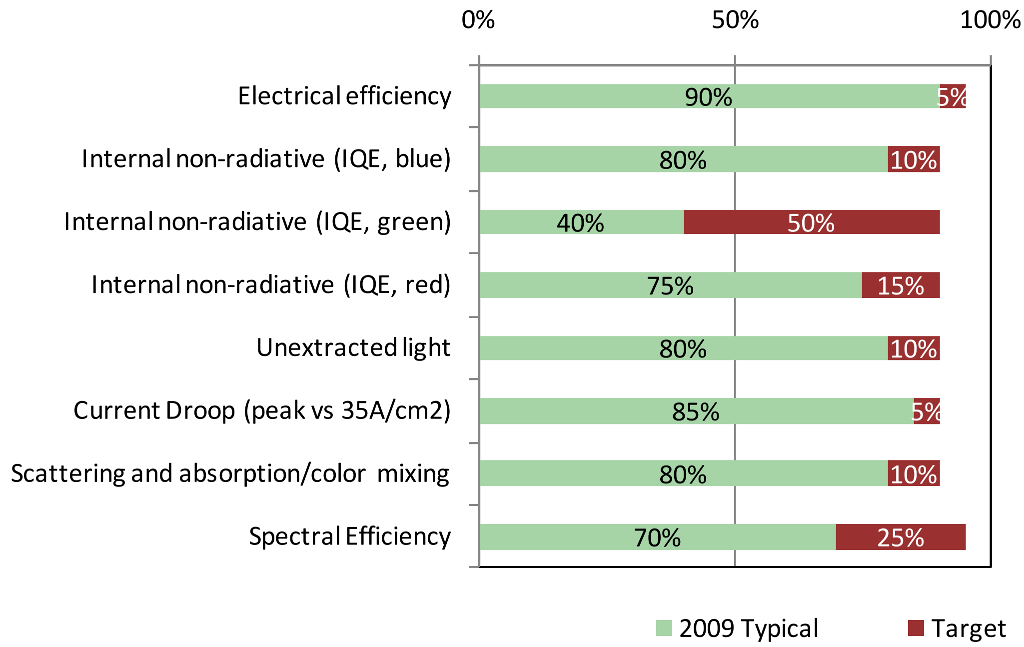

Figure 4.7: Color-Mixing LED Package Loss Channels and Efficiencies

Notes:

1. Efficiencies are as typically reported at 25°C and 35 A/cm^2.
2. The analysis assumes a CCT of 3100K and CRI of 85. Different choices of CCT/CRI will lead to slightly different results.
3. IQE statuses and targets assume wavelengths of 610 nm for red, 540 nm for green, and 450 nm for blue.
4. The efficiency allocation shown in this figure is only one example of how the luminaire efficiency target can be met.

Over the course of the program, performance improvements will make possible the manufacturing of packages with lower color temperature and better CRIs without seriously degrading the efficiency. Achieving the efficiency targets identified in Figure 4.7 will require more efficient emitters (particularly in the green area of the spectrum) and other improvements elsewhere in the luminaire. The internal quantum efficiencies of the LEDs range from 40% to 80%, depending on color. The ultimate goal is to raise the IQE to 90% across the visible spectrum, bringing the total package conversion efficiency, independent of spectral efficiency, to 50%. As the LEDs become more efficient, there will necessarily be more emphasis on the other luminaire losses in order to maximize overall efficiency.

Figure 4.8 shows the additional sources of loss for a color-mixed luminaire, differing from the PC-LED in the lack of phosphor sensitivity and present driver performance.

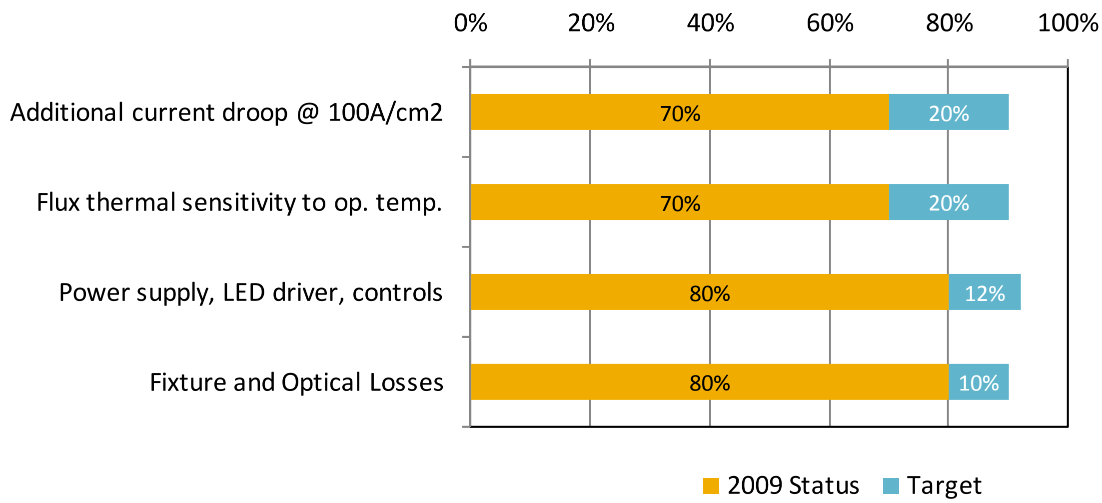

Figure 4.8: Sources of Loss in an LED Color-Mixing Luminaire

Table 4.2, below, provides an overall summary of the efficiency and resulting efficacy for a color mixed LED. Present performance is only estimated, of course, but is strongly affected by the absence of good green LEDs and availability of optimal wavelengths for the other colors. On the other hand, the potential is quite a bit higher than for the PC-LED - 163 lm/W for the luminaire.

Table 4.2: Summary of Color-Mixed LED Luminaire Efficiencies and Efficacies

Metric	2009 Status	2020 Target
LED Package Conversion Efficiency	31%	62%
Spectral Efficiency	70%	95%
LED Efficiency including spectrum	21%	59%
LED Efficacy (LER_{max} = 411 lm/W)	88	243
Overall Luminaire Efficiency (at 100C, 100A/cm^2)	7%	40%
Luminaire Efficacy	28	163

4.2.4 Organic Light-Emitting Diodes -Based Luminaires

For ease of comparison, OLED efficiencies have typically been reported assuming an OLED pixel, as defined in Section 4.2.4, at a fixed luminous emittance of 3,000 lm/m^2.[59] For cost and performance considerations, luminaire manufacturers have recommended that OLED performance data should be reported at higher lumen density levels. Thus future performance targets will assume a luminous emittance of 6,000 lm/m^2 for 2012 performance targets and then 10,000 lm/m^2 for performance targets in 2015 and beyond. .

[59] The light emitted by an OLED has been reported for display applications in terms of candela/m^2 from which *luminous emittance* (lm/m^2 of the source)can be estimated by assuming a lambertian distribution. Lumens per area of the source (not to be confused with *illuminance* of a lighted surface) is a more appropriate reporting metric for general illumination applications and will be used in DOE status reports from this point forward.

These values are used to compare efficiency levels and set performance targets to a common reference. It is not the DOE's intention to dictate the brightness, size, or current drive of devices used in practice

Figure 4.9 analyzes the efficiency of an OLED panel and compares the current typical values for the individual system elements to a set of suggested program targets.[60] The breakdown of loss mechanisms may differ with alternative OLED architectures but, regardless of architecture the drive voltage and out-coupling enhancement show the most room for improvements. The elements in this chart are:

- *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 325lm/W and the estimated LER_{max} is 350 lm/W[61]. It is possible that the LER_{max} could be increased through the development of emitters with narrower spectral power densities and peak wavelengths tuned for the eye response while still maintaining the desired color quality, although this is uncertain.
- *Electrical efficiency* accounts for the ohmic losses within the OLED panel and energy lost to other excitation modes in the conversion of each electron-hole pair into a visible photon. In OLED panels the electrical efficiency accounts for losses due to current spreading in the panel, internal device resistance, the barrier to charge injection at the electrode-organic interface, energy losses in the electrodes, and energy lost to other excitation modes.
- *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.
- *Light Extraction efficiency* is the ratio of visible photons emitted from the panel to the photons generated in the active region. This takes into account absorption in the electrodes and transparent substrate as well as the trapping of photons in the inner layers.

[60] 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.

[61] *The Limits of OLED Efficacy*, Mike Hack and Peter Levermore, UDC presentation in OLED panel at the DOE SSL R&D Workshop in Raleigh, NC, Feb. 2010.

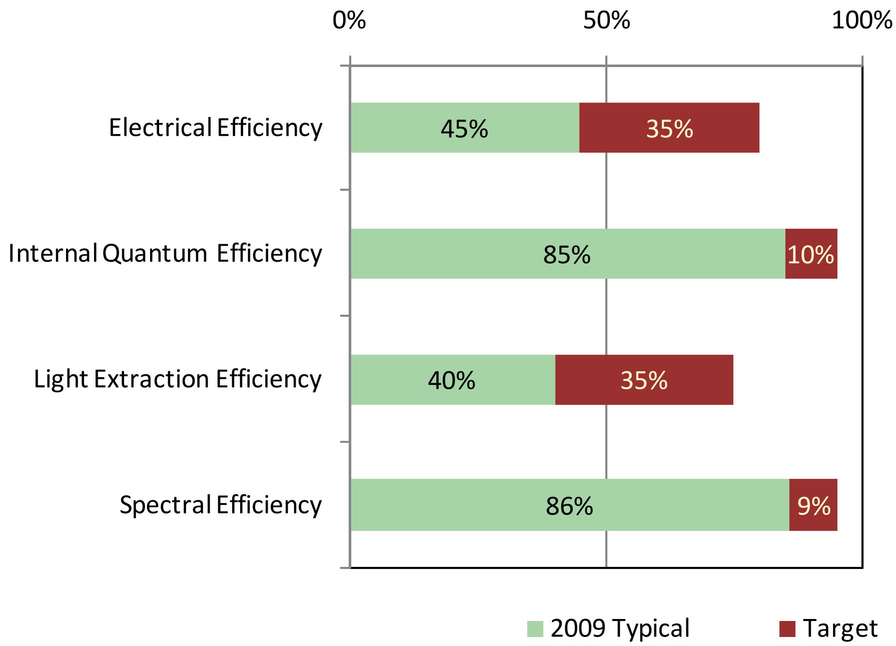

Figure 4.9: OLED Panel Loss Channels and Efficiencies
Note: Assumptions for "Target" figures: CCT: 2580-3710 CRI> 85, 10,000 lm/m^2, panel area ≥ 200 cm^2

In principal, substantial gains in electrical efficiency can be made by lowering the drive voltage from current levels of around 3.8V closer to the threshold for photon creation and by reducing the losses from other excitation modes. The target value of 80% seems appropriate for architectures with a single drive voltage. Higher values may be reached if there are separate red, green and blue emissive layers, each with their own drive voltage. In addition to reducing the device level operating voltage, new current spreading techniques for OLED panels need to be developed which do not add significantly to the operating voltage.

The cited status (85%) and target (95%) for IQE assume the use of phosphorescent materials and rely on the accuracy of the methods used to estimate IQE. Some analysts believe that these values are overestimated and that a more reliable means of measuring IQE is needed.

The existing data for IQE indicate that a 3-fold increase in brightness does 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 5 or more, unless steps are taken to reduce degradation.

The greatest opportunity for improvement is in the extraction of light from the panel. Since the light is created in thin films with a relatively high refractive index (~1.8), the planar layers form waveguides and most of the light is trapped within the substrate, transparent electrode, or the active layers. 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 and does not interfere with the operation of the OLED.

Discussions at the 2010 R&D Workshop revealed that there is considerable uncertainty regarding appropriate targets for extraction efficiency. Some argue that a significant fraction of the photon energy is transferred to charge oscillations in the metal electrode and that it will be very difficult to extract this energy. The development of a reliable technique to measure the extraction efficiency could lead to a major advance of the understanding of OLED efficiency.

Increasing the size of OLED devices from pixels to larger panels brings a significant challenge in ensuring efficient and uniform current spreading over the area of the panel. This may require a current spreading metal grid and/or engineering of the transparent conducting layer. The use of a grid and changes to the transparent conducting layer could 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.

If all the improvements shown in Figure 4.7 are achieved including spectral efficiency, the efficiency of the OLED panel would rise from the current typical value of 13% to 54%. The corresponding efficacy would rise from 45 lm/W to as much as 190 lm/W eventually.

The additional losses in converting an OLED panel to a luminaire are summarized in Figure 4.10.

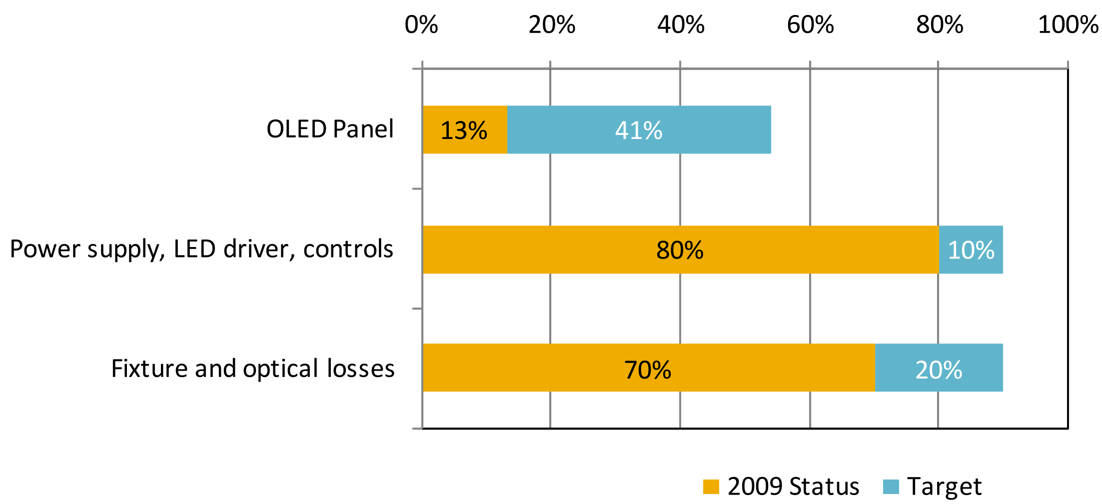

Figure 4.10: Sources of Loss in an OLED Luminaire

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

The progress anticipated in this chart would raise the efficiency of an OLED luminaire from 7% (26 lm/W) up to a limit of about 44% (154 lm/W), probably beyond 2020. It should be noted that while no fundamental roadblocks to the OLED efficacy performance projections have been identified, there is also very little performance data for OLED panels and luminaires. As more integration of OLEDs into panels and luminaires occurs additional loss mechanisms may be identified similar to LED luminaires, such as current droop and flux thermal sensitivity to the operating temperature.

Since OLED luminaires have only been manufactured as prototypes in small quantities, the values in this chart are estimates based on other lighting technologies. Discussions between OLED developers and luminaire manufacturers are urgently needed to define the electrical, optical, mechanical, and possibly, thermal requirements of the OLED panel. 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.

Keys to efficiency improvements in OLEDs continue to revolve around finding suitable stable materials with which to realize white light, with blue colors being the most difficult. Progress on efficiencies for OLEDs has been relatively rapid, as discussed in the next section. However, 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, as noted above and in the figure, and may also limit materials choices.

Improvements to OLED panel and luminaire operating lifetime, as well as shelf life, also must be realized in order to ensure a commercially viable product. OLEDs are sensitive to oxygen, moisture, and other pollutants in the operating environment which necessitate extensive encapsulation of the OLED panel, particularly in the case of OLEDs on flexible substrates. In addition, oxygen, moisture, and other contaminants can get embedded into the OLED in the fabrication process reducing the panel lifetime. Operation at higher lumen outputs can also dramatically reduce the lifetime of OLED devices, if the increase is achieved solely by raising the drive current rather than by improvements in efficacy. It is estimated that an increase in luminous emittance from 3000 lm/m^2 to 10,000 lm/m^2 could reduce the lifetime of the OLED by as much as 80%. However, improvements to light extraction efficiency could also lead to higher emittance but without increased applied current and possibly avoid this problem. 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 45 lm/W to 190 lm/W and OLED luminaire performance can improve from

26 lm/W to 154 lm/W. However, all of these gains need to be developed while keeping the cost of the OLED panels and luminaire luminaires competitive with alternative lighting technologies. Increasing the lumen density of the OLED panels can have a large impact on the cost of OLED panels and luminaires. However, as the lumen density of OLED panels is increased the lifetime of the OLED panels needs to remain competitive with other lighting technologies. This could be particularly challenging.

4.3 SSL Performance Targets

The projections of the performance of SSL devices created in consultation with the Roundtable groups assume sufficient funding by both government and private industry for the duration of the program. Total funding in 2009 included about $24.5M in regular appropriated funding, similar to earlier years, but was also augmented by an additional $50M from the American Relief and Recovery Act (ARRA). Funding for 2010 is $27M and the administration request for 2011 is $26.5M.

In order to capture the ultimate objectives of the SSL program that relate to luminaire efficacy or cost, objectives for luminaire performance are also included along with device performance objectives. Although the graphs show large improvements in device performance, reaching the luminaire objectives will take longer, as shown by the luminaire efficacy values in Table 4.5 and Table 4.8. Innovative fixtures for LEDs can have a significant impact on overall efficacy. For example, package efficiencies (and operating lifetime) can be degraded by 30% or more when operating at full temperature at steady state in a luminaire. Despite this degradation, SSL will still help DOE meet its ZEB goals by providing a luminaire that is more efficient than luminaires of other lighting technologies. The simultaneous accommodation of aesthetic and marketing considerations along with the preservation of the energy-saving advantages of SSL is a challenge in commercializing this technology. Section 5.7of the SSL MYPP discusses DOE's commercialization support plan.

4.3.1 Light-Emitting Diodes

LED Package Efficacies

The performance of white-light LED packages depends on both the correlated color temperature of the package and, to a lesser extent, the color rendering index. Some changes have been made in this report with regard to the designation of color temperature ranges as cool, neutral and warm. These changes have been made to reflect newly defined ANSI binning ranges[62] and to correct earlier inconsistencies. CRI ranges have also been revised for similar reasons. While every case cannot be examined, efficacy projections have been shown for two choices: one for cooler CCT (4746 K to 7040 K) with CRI=70-80, and the other for warmer CCT (2580 K to 3710 K) with CRI = 80-90.

In the 2009 MYPP, we noted that progress in efficacy may be slowing down as researchers come closer to practical limits. However, any slowing was not readily apparent given the results of the past year. Single LED package efficacies over 200

[62] ANSI C78.377-2008

lm/W have been reported in press releases, while commercial product also continues to improve. So a fair question to ask is: Just what are the limits? This was the theme of the 2009 R&D Workshop in Raleigh, NC, and participants came up with some interesting new understandings of barriers to higher efficacies and means to attack them.

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

Table 4.3 shows LER_{max} for a range of choices for CCT and CRI, and the resulting package efficacy for assumed overall package conversion efficiencies of 67%, the estimated potential maximum conversion efficiency.[63] These figures assume a narrow band LED RGBA configuration. Somewhat surprisingly, under these conditions, the analysis suggests that warm white LEDs could have higher efficacies than cooler ones. This may not be the case with phosphor converted LEDs or OLEDs, however, where broad spectra will spill a considerable amount of the long-wavelength energy outside of the visible spectrum. Still, an efficacy target on the order of 250 lm/W seems like a reasonable program goal.

Table 4.3: Estimated efficacies as a function of CCT and CRI (R_a)[63]

	Maximum LER (lm/W)			Efficacy for 67% Conversion (lm/W)		
CCT	**CRI 70**	**CRI 80**	**CRI 90**	**CRI 70**	**CRI 80**	**CRI 90**
2700	433	424	416	290	284	279
4100	408	399	390	273	267	261
6500	366	358	349	245	240	234

Figure 4.11 shows revised package efficacy improvement forecasts over time. There are a number of changes from the 2009 version:

- The separate asymptotes for warm and cool white are deleted. In keeping with the earlier discussion, a common 250 lumen/Watt limit is indicated.
- Data points are indicated as either "qualified", i.e. within the parameters defined for the various curves, or "not-qualified", meaning one or more parameters is either outside the indicated limits, or is unknown.
- Limits have been adjusted somewhat to more closely follow industry practice for the qualitative terms for various color temperatures as follows:
  - "Cool White": CRI 70-80; CCT 4746-7040 K
  - "Warm White": CRI 80-90; CCT 2580-3710 K
  - Current density: 35A/cm^2 (note, current density is now given because of varying chip sizes)

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

    - These results are at 25°C package temperature, not steady state operating temperature. Thermal sensitivity will reduce efficacies by 15% or so in normal operation, depending on luminaire thermal management.
- In an attempt to clear up past confusion, this chart is intended to show results for a single package product or lab demonstration, but that package *could include more than one LED*, and more than one color. So, RGB solutions or hybrid R-W solutions, for example, might be shown, as long as they are packaged together. In fact, it may require such solutions to reach the higher levels of efficacy shown in this chart.

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

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

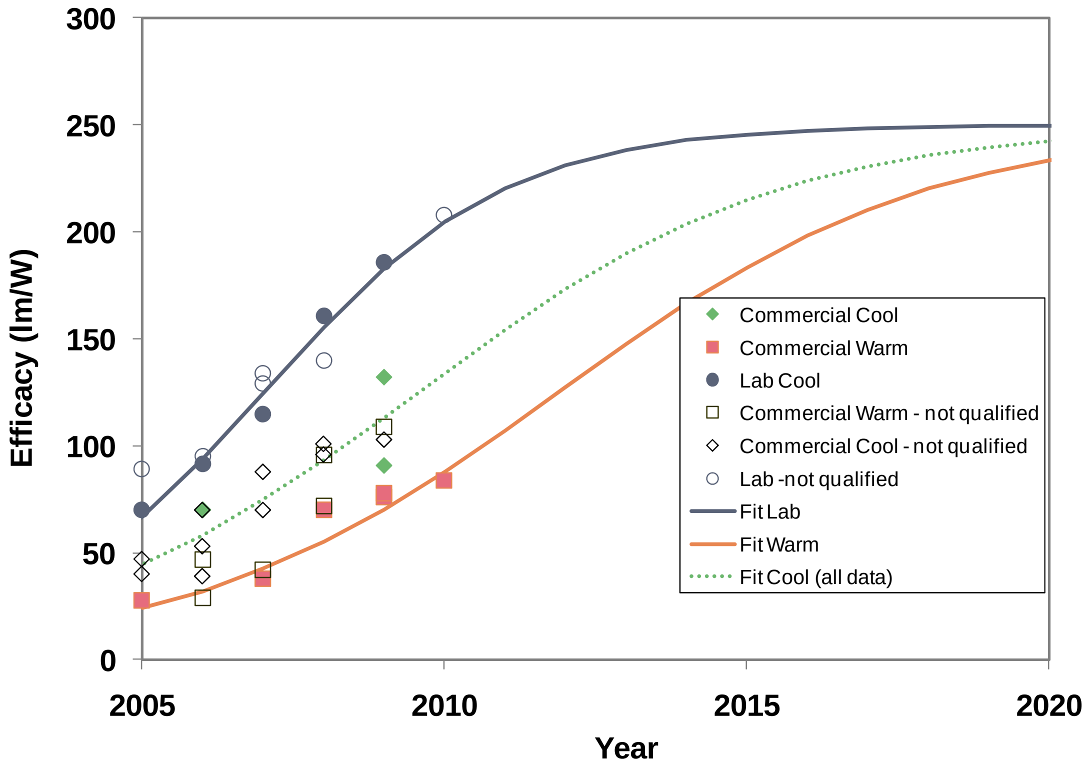

Figure 4.11: White-Light LED Package Efficacy Targets[64], Laboratory and Commercial

Based on progress over the last five years using data that can be qualified according to the criteria, the projections indicate that while improvements in warm white have been somewhat slower than for cool, our expectation is that this gap will close over time, as shown. The lab results may be reaching their limits fairly soon.

The LED package life, as commonly defined by 70% lumen maintenance, has increased steadily over the past few years and several manufacturers claim that lumen maintenance is currently at its target of an average of 50,000 hours. Although it appears that many LEDs have reached this level, there is limited field data and little published data to substantiate the claim. Also, lumen maintenance, while thought to dominate the useful life of an LED package, does not account for other failure mechanisms such as manufacturing defects nor ageing of encapsulants or other packaging materials, and so forth.

Nevertheless an average package life of 50,000 hours or something close to it, would allow LED packages to last more than twice as long as conventional linear fluorescent lighting products, five times longer than compact fluorescent lamps, and fifty times longer than incandescent lighting products. This long life would make LEDs very

[64] Projections are a simple logistical function fit to the qualified data points for "Warm" and "Lab" using an asymptote of 250 lumens/Watt. There were insufficient qualified points for "Cool", so all available data was used in the fit. Projections are for 35 A/cm^2 at 25°C.

competitive with conventional technologies on a “Cost of Light” basis (See Section 2.3.3).

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

Especially for luminaires, where full product testing is very expensive, methods for characterizing lifetime, especially as changes in materials or processes are introduced, will likely require accelerated aging tests which so far have not been established for LED technologies. This is an important area of work, and there is an identified task for it described in Section 4.5.

LED Package Prices

The following price estimates represent typical retail prices for packaged LEDs purchased in quantities of 1000 from major commercial distributers such as Digi-Key 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 bin, which falls within specified ranges of color temperature and CRI (as defined previously). 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

It is encouraging to note that prices continue to decline rapidly. On average, packaged LED prices declined by a factor of 2 during the second half of 2009 for both cool and warm white devices. For cool white LEDs, the prices continue to keep pace with the original targets however for warm white LEDs the prices have begun to run ahead of these targets. Consequently we have revised our price targets for warm white LEDs on the assumption of approximate price parity (\$/klm) with cool white LEDs by 2020.

Figure 4.12 illustrates the price-efficacy trade-off for cool white (blue points) and warm white (red points) packaged LEDs. There is a lot of scatter in the 2009 data so ellipses have been superimposed on the chart to identify the mean and standard deviation of each distribution. Nevertheless the large price reduction from the middle of 2009 to the end of 2009 is clearly observed. The overall trend we observe for commercially available devices is in very good agreement with the revised MYPP targets that are superimposed on the chart.

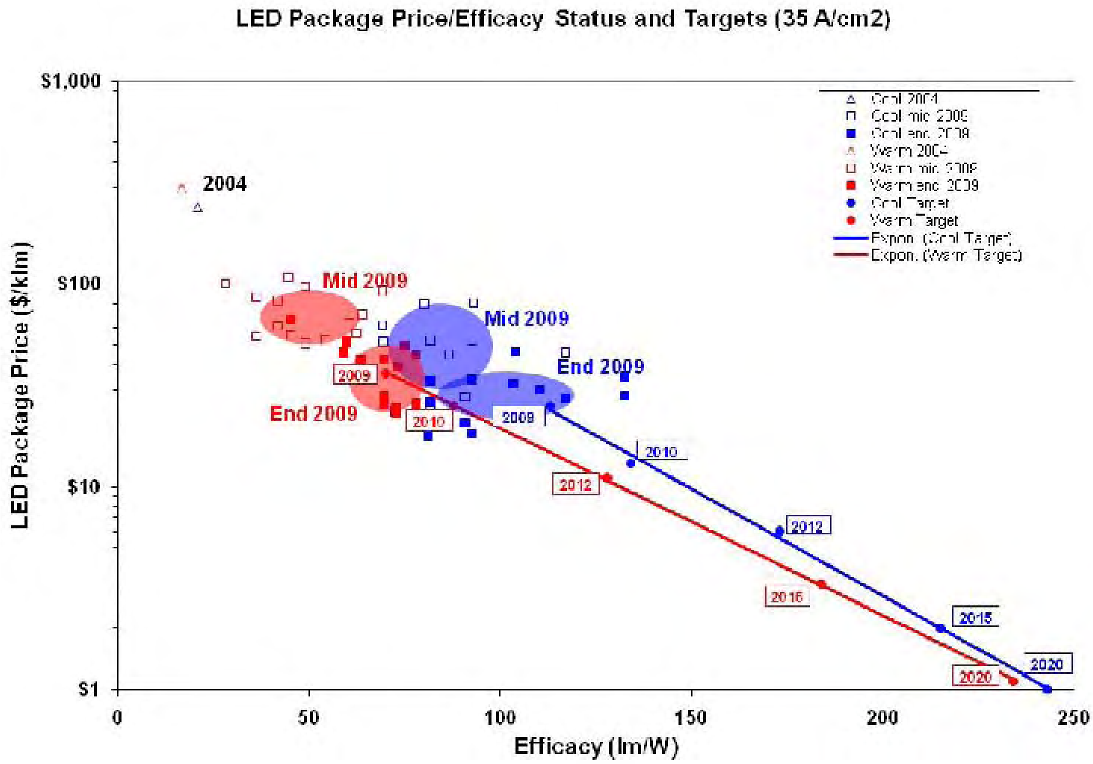

Figure 4.12: Status of LED package price and efficacy for cool and warm white LEDs
Note:
1. Ellipses represent the approximate mean and standard deviation of each distribution.
2. MYPP targets have been included to demonstrate anticipated future trends.

Table 4.4 summarizes the LED package price and performance projections in tabular form. The 2009 statuses in the table represent the fitted efficacies and prices presented in Figure 4.11 and Figure 4.12.

Table 4.4: Summary of LED Package Price and Performance Projections

Metric	2009	2010	2012	2015	2020
Cool White Efficacy (lm/W)	113	134	173	215	243
Cool White Price ($/klm)	25	13	6	2	1
Warm White Efficacy (lm/W)	70	88	128	184	234
Warm White Price ($/klm)	36	25	11	3.3	1.1

Note:

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

4.3.2 LED Luminaires

As stated in Section 4.2.3, the LED package is only one component of an LED luminaire. To understand the true performance metrics of a SSL source, one must also take into account the efficiency of the driver and the efficiency of the fixture, and, importantly, the effects, primarily thermal, of the assembly on the performance of the packaged LED. Provided below in Table 4.5 are luminaire performance projections to complement the package and lamp performance projections given in

Table 4.4 and Table 4.5 assumes a linear progression over time from the current 2008 fixture and driver efficiency values to eventual fixture and driver efficiency 2015 program targets as given in Section 4.2.1. Estimating the factors that affect the performance of an LED luminaire, it appears that a cool-white luminaire in 2009 was capable of achieving 69 lm/W (although not all did so). By 2015 cool-white luminaire efficacies should reach a capability of 172 lm/W.

Table 4.5: Summary of LED Luminaire Performance Projections (at operating temperatures)

Metric	2009	2010	2012	2015	2020
Package Efficacy-Commercial Cool White (lm/W, 25 C)	113	134	173	215	243
Thermal Efficiency	87%	89%	92%	95%	98%
Efficiency of Driver	86%	87%	89%	92%	96%
Efficiency of Fixture	81%	83%	87%	91%	96%
Resultant luminaire efficiency	61%	64%	71%	80%	90%
Luminaire Efficacy- Commercial Cool White (lm/W)	69	86	121	172	219

Notes:

1. Efficacy projections for cool-white luminaires assume CRI=70-80 and a CCT = 4746-7040°K.
2. All projections assume a drive current density of 35 A/cm^2, reasonable package life and operating temperature.
3. Luminaire efficacies are obtained by multiplying the resultant luminaire efficiency by the package efficacy values.

LED Lamp Prices

Luminaire prices can vary widely depending upon the application, the addition of decorative or control features, and so forth. So, to evaluate progress on cost control and prices, comparison to a replacement lamp may be more appropriate. Figure 4.13 shows a comparison of an integrated white light LED replacement lamp to fluorescent systems. The price estimates represent the average retail purchase price. The price is expected to decrease exponentially from approximately $200/klm in 2007 to $2/klm in 2025. Example data for such products are shown for 2007 and 2009. By way of rough comparison, a band representing a range of current prices for conventional fluorescent technologies (with a self-ballasted 13 W compact fluorescent lamp at the bottom and a two-lamp 32 W T8 linear fluorescent lamp-and-ballast system at the top) are shown on the same chart. 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 certain incandescent products.[65]

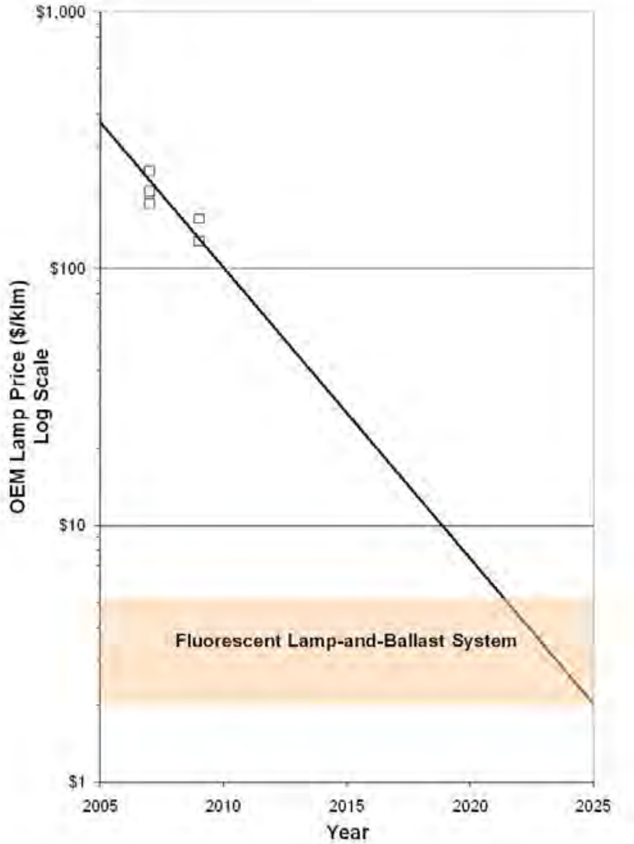

Figure 4.13: White-Light Integrated LED Lamp Price Projection (Logarithmic Scale)
Note: Assumes current prices for fluorescent price range (13 W self-ballasted compact fluorescent lamp at bottom, and 2-lamp 32 W T8 linear fluorescent lamp-and-ballast system at

4.3.3 Organic Light-Emitting Diodes

OLED Panel Efficacies

The efficacy of OLEDs has continued to improve at a dramatic pace over the last year. As described in Chapter 1.0**,** an efficacy of approximately 45 lm/W has been reported by UDC and Eastman Kodak for an OLED panel, and OLED pixels have been reported with efficacies as high as 90 lm/W in the laboratory. The difference in these values reflects efficiency loss mechanisms which occur when a small, laboratory scale OLED pixel is translated to a larger, more practical OLED panel. As noted in Section 4.2.4 these effects are primarily related to ohmic losses due to the necessity of spreading the input current over a larger area and optical losses due to current spreading structures or non-optimized light extraction over the larger area. In consideration of the need to move beyond laboratory scale OLED pixel results and the ongoing need to develop the practical building blocks for OLED lighting products, the DOE has begun reporting OLED panel results as shown in Figure 4.14.

As with LED projections a good starting point for efficacy performance projections is the luminous efficacy of radiation (LER). This is the efficacy for a given spectral power density as defined by the overlap of that spectrum with the photopic curve representing the response of the human eye to color. The maximum LER (LER_{max}) is a function of CCT and CRI, and the emitter characteristics. As noted earlier, it has been estimated for OLEDs to be about 350 lm/W for an optimized spectral distribution within the present constraints of the technology[66]. The spectral efficiency is defined as the ratio of the LER

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[65] Typical current lamp prices for conventional light sources listed in Section 2.3.2are also listed here for comparison: incandescent lamps (A19 60W), $0.30 per klm; self-ballasted compact fluorescent lamps (13W), $2 per klm; 2-lamp fluorescent lamp-and-ballast system (F32T8), $4 per klm.
[66] Hack and Levermore, *ibid*.

of the actual spectral power density to LER_{max}, which value depends on the characteristics of the emitter. For both PC-LEDs and for OLEDs, present devices show a broad distribution in the red part of the spectrum which spills beyond the visible. In either case designing or improving the emitters, changing their characteristics so as to have a tighter distribution in the red, could lead to higher LER_{max}, hence higher efficacies. The performance targets described in Section 4.2.4 yield a projected maximum efficacy for OLED panels of ~190 lm/W. Based on historical panel performance and this projected maximum efficacy a logistic fit was used to show a likely projection of OLED panel efficacy using a maximum of 200 lm/W as well as for a more conservative maximum efficacy of 150 lm/W. Both projections have very similar trajectories over the next five years and ongoing OLED research will continue to clarify the practical maximum efficiencies described in Section 4.2.4. As OLED technology progresses it is expected that there will be increased reporting of OLED panel performance results and that OLED panels will begin to be integrated into OLED based luminaires.

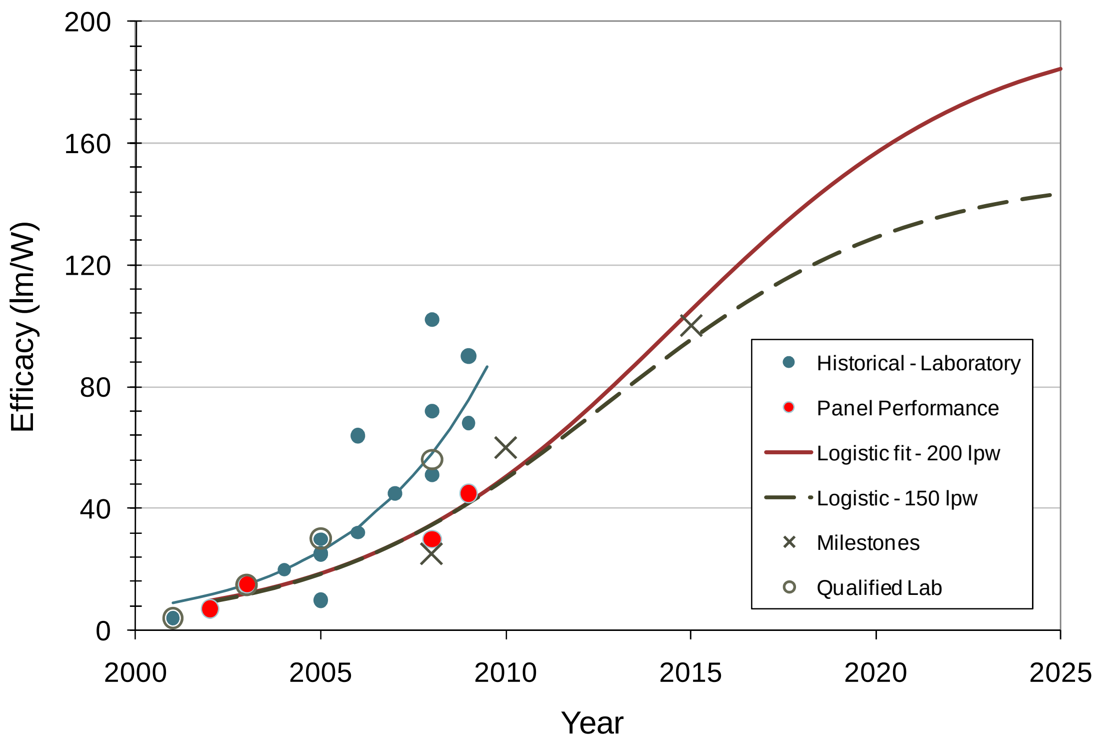

Figure 4.14: White-Light OLED Panel Efficacy Targets

Notes: Efficacy projections assume:
1. CRI > 85, CCT falling in ANSI bin color requirements
2. Panel data prior to 2005 is for a minimum panel size of 4 cm^2; subsequently minimum size is 200 cm^2
3. Panel luminance of 3000 lm/m^2

Based on the rapid pace of development of OLED technology and suggested by the efficacy projections in Figure 4.14 it is likely that OLED panel performance will exceed 100 lm/W within five years. At this performance and assuming luminaire power supply and optical efficiencies of 90% an OLED luminaire with an efficacy of 85 lm/W is forecasted by 2015 (Table 4.8, below). This efficacy level would surpass the efficacy of the most efficient existing conventional large area lighting, linear fluorescent based lighting.

These performance advancements need to occur while simultaneously increasing the luminous emittance of OLED panels. Increasing the luminance from 3,000lm/m^2 to ~10,000 lm/m^2 (10,000 lm/m^2) is essential to achieve a product price that will enable widespread adoption of this lighting technology. Analysis has shown that increasing the luminance can dramatically reduce the cost per kilolumen for an OLED light source. However, the efficiency and lifetime of OLED sources can degrade at higher luminance levels and ongoing research will be required to achieve these luminance levels while maintaining efficiency and lifetime.

OLED Costs

While several prototype, demonstration, and development type OLED products have become somewhat available in the last year there are not yet actual OLED general illumination products available. Therefore, reliable price data is still not available for OLED panels or luminaires and cost projections contain a high degree of uncertainty. Similarly, lifetime values for OLED panels and luminaires are highly speculative at this point in time due the lack of actual OLED general illumination products. As noted above, increasing the luminance by increasing the drive current is known to have deleterious effects on OLED lifetime so advancements in OLED material purity, material deposition, and panel encapsulation will be required to achieve competitive product lifetimes. Figure 4.15 shows a cost track, taken from the DOE SSL Manufacturing Roadmap, in terms of \$/m^2. In order to get OLED panels to a level within the range of other lighting sources, faster cost reductions need to be realized in terms of \$/klm. This can be done by increasing the luminous emittance. By 2012 an increase in luminous emittance to 6,000 lm/m^2 is targeted and expected to have little negative impact on panel efficiency or lifetime. By 2015 a further increase in luminance to 10,000 lm/m^2 is targeted, again with little negative impact on panel efficiency or lifetime. The results in terms of \$/klm are summarized in Table 4.6, below the figure for both web and sheet processing.

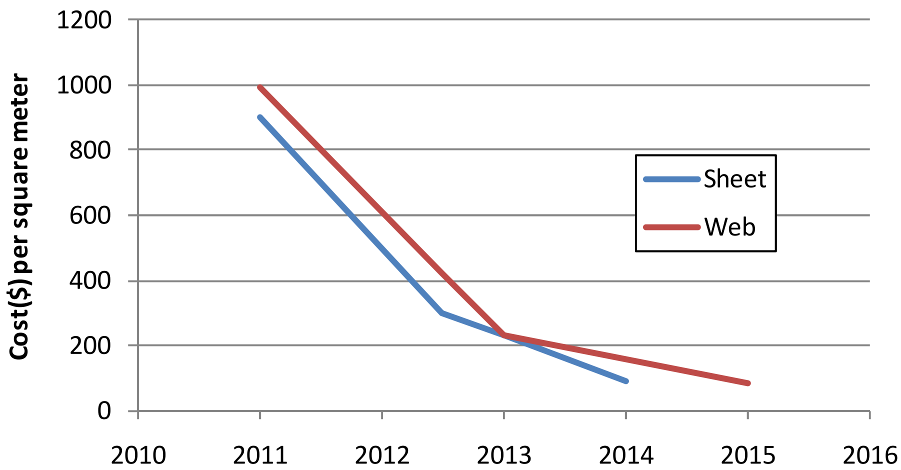

Figure 4.15: OLED Panel Cost Targets

Note: Cost targets are for sheet processed and web processed OLEDs. Additional discussion of sheet and web processing is available in the DOE SSL Manufacturing Roadmap.

Table 4.6: Summary of cost projections for OLED panels by sheet and web processing

Metric	Sheet		Web	
	2011	2014/15	2011	2014/15
$/m^2	900	90	995	84
$/klm	300	9	320	8.4

Source: DOE SSL Manufacturing Roadmap, 2009

The table shows how increases in the luminous emittance will lead to a more rapid reduction in the cost/klm for OLEDs than will be seen in the cost/m^2 of OLED material. The OLED cost projections also show that the different processing techniques, sheet and web, do not project to have different costs for the OLED material or in terms of cost/klm. Both lead to estimates of about $9/klm.

In order to meet overall goals for economic viability, the panel life for commercial products, defined as 70% lumen maintenance, will need to be approximately 50,000 hours by 2018, together with increased luminous emittance. Although 50% lumen maintenance is a useful target for OLED displays, 70% lumen maintenance[67] is required in order to compare lifetimes with other lighting products.

Table 4.7 presents a summary of the OLED performance projections in tabular form. Projections below represent the performance of the OLED panel, not an entire OLED luminaire. Although the OLED panel may reach long lifetimes, other components of the OLED luminaire, such as the driver, may limit the luminaires lifetime. Therefore, improving the lifetime of these additional components to at least equal that of the OLED device is a goal of the SSL program.

[67] Like LED package lifetimes shown in this section, OLED device lifetimes account for the lumen maintenance of the OLED but do not account for other failure mechanisms.

Table 4.7: Summary of OLED Panel Performance Projections (200 lm/W asymptote)

Metric	2009	2010	2012	2015	2020
Panel Efficacy- (lm/W)	45	50	70	105	157
OEM Panel Cost- ($/klm)	NA	450	45	9	6
OEM Panel Cost- ($/m2)	NA	1200	270	90	80
Panel Life- (1000 hours)	NA	5	25	50	50
Luminous emittance	3,000	3,000	6,000	10,000	10,000

Notes: 1. Projections assume CRI > 85, CCT within ANSI color bin requirements
2. Panel size of 200 cm^2

4.3.4 OLEDs in Luminaires

The Table 4.8, below, details a summary of the efficiency losses that occur when considering the entire OLED luminaire. Ultimately, losses in the driver (10%) and optical losses in the luminaire (10%) are expected to account for a ~20% degradation in the panel efficacy. Based on the efficacy projection for OLED panels and the driver and luminaire optical losses the 2015 OLED luminaire efficacy projection is 85 lm/W.

Table 4.8: Summary of OLED Luminaire Performance Projections beginning 2010

Metric	2009	2010	2012	2015	2020
Panel Efficacy (lm/W)	45	50	70	105	157
Optical Efficiency of Luminaire	70%	75%	85%	90%	90%
Efficiency of Driver	80%	80%	85%	90%	90%
Total Efficiency from Device to Luminaire	56%	60%	72%	81%	81%
Panel emittance (lm/m^2)	3,000	3,000	6,000	10,000	10,000
Resulting Luminaire Efficacy- (lm/W)	26	30	50	85	127

Note: Efficacy projections assume CRI > 85, CCT within ANSI color bin requirements.

4.4 Barriers

The following lists some of the technical, cost, and market barriers to LEDs and OLEDs. Overcoming these barriers is essential to the success of the SSL program.

1. Cost: The initial cost of light from LEDs and OLEDs is too high, particularly in comparison with conventional lighting technologies such as incandescent and fluorescent (see Sections 2.3.2 and 2.3.3). Since the lighting market has been strongly focused on low first costs, lifetime benefits notwithstanding, lower-cost LED package and OLED device and luminaire materials are needed, as well as low-cost, high-volume, reliable manufacturing methods.

2. Luminous Efficacy: As the primary measure of DOE's goal of improved energy efficiency, the luminous efficacy (lm/W) of LED and, in particular, OLED luminaires still need improvement. Although the luminous efficacy of LED luminaires has surpassed that of the incandescent lamps, improvement is

still needed to compete with other conventional lighting solutions. For example, the industry must find ways to minimize the amount of “droop” in efficiency that occurs at high drive currents for LEDs. Improving red light emission in wavelengths specifically for color quality in efficacious lighting would also benefit LED lighting products. While laboratory experiments demonstrate that OLED devices can be competitively efficacious as compared to conventional technologies, no products are yet available.

3. Lifetime: The lifetime of LEDs and OLEDs is defined as the number of hours for which the device maintains at least 70% of its initial lumen output. It is unclear what lifetimes LED luminaires are achieving. Furthermore, a definition of lifetime that focuses on lumen maintenance is inadequate for luminaires. Lumen maintenance is only one component of the lifetime of a complex system such as a luminaire that may be subject to other failure mechanisms like color shifts, reflector degradation, or even catastrophic failure. Premature failures due to excessive temperature are still relatively common. OLED lifetimes for both devices and luminaires still require improvement. The development of a long-lasting blue emitter for OLEDs is critical.

4. Testing: The reported lumen output and efficacies of LED and OLED products in the market do not always match laboratory tests of performance. Improved and standardized testing protocols for performance metrics need to be developed. An important barrier appears to be a lack of understanding of the meaning of device specifications versus continuous operation in a luminaire on the part of designers. Furthermore, accelerated reliability testing methods for systems and materials are absolutely necessary for market penetration. 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. Lumen Output: LED luminaires are reaching reasonable total lumen output levels although many still perceive LEDs as offering only “dim” light, a significant market barrier. OLED packages with useful levels of output remain yet to be developed.

6. Manufacturing: While OLEDs have been built off of display manufacturing capabilities, there has been little investment by manufacturers in the infrastructure needed to develop commercial OLED lighting products. A breakthrough is necessary to produce low-cost OLEDs for general illumination. Lack of process uniformity is an important issue for LEDs and is a barrier to reduced costs as well as a problem for uniform quality of light.

7. Codes and Standards: New guidelines for installation and product safety certifications such as the UL provided by the Underwriters Laboratory must be developed. Common standards for fixture (or socket) sizes, electrical supplies and control interfaces may eventually be needed to allow for lamp interchangeability. Standard test methods are still lacking in some areas. In

general, the development of appropriate codes and standards will enable consistency from brand to brand and year to year, reducing uncertainty for consumers.

For more information about individual research tasks that address these technical, cost and market barriers, refer to Section 4.5.

4.5 Critical R&D Priorities

4.5.1 Introduction

In order to achieve these projections, progress must be achieved in several research areas. The original task structure and initial priorities were defined at a workshop in San Diego in February 2005. These priorities were updated in subsequent editions of the Multi-Year Program Plan. 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 2010 MYPP, DOE first held SSL roundtable sessions Washington, D.C. in November of 2009 (see Appendix G for the entire task list). The tasks were further discussed and refined at the February 2010 "Transformations in Lighting" workshop in Raleigh, NC. Using these recommendations, and after further internal review, the DOE defined the task priorities for 2010 as follows:

For LED Core Technology:

- Subtask A.1.2 (Emitter materials research) encourages the development of highly-efficient green and red emitters to greatly improve the efficiency of color-mixing LED packages.
- Subtask A.1.3 (Down-converters) emphasizes improvements in phosphor lifetime, color control, and conversion efficiency, necessary to meet DOE's long-term LED milestones.
- Subtask A.2.2 (Novel emitter materials and architectures) investigates the development of new emitter materials and alternative emitter geometries to achieve a significant performance enhancement over existing approaches.
- Subtask A.6.3 (System reliability methods) is intended to encourage the development of high-quality system reliability methods that could lead to improved efficiency and can also be used with a variety of LED luminaires.
- Subtask A7.5 (Electronics reliability research) reflects the need to improve the reliability of electronic components in an SSL luminaire through improved designs and the introduction of methods to more accurately predict lifetimes.

The need for subtask A4.4 (Manufacturing Simulations) will be addressed in the Manufacturing R&D Roadmap.

For LED Product Development:

- Subtask B.1.1 (Substrate development) was prioritized following recommendations from the manufacturing initiative due to the potential for alternative high quality substrates such as GaN to enable the growth of higher quality epitaxial layer structures which should lead to significantly enhanced LED performance.

- Subtask B.1.2 (Semiconductor materials) was made a priority to further encourage the development and deployment of efficient green and red emitters with an emphasis on the production of white light with improved droop and thermal sensitivity parameters.

- Subtask B.1.3 (Phosphors) was prioritized because advances in phosphors can improve LED efficiency as well as color quality, which will both encourage market adoption of LED products.

- Subtask B.3.6 (Package architecture) was prioritized to support the development of alternative, novel LED components and modules optimized for integration into general illumination products. Specific features can include potential for low cost, ease of integration, color quality, color stability, color consistency, thermal handling, and optical distribution optimized for luminaire performance.

- Subtask B.5.2 (Color maintenance) reflects a growing realization of the need for accurate control of the initial color point and for effective maintenance of color quality over the life of the luminaire.

- Subtask B.6.3 (Optimizing system reliability) will encourage the development of consensus as to what methods should be used to assess and model system reliability.

Issues associated with subtasks B4.1 (Yield and Manufacturability), B4.2 (Epitaxial Growth), and B4.3 (Manufacturing Tools) will be addressed in the Manufacturing R&D Roadmap.

For OLED Core Technology:

- Subtask C1.2 (Novel materials and structures) will support the development of stable white-light OLED materials and structures to reduce voltage, increase EQE, and improve lifetime that have the potential for large-scale, low-cost production and processing. The principal function of the new materials can be to create light or transport charge, but they must be compatible with all other elements of an efficient, long-lived OLED. The purpose of structural changes may be to improve the performance of the device or to provide a better match with the requirements of luminaire manufacturers.

- Subtask C2.2 (Electrode research) is meant to encourage the development of anode and cathode structures that feed current efficiently and uniformly across large area panels. Both electrodes must be smooth and chemically stable and so be compatible with the targets for operational and storage lifetimes. One of the electrodes must be transparent and electrical losses must be minimized in both electrodes. The electrodes may be designed as uniform sheets or may be patterned or segmented. Transparent electrodes may be supported by metallic grids. The cost of purchasing and processing electrode materials is critical.

- Subtask C.3.1 (Fabrication technology research) is intended to support the creation of entirely novel, practical, scalable techniques for organic material deposition, device fabrication, and encapsulation at low cost.

- Subtask C.6.3 (Light extraction approaches) supports the development of new optical designs within the OLED device structure and in the panel to improve OLED panel light extraction. The structures should not lead to significant increases in the thickness or the cost of large area panels.

For OLED Product Development:

- Subtask D.2.2 (Low-cost electrodes) supports the development of low cost, low-voltage, transparent and stable electrode structures for efficient and uniform current injection. These must be compatible with high-efficiency organic materials.

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

- Subtask D.6.2 (Panel packaging) supports scalable, low cost panel package designs that improve environmental resistance and thermal handling.

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

- Subtask D.6.4 (Panel reliability) supports investigation of the failure mechanisms of OLED panels and the demonstration of OLED panels with improved lifetime.

The sections that follow provide a description of the task and defined metrics. There is also an estimate of the current status and a target for year 2015. Prioritized tasks for 2009 are listed first, and other tasks that were defined during the course of the updating progress are listed next.

4.5.2 LED Priority Core Technology Tasks for 2010

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

Table 4.9: LED emission wavelength and color definitions for this section

Color		Wavelength/CCT range	CRI
Blue		440-460 nm	-
Green		520-540 nm	-
Red		610-620 nm	-
White	Warm	2580-3710 K	80-90
	Neutral	3711-4745 K	70-80
	Cool	4746-7040 K	70-80

A1.2 Emitter Materials Research: Development of efficient green LEDs and a broader range of red (610-650 nm) LEDs to allow optimization of spectral efficiency for high color quality over a range of CCT. This task additionally includes efforts at reducing current droop and minimizing thermal sensitivity for all colors including blue LEDs.

Metric(s)	2009 Status(s)	2020 Target(s)
Internal Quantum Efficiency (IQE) @ 35 A/cm2	80% (Blue) 40% (Green) 75% (Red)	90% (Blue, Green, Red)
External Quantum Efficiency (EQE) @ 35 A/cm2	64% (Blue) 30% (Green) 38% (Red)	81% (Blue, Green, Red)
Wall Plug Efficiency (WPE) @ 35 A/cm2	50-55% (Blue) 21% (Green) 35% (Red)	75% (Blue, Green, Red)
Droop - Relative WPE at 150A/cm2 vs. 35A/cm2 (WPE_{150}/WPE_{35})	50%	90%
Thermal Sensitivity - Relative Optical Flux at 100ºC vs. 25ºC (Opt_{100}/Opt_{25})	85% (Blue, Green) 50% (Red)	95% (Blue, Green) 75% (Red)

A1.3 Down Converters: High-efficiency wavelength conversion materials for improved quantum yield, optical efficiency, and color stability over temperature and time. Explore novel approaches to conversion.		
Metric(s)	**2009 Status(s)**	**2020 Target(s)**
Quantum Yield (25C)	95% (cool @ 550±50 nm peak) 80% (warm @ 600±50 nm peak)	95% across visible spectrum
Quantum Yield (150C)	80% (cool @ 550±50 nm peak) 70% (warm @ 600±50 nm peak)	85% across visible spectrum
Temperature Stability - Relative Quantum Yield at 150ºC vs. 25ºC (QY_{150}/QY_{25})	85% across visible spectrum	90% across visible spectrum
Average Conversion Efficiency (phosphor converted LED)	65% (cool) 50% (warm)	73% (cool) 66% (warm)
Spectral Full Width Half Maximum (FWHM)	150 nm (Red)	<50 nm (Red[68])
Color Stability (phosphor converted LED)	Color Shift of 0.012 u'v' over life	Color Shift < 0.004 u'v' over life

A2.2 Novel Emitter Materials and Architectures: Devise alternative emitter geometries and emission mechanisms in manufacturable configurations that show genuine improvement over existing approaches. (Possible examples: monolithic integrated RGB, 360 degree emitters, microcavities, lasers, photonic crystals).		
Metric(s)	**2009 Status(s)**	**2020 Target(s)**
External Quantum Efficiency (EQE) @ 35 A/cm2	64% (Blue) 30% (Green) 38% (Red)	81% (Blue, Green, Red)

A6.3 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.		
Metric(s)	**2009 Status(s)**	**2020 Target(s)**
Model Accuracy vs. Experiment	LM-80	99% at 6 kHrs, 90% at 50 kHrs

A7.5 Electronics Reliability Research: Develop designs that improve and methods to predict the lifetime of electronics components in the SSL luminaire.		
Metric(s)	**2009 Status(s)**	**2020 Target(s)**
Potential Installed Lifetime or Accuracy of Predictive Model vs. Long Term Actual Results	Significant cause of early failures	Much greater than LED installed life

4.5.3 LED Priority Product Development Tasks for 2010

See Table 4.9 for definitions that are used throughout this section for LED emission wavelength and white LED color point.

[68] Peak wavelengths longer than 620 nm are acceptable for narrower emission spectra provided this is consistent with maximizing spectral efficiency.

B1.1 Substrate Development: Develop alternative low cost, high quality substrates amenable to high efficiency manufacturing at low cost and demonstrated improvement in LED performance (e.g., reduced droop, better thermal performance, Green EQE)

Metric(s)	2009 Status(s)	2020 Target(s)
Price of LED Package @ 35 A/cm2	\$20-30/klm (cool) \$30-40/klm (warm)	\$1/klm
GaN Substrate Price	>\$2,000 (50 mm)	\$1,000 (100 mm)
Droop - Relative WPE at 150A/cm2 vs. 35A/cm2 (WPE_{150}/WPE_{35})	50%	90%
Thermal Sensitivity - Relative Optical Flux at 100ºC vs. 25ºC (Opt_{100}/Opt_{25})	85% (Blue, Green) 50% (Red)	95% (Blue, Green) 75% (Red)

B1.2 Semiconductor Material: Improve wall plug efficiency at optimal wavelengths for producing white light across the visible spectrum. Improve droop and thermal sensitivity.

Metric(s)	2009 Status(s)	2020 Target(s)
Wall Plug Efficiency (WPE) @ 35 A/cm2	50-55% (Blue) 21% (Green) 35% (Red)	75% (Blue, Green, Red)
Droop - Relative WPE at 150A/cm2 vs. 35A/cm2 (WPE_{150}/WPE_{35})	50%	90%

B1.3 Phosphors: Optimize phosphors for high efficacy LED white light applications, including color uniformity, color maintenance, thermal sensitivity and stability.

Metric(s)	2009 Status(s)	2020 Target(s)
Quantum Yield (25C)	95% (cool @ 550±50 nm peak) 80% (warm @ 600±50 nm peak)	95% across visible spectrum
Quantum Yield (150C)	80% (cool @ 550±50 nm peak) 70% (warm @ 600±50 nm peak)	85% across visible spectrum
Temperature Stability - Relative Quantum Yield at 150ºC vs. 25ºC (QY_{150}/QY_{25})	85% across visible spectrum	90% across visible spectrum
Average Conversion Efficiency (phosphor converted LED)	65% (cool) 50% (warm)	73% (cool) 66% (warm)
Spectral Full Width Half Maximum (FWHM)	150 nm (Red)	<50 nm (Red[69])
Color Stability (phosphor converted LED)	Color Shift of 0.012 u'v' over life	Color Shift < 0.004 u'v' over life

[69] Peak wavelengths longer than 620nm are acceptable for narrower emission spectra provided this is consistent with maximizing spectral efficiency.

B3.6 Package Architecture: Develop novel LED package and module architectures which can be readily integrated into luminaires. Architectures should address some of the following issues: cost, color, optical distribution, thermal handling and integration, electrical integration, 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, or hybrid approaches to address these issues.
Product: LED package/module

Metric(s)	2009 Status(s)	2020 Target(s)
Change in CCT over time	7-8 step MacAdam Ellipse	1-step MacAdam Ellipse over lifetime
Price of LED Package @ 35 A/cm2	\$20-30/klm (cool) \$30-40/klm (warm)	\$1/klm
Price of Luminaire or replacement lamp	\$120-\$150/klm	\$8/klm
Flux Thermal Sensitivity	80%	90%
Luminaire Optical Efficiency	80%	90%

B5.2 Color Maintenance: Ensure luminaire maintains the initial color point and color quality over the life of the luminaire.
Product: Luminaire/ replacement lamp

Metric(s)	2009 Status(s)	2020 Target(s)
Change in CCT over time	7-8 step MacAdam Ellipse	1-step MacAdam Ellipse over lifetime

B6.3 Optimizing System Reliability: Includes system reliability analysis to determine and analyze (collect industry wide data) failure mechanisms and improve. Develop an openly available and widely usable software tool verified by experimental data.

Metric(s)	2009 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

4.5.4 OLED Priority Core Technology Tasks for 2010

C1.2 **Novel OLED Materials and Structures:** Explores novel materials and structures that can be used to transport charge and emit white light more effectively; increasing EQE, reducing voltage and improving device lifetime . Improvement in the blue component remains of critical importance. Potential for radically reduced cost is desirable, for example through increased material robustness or by enabling simpler device fabrication. Investigation of structures that offer greater control of the color or directionality of the light would be particularly timely.

Metric(s)	2009 Status(s)	2020 Target(s)
Voltage[70] @ $2mA/cm^2$	~3.8V	<3V
Operating lifetime	L50=20kHrs	L70=50 kHrs
EQE without extraction enhancement	22%	25-30%

[70] This value assumes the use of a single voltage to drive each of the emitters. It should be regarded as an average value for tandem structures or those with separate drive for the RGB components.

C2.2 Electrode Research: Develop a novel electrode system for uniform current distribution across a (>200 cm^2) panel. Solutions must have potential for substantial cost reduction with long life while maintaining high OLED performance. Work could include more complex architectures such as grids or patterned structures, p-type and n-type degenerate electrodes, two-material electrodes, electrodes that reduce I*R loss, flexible electrodes, or other low-voltage electrodes.

Metric(s)	2009 Status(s)	2020 Target(s)
Cost reduction potential	$20/$m^2$	$4/$m^2$
Absorption in transparent electrode	<1% absorption	Maintain
Effective area resistivity[71] (including any grid structure)	ITO/Glass: 18 ohms/sq	~0.1 ohm/sq

C3.1 Fabrication Technology Research: Develop new practical techniques for materials deposition, device fabrication, or encapsulation. Should show potential for scalability and low cost.

Metric(s)	2009 Status(s)	2020 Target(s)
Relative material and processing cost reduction potential	1 relative cost	1/10 cost
Material Utilization	5-50%	>70%
Uniformity	5% variation over small areas	<5% variation over 200 cm^2
Yield of good panels		>90%

C6.3 Light Extraction Approaches: Devise new optical and device designs for improving OLED light extraction while retaining the thin profile of OLED panels. The proposed solution could involve modifications within the OLED stack, within or between the transparent electrode and substrate, or additional layers outside the substrate. The approach should be scalable to large sizes and provide potential for low costs.

Metric(s)	2009 Status(s)	2020 Target(s)
Extraction Efficiency	40%	75%

[71] The resistance of the electrode structures should be low enough to reduce the variation in current distribution across the panel to ~20% and ohmic losses in the electrodes to ~1%.

4.5.5 OLED Priority Product Development Tasks for 2010

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.

Metric(s)	2009 Status(s)	2020 Target(s)
Cost reduction potential	$\$20/m^2$	$\$5/m^2$
Absorption over the visible spectrum	<1% absorption	Maintain
Current uniformity		<5% variation over 200 cm^2 panel
Voltage @ 2mA/cm^2	~3.8V	<3V
Peak-to-peak roughness	20 nm	10 nm

D6.1 Large Area OLED: Investigate and remove obstacles to the fabrication of large OLED panels. Demonstrate a high efficiency OLED panel, with an area of at least 200cm^2, with high light uniformity and long operating lifetime, employing low cost designs, processes, and materials and with the potential for high-volume manufacturing.

Metric(s)	2009 Status(s)	2020 Target(s)
Lumen Output	100 lumens	> 200 lumens
Efficacy	45 lpw	>150 lpw
Color uniformity	3000K – 1 quadrangle	Energy Star Color
Brightness uniformity	20% over small area	20% over 200 cm^2
Cost of panel		<$10

D6.2 Panel Packaging: Scale up practical, low-cost packaging designs that result in improved resistance to the environment (particularly water and oxygen impermeability) and thermal management. Encapsulation considerations should involve compatible materials, appropriate processes, etc. Edge effects should also be considered. Demonstrate a high-efficiency OLED panel that employs such a packaging design and exhibits improved lifetime.

Metric(s)	2009 Status(s)	2020 Target(s)
Panel Operating Lifetime	20khrs (L50)	50khrs (L70)
Panel Shelf Life	>6 year (display)	20 yr
Packaging Cost	$\$50\text{-}75/m^2$ barrier cost (flexible)	<$\$5/m^2$

D6.3 Light extraction: Demonstrate manufacturable approaches to fabricate OLED panels with improved light extraction efficiency. The proposed solution could involve modifications within the OLED stack, within or between the transparent electrode and substrate, or additional layers outside the substrate. The approach should be scalable to large sizes and provide potential for low costs.

Metric(s)	2009 Status(s)	2020 Target(s)
Extraction Efficiency	40%	75%
Cost		$\$10/m^2$

D6.4 Panel Reliability: Analyze and understand failure mechanisms of OLED panels and demonstrate a packaged OLED panel with significant improvements in operating lifetime. Specific issues may include enhanced thermal management to support operation at higher luminance levels, or the dependence of shorting on layer thickness and uniformity.		
Metric(s)	**2009 Status(s)**	**2020 Target(s)**
Median L70 lifetime at >10,000lm/m^2	~2kHrs	>50kHrs

4.6 Interim Product Goals

To provide some concrete measures of progress for the overall program, the committee identified several milestones that will mark progress over the next ten years. These milestones 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.

4.6.1 Light-Emitting Diodes

The FY09 LED goal described in the 2009 MYPP was to produce a cool white LED package with an efficacy of 132 lm/W, an OEM price of $25/klm (device only), a CRI of 70-80, and a CCT between 4100 and 6500 K. The corresponding target for a warm white LED package was an efficacy of 83 lm/W, an OEM price of $46/klm, a CRI >85, and a CCT between 2800 and 3500K. These performance characteristics represent a "good" general illumination product that can achieve significant market penetration. These goals have been almost entirely met. The best commercial products have demonstrated 132 lm/W at a selling price of $28/klm (1000 quantity) for a cool white device (CRI=75), and 78 lm/W at a selling price of $26/klm for a warm white device (CRI=80).

Similarly, the FY09 goal was to produce a cool white lamp with an efficacy of 69 lm/W (43 lm/W for a warm white lamp) and an OEM price of $130/klm. These targets have been largely met for certain warm white downlight products (CCT=2700-3500K, CRI=92) which have achieved an efficacy of 62 lm/W at a retail selling price of $128/klm.

The revised goals introduced in the present report for commercial products reflect an average performance rather than peak performance. The average efficacy goals for cool and warm white LEDs are 113 and 70 lm/W respectively, which compare well with actual values of 102 and 70 lm/W. Similarly, average price goals for cool and warm white LEDs of $25/klm and $36/klm respectively are in excellent agreement with average LED package prices of $29/klm and $36/klm.

FY10 and FY15 milestones represent efficacy or price targets of LED packages with a lifetime (lumen maintenance value) of 50,000 hrs. Also, DOE expects to see a high efficiency luminaire on the market by 2012 that has the equivalent lumen output of a 75W incandescent bulb and an efficacy of 100 lm/W. By FY15, costs should be below $2/klm for LED packages while also meeting other performance goals. By 2020, DOE expects the focus to shift toward realization of a commodity grade luminaire product with output exceeding 3500 lumens and price below $100, while maintaining reasonable efficacy.

Table 4.10: LED Package and Luminaire Milestones

Milestone	Year	Milestone Target
Milestone 1	FY08	LED Package: >80 lm/W, <$25/klm, 50,000 hrs
Milestone 2	FY10	LED Package: >140 lm/W cool white; >90 lm/W warm white; <$13/klm (cool white)
Milestone 3	FY12	Luminaire: 100 lm/W; ~1700 lumens (neutral white)
Milestone 4	FY15	LED package: <$2/klm
Milestone 5	FY20	Luminaire: >3500 lumens (neutral white); <$100; >140 lm/W

Assumptions:
1) Packaged devices measured at 35 A/cm^2.
2) Cool white – CCT = 4745-7040 K, CRI=70-80
3) Neutral white – CCT = 3710-4745 K, CRI=70-80
4) Warm white – CCT=2580-3710 K, CRI=80-90

LED subtasks are shown in four phases of development corresponding to the four milestones. The first phase, essentially complete, is to develop a reasonably efficient white LED package that is sufficient for the lighting market. Phase 2 is to further improve efficiency while further decreasing price in order to realize the best possible energy savings. This phase should be completed in about two years. Developing a more efficient luminaire is the thrust of Phase 3, expected to last until about 2012. Finally, the fourth phase is to significantly reduce the cost of LED lighting to the point where it is competitive across the board. This phase, currently underway, is expected to continue past 2015 and will be supported through the R&D Manufacturing Program.

4.6.2 Organic Light-Emitting Diodes

The FY08 OLED milestone was to produce an OLED niche product with an efficacy of 25 lm/W, an OEM price of $100/klm (device only), and a life of 5,000 hrs, with a CRI greater than 80 and a CCT between 3,000K and 4,000K. A luminance of 1000 cd/m^2 and a lumen output greater than 500 lumens should be assumed as a reference level in order to compare the accomplishments of different researchers. That is *not* to say that lighting products may not be designed at higher luminance or higher light output levels.

According to industry experts, major manufacturers are likely to wait for OLED laboratory prototypes to achieve higher efficacies before investing in the manufacturing infrastructure to produce high efficacy, competitively priced OLED products for general illumination purposes. Milestone 2 targets an efficacy greater than 60 lm/W by FY10. Reaching a marketable price for an OLED lighting product is seen as one of the critical steps to getting this technology into general use because of the large area of OLED panels, so although the FY08 milestone may be late in coming, cost reduction remains the focus of the milestone for FY12.[72] By FY15 the target is to get a 100 lm/W OLED panel. Cost and lifetime should show continuous improvement as well.

Table 4.11 shows the overarching DOE milestones for OLED based SSL. The 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.

Table 4.11: 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	< $45/klm panel
Milestone 4	FY15	> 100 lm/W panel @ 10,000 lm/m^2
Milestone 5	FY18	50,000 hour lifetime; 10,000 lm/m^2 panel

Assumptions: CRI > 85, CCT < 2580-3710 K for an OLED panel >200 cm^2. All milestones assume continuing progress in the other overarching parameters - lifetime and cost.

4.7 Unaddressed Opportunities

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 among proposed projects. There are also new topics that could benefit from additional funding.

During 2009 and earlier, the two general areas most often cited as needing more investigation are reliability and color. The feature of both of these is that there is a temptation to make compromises in efficiency in order to compensate for some of these aspects of product performance to increase market acceptance. It is our belief that they are both amenable to systematic investigation that could lead to improvements without compromising energy efficiency, but they are not fully addressed at present.

Some of these opportunities are as follows:

1. *Funding of additional projects.* As DOE's SSL program has grown, 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 in

[72] Initially, cost reductions were targeted for FY10, however this was moved to FY12 for the 2009 report as products have just begun to enter the market.

2009, it will become all the more difficult to fund all of the worthwhile projects proposed. This is a very large lost opportunity.

2. *Devise methods to accelerate life testing of luminaires.* While means 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 unacceptably. We do not have 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 some help.

3. *Understanding of failure mechanisms.* This topic is of rapidly increasing importance. The use of chemicals in luminaire assembly that are incompatible with SSLs and overstress of SSLs 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. But the truth is we have no clear understanding of all of the types or frequency of premature failures.

4. *Testing of driver subsystems*. DOE's testing program for luminaires is highly valued by the industry as a source of reliable information. Such information on off-the-shelf drivers would also be extremely valuable and has been requested numerous times in SSL workshops and working groups. It should be added to the existing testing support programs.

5.0 Solid-State Lighting Portfolio Management Plan

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

1. Emphasis on competition
2. Cost- (and risk-) sharing – exceeding Energy Policy Act of 1992 cost-share requirements
3. SSL industry partners involved in planning and funding
4. Targeted research for focused R&D needs
5. Innovative intellectual property provisions
6. Open information and process
7. Success determined by milestones met and ultimately energy-efficient, long-life, and cost-competitive products developed

This chapter presents each of the aspects of the SSL Portfolio management plan, including: (1) the DOE SSL Strategy, (2) the SSL R&D Operational Plan (3) the SSL R&D Funding Plan, (4) the Portfolio Decision-Making Process, (5) the SSL Quality Control and Evaluation Plan, (6) the Stage-Gate Project Management plan, and (7) the SSL Commercialization Support Plan.

5.1 DOE Solid-State Lighting Strategy

The U.S. DOE's SSL portfolio draws on DOE's long-term relationships with the SSL industry and research community to guide SSL technology from laboratory to marketplace. DOE's comprehensive approach includes Basic Energy Science, Core Technology Research, Product Development, Manufacturing R&D, Commercialization Support, Standards Development, and an SSL Partnership. Figure 5.1 shows the connections and interrelationships between these elements of the program.

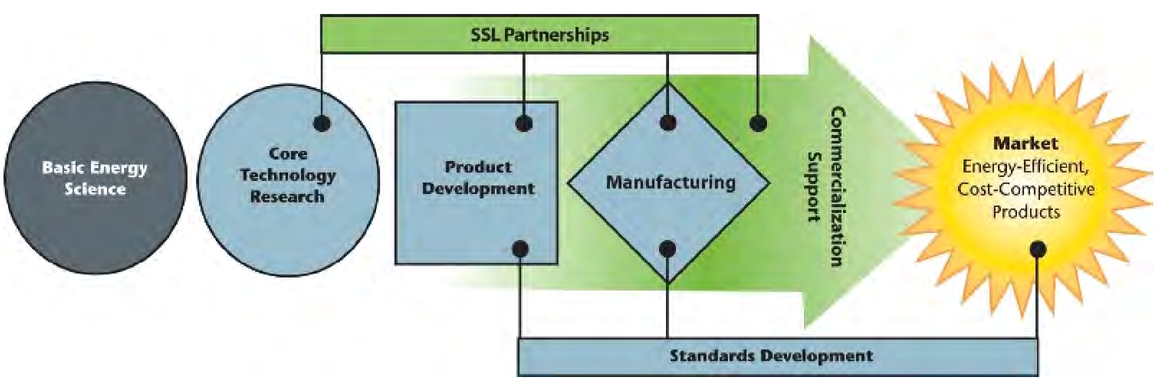

Figure 5.1: Interrelationships within DOE SSL Activities

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

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

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

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

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

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

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

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

SSL Partnership provides manufacturing and commercialization focus. Supporting the DOE SSL portfolio is the SSL Partnership between DOE and the NGLIA, an alliance of for-profit lighting manufacturers. DOE's Memorandum of Agreement with NGLIA, signed in 2005, details a strategy to enhance the manufacturing and commercialization focus of the DOE portfolio by utilizing the expertise of this organization of SSL manufacturers. The Partnership members confer among themselves and communicate their R&D needs to DOE program managers, who in turn, shape these needs into the project solicitations.

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

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

Standards Development Enables Meaningful Performance Measurement. LEDs differ significantly from traditional light sources, and new test procedures and industry standards are needed to measure their performance. DOE provides national leadership and support for this effort, working closely with IESNA, NEMA, NGLIA, ANSI, and other standards setting organizations to accelerate the standards development process, facilitate ongoing collaboration, and offer technical assistance.

5.2 SSL R&D Operational Plan

DOE has structured an operational plan for SSL R&D (see Figure 5.2) that depicts the various activities in which DOE, industry, and researchers engage in order to facilitate the bringing of SSL products to market. Each of these activities is discussed in further detail in the following sections. First, through collaboration with the SSL partnership and a series of workshops and roundtables, DOE identifies and prioritizes core technology, product development, and manufacturing needs. Based on the priority areas, DOE then issues competitive solicitations to industry, academia, national laboratories, and research institutions. Subject to an "exceptional circumstance" to the Bayh-Dole Act (discussed in the previous section) intellectual property and royalties can be exchanged between core technology researchers and the SSL Partnership. DOE annually tracks the status of SSL technology and reports progress toward the program milestones to the United States Congress.

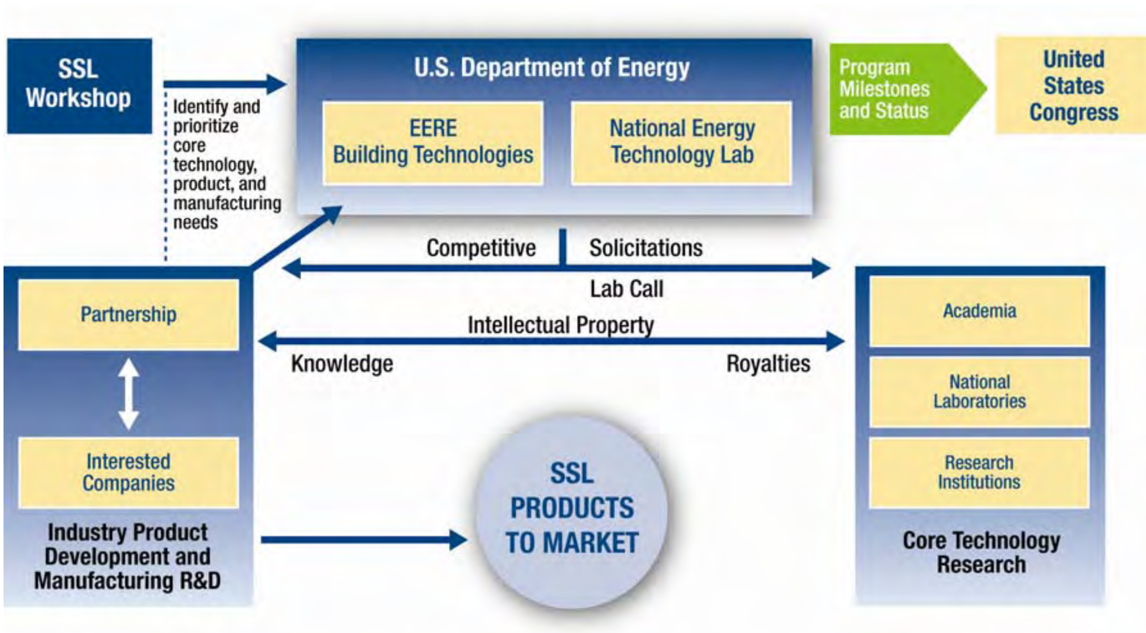

Figure 5.2: Structure of DOE SSL R&D Operational Plan

Figure 5.3 details the high-level timeline for the SSL R&D operational plan. Each year, DOE expects to issue at least four competitive solicitations: the Core Technology Solicitation, the Core Technology to National Labs (Lab Call), the Product Development Solicitation, and the Manufacturing R&D Solicitation. A number of annual meetings are held to provide regular DOE management and review checks, and to keep all interested parties adequately informed. More specifically, these meetings:

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

- At DOE's discretion, provide a peer review of Core Technology. Product Development, and Manufacturing R&D projects

- Provide individual project reviews by DOE

Figure 5.3: SSL Operational Plan Process

5.3 Research and Development Funding Plan

DOE supports the research, development, and demonstration of promising SSL technologies. As a technology matures, different funding programs are available to support its development, as detailed in Figure 5.4 .

SSL research partners and projects are selected based on such factors as energy savings potential, likelihood of success, and alignment with the SSL R&D plans.

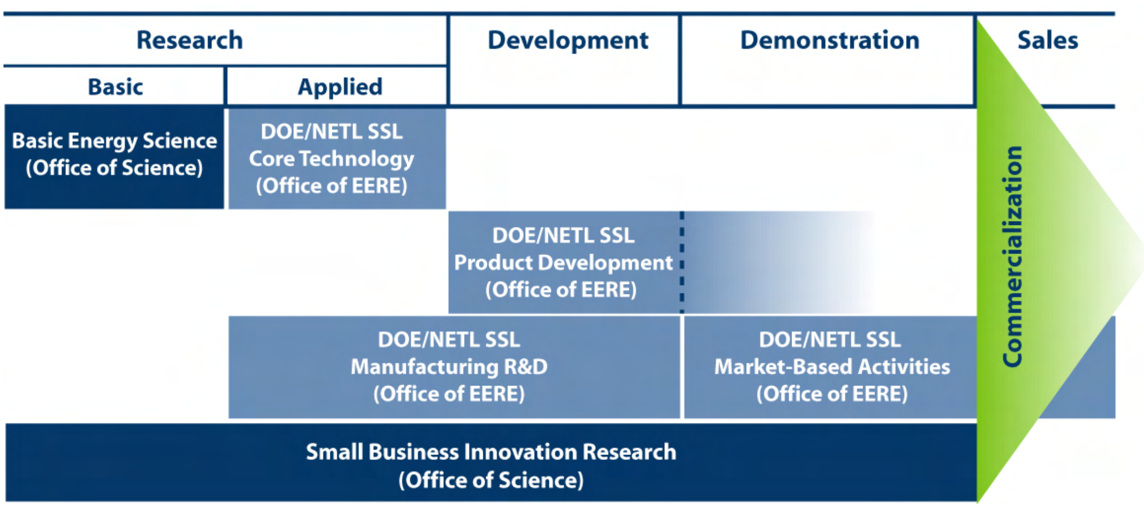

Figure 5.4: DOE Funding Opportunities

DOE funding programs supporting the Solid-State Lighting R&D Portfolio include:

- **Basic Energy Science** — Precedes the mission of the DOE SSL R&D program. Grants supporting basic energy science are provided by DOE's Office of Science through an annual solicitation process.

- **Small Business Innovation Research (SBIR)** — Seeks to increase participation of small businesses in federal R&D. Supports annual competitions among small businesses for Phase 1 (feasibility of innovative concepts) and Phase 2 (principal research or R&D effort) awards, and includes topics related to SSL.

- **DOE/NETL Solid-State Lighting Program** — Seeks to advance and promote the collaborative atmosphere of the Lighting R&D SSL program to identify product concepts and develop ideas that are novel, innovative and groundbreaking.

There are two types of financial assistance awards[73], cooperative agreements, used by the DOE/NETL SSL Program, and grants, which are used by both the Basic Energy Sciences and SBIR programs. These awards are basically the same except cooperative agreements include "substantial involvement" by the government. Given the innovative structure of the SSL Program, it is imperative that the government be given the opportunity to assist the recipients, the entity awarded the cooperative agreement, in managing the project to successful completion.

5.4 Portfolio Decision-Making Process

DOE establishes its SSL R&D priorities and projects through a consultative process with industry, expert technical reviewers and other interested parties. The portfolio decision-making process is based upon (1) the output of consultative workshops, (2) a competitive solicitation process based on the seven guiding principles of the SSL program (see Section 5.4.2), and (3) consultation with the SSL partnership. Each of these three components of the portfolio decision making process is discussed below.

5.4.1 Consultative Workshops

The SSL R&D program hosts consultative workshops to solicit input from industry and researchers on the near-term priority R&D activities. Stakeholder consultation and participation are integral to the SSL R&D agenda planning process. Industry, national laboratories, and academia participated in the R&D agenda planning process to provide input to future SSL R&D Portfolio priorities DOE may pursue through several consultative workshops held by DOE[74]:

- **Basic Energy Sciences Workshop:** This workshop was jointly held by the DOE's Basic Energy Sciences Program and the Building Technologies Program in Bethesda, MD in 2006. The workshop focused on basic research needs for SSL and provided the forum for a coordinated approach to R&D between the two programs that include core technology research, product development, commercialization support, DOE ENERGY STAR® criteria for SSL, standards development, and an SSL partnership with industry.

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[73] Financial Assistance awards are used when the principal purpose of the relationship is to affect a public purpose of support or stimulation. In contrary, an acquisition contract is used when the principal purpose is to acquire goods and services for the direct benefit or use of the Federal Government

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

- **CALiPER Roundtables**: These roundtables are held to gather feedback from SSL representatives on CALiPER test results and procedures as well as additional testing needs for SSL. These roundtables are held among standards-setting efforts, lighting testing laboratories, and key SSL industry stakeholders in order to gather feedback on CALiPER test results and to discuss current issues related to SSL testing and related standards development. The last CALiPER roundtable took place in Denver, CO in March 2009.

- **ENERGY STAR® Manufacturer Stakeholder Meetings:** The DOE hosts this workshop for manufacturers to review the DOE ENERGY STAR criteria for SSL, the status of related test procedures, and the program launch and qualification process, as well as to learn more about future plans for the DOE ENERGY STAR program for SSL. The last ENERGY STAR stakeholder meeting took place in May 2008 in Washington, DC.

- **Lighting Designer Roundtable:** The DOE hosts this roundtable in coordination with the International Association of Lighting Designers (IES), and the Illuminating Engineering Society of North America (IALD). Lighting designers, along with DOE representatives, discuss SSL market and technology issues and share experiences and recommendations regarding the SSL industry. The last roundtable was held in Chicago, IL in March 2008.

- **Manufacturing Workshops and Roundtables**: The manufacturing workshops and roundtables gather SSL manufacturers in order to seek guidance on updates to the SSL Manufacturing Roadmap and a DOE manufacturing initiative. This guidance leads to the priority tasks which are then used to shape the competitive solicitations in the Manufacturing R&D program. The last manufacturing workshop took place in Vancouver, WA in June 2009, while the last roundtable took place in Washington, DC in March 2010.

- **Market Introduction Workshops**: These workshops are held in order to facilitate a dialogue among the DOE and SSL experts on how federal, state, and private-sector organizations can work together to guide market introduction of SSL products. The last market introduction workshop took place in Chicago, IL in July 2009.

- **R&D Planning Workshop and Roundtables**: These sessions bring together lighting industry leaders, chip makers, fixture manufacturers, researchers, academia, lighting designers, architects, trade associations, energy efficiency organizations, and utilities in order to share insights and updates on technology advances and market developments. The opportunity is given to attendees to provide input and research areas in need of DOE funding which guides updates to this R&D Multi-Year Program Plan. The last R&D planning workshop took place in February 2010, and was held in Raleigh, NC, while the last R&D planning roundtables occurred in November 2010, in Washington, DC.

5.4.2 Competitive Solicitations

The SSL R&D program issues competitive solicitations annually to the SSL industry. The subjects of these solicitations are based on the priority areas developed throughout the fiscal year at the consultative workshops and internal meetings. Starting in FY2009, three competitive solicitations are released in accordance with the three operational pathways: Core Technology, Product Development, and Manufacturing Support. These solicitations are conducted by the National Energy Technology Laboratory (NETL), and are open to all industry participants.

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

5.4.3 Consultation with the SSL Partnership

In February 2005, DOE signed a Memorandum of Agreement with the Next Generation Lighting Industry Alliance, creating and clarifying the expectations for the Partnership.

The NGLIA, administered by NEMA, is an alliance of for-profit corporations, established to accelerate SSL development and commercialization through government-industry partnership. As of January 2010, the NGLIA was made up of sixteen corporations – 3M, Acuity Brands Lighting, Applied Materials Inc., CAO Group Inc., Corning Inc., Cree Inc., Eastman Kodak Company, GE-Lumination, Light Prescriptions Innovators, LLC (LPI, LLC), LSI Industries, Luminus Devices Inc., OSRAM Sylvania Inc., Philips SSL Solutions, QuNano Inc., Ruud Lighting Inc., and Universal Display Corporation[75] – though NEMA is actively seeking to extend membership to any firms active in SSL R&D.

In selecting the NGLIA to serve as its partner, DOE improved its access to the technical expertise of the organization's members. The Alliance provides input to shape DOE's SSL R&D program priorities, and as requested by DOE, provides technical expertise for proposal and project reviews. In addition, the Alliance will accelerate the implementation of SSL technologies by:

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

[75] Current NGLIA Members.January 5, 2010. Next Generation Lighting Industry Alliance. Available at: http://www.nglia.org/membership.html

The NGLIA's mission involves public advocacy on issues related to SSL, promotion and support of SSL technology and DOE's research program in SSL, and facilitation of communications among members and other organizations with substantial interest in the NGLIA activities. For more information on NGLIA, see their website at: http://www.nglia.org. To see a complete version of the MOA, see Appendix C.

5.5 Quality Control and Evaluation Plan

The SSL Research & Development Portfolio uses a quality control and evaluation plan (QC&E) to judge both the merit of individual projects as well as the soundness of the overall portfolio. At key intervals, comprehensive reviews are conducted, supported by analysis and objective review and recommendations by panels of experts (merit review/peer review). Performance is a criterion in project selections and performance evaluation is used to reshape plans, reassess goals and objectives, and re-balance the overall portfolio.

This QC&E plan for the Lighting Research and Development (LR&D) program, of which the SSL portfolio is a part, has three objectives:

1. Improve the performance, cost-effectiveness and timeliness of individual contracts;
2. Improve the portfolio of projects in the LR&D program; and
3. Assure future quality by bringing new high quality researchers into the solicitation process.

The QC&E plan for the LR&D program is built around the four critical stages of the annual program cycle. At each stage, the objectives, questions, quality assurance tools and metrics, and performance schedules are discussed. The four stages are:

1. Planning the LR&D program direction;
2. Selection process for LR&D projects;
3. Concurrent monitoring and evaluation; and
4. Post project evaluation and review.

These four discrete stages occur sequentially throughout the fiscal year and feed directly into each other. However, there could be feedback mechanisms such as a project's final findings and recommendations resulting in a slight modification to the overall program direction or the selection of future projects.

The figure below illustrates the four critical stages and some of the most important interactions. Using this framework, this plan identifies all the QC&E tools and processes in place designed to keep the LR&D program in step with the current objectives of the DOE and the research and development interests of industry, academia and the National Laboratories.

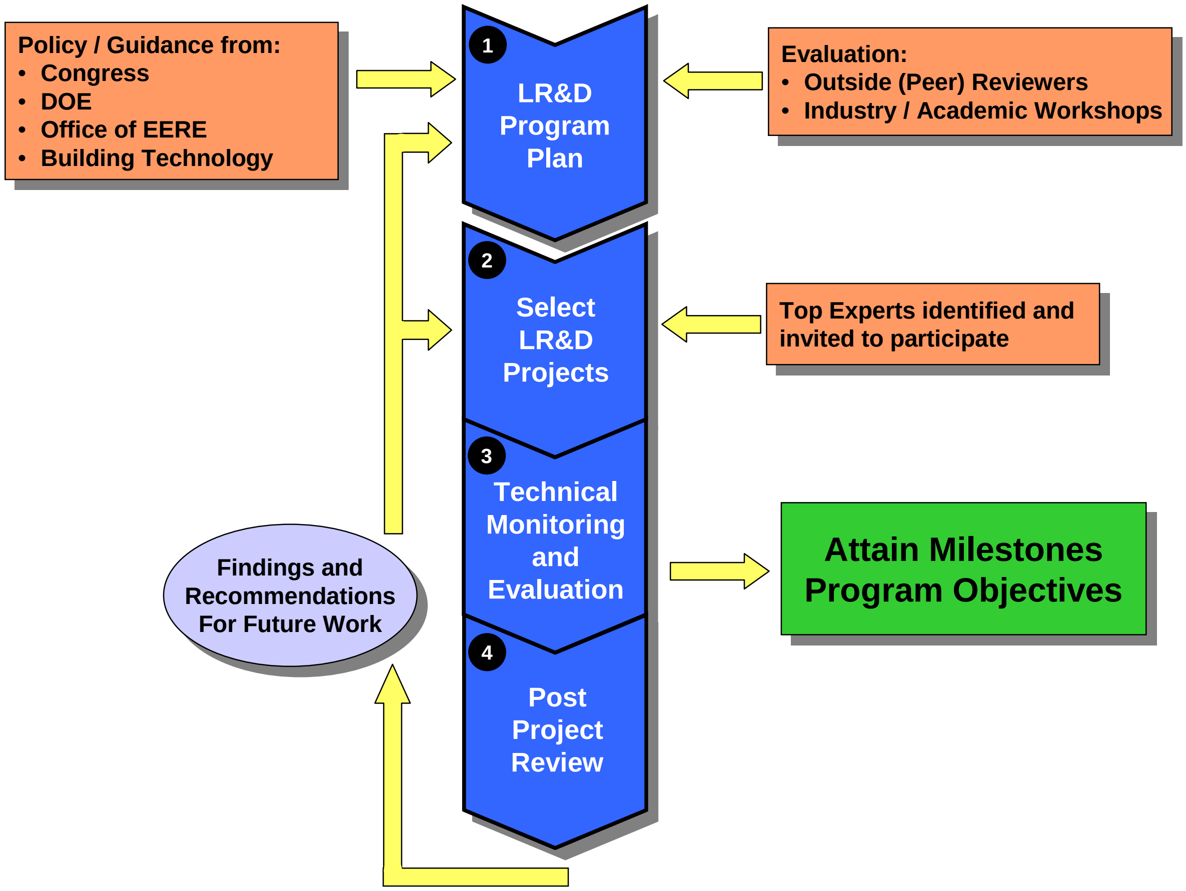
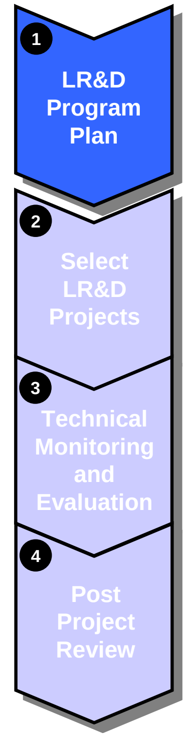


Figure 5.5: Four-Step Quality Control and Evaluation Plan for LR&D Program

5.5.1 Planning LR&D Program Direction



Objective of the Planning Stage:

- Review the LR&D Program Plan and determine if it conforms with the goals of Congress, the DOE, EERE, the Building Technologies Program, and key stakeholders and researchers.

Questions in the Planning Stage:

- Does this program plan solicit projects where there is a clear public benefit and result in energy conservation?
- Does this program plan identify and solicit research investment barriers perceived by private-sector researchers?
- What are the priority lighting-use areas and technologies that are consuming the most energy?
- Which technologies show the most promise of energy savings benefit?
- Is the plan structured to capture incremental improvements that could capture energy savings potential?
- How should the portfolio of projects be modified based on the review of the preceding year's projects?
- What are the research priorities and how should funding be appropriated, given all these inputs?

Analysis for the Planning Stage:

- The LR&D Program conducts analyses that provide input to the strategy and planning phase. Some examples include:
    - Lighting Market Characterization - Volume I: National Lighting Inventory and Energy Consumption Estimate: a national estimate of the number of lamps, operating and performance metrics, and energy consumption. Completed September 2002.[76]
    - Lighting Market Characterization - Volume II: Technology Options and Energy Savings Estimate: a review and prioritization of all the energy savings opportunities in lighting technology. Completed September 2005.[77]
    - Lighting Market Characterization - Volume III: Economic and Market Performance Targets. Analysis of lighting market milestones and targets that must be achieved in order to secure adoption and transformation. Ongoing assignment, as needed.
    - SSL Energy Savings Forecast – Specific to SSL, this study looks at a series of "what-if" scenarios of the energy savings potential if SSL achieves certain price and performance targets. Based on the national lighting inventory (Phase I) and a detailed market model based on

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[76] This report is located at http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/lmc_vol1_final.pdf
[77] This report is located at http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ee_lighting_vol2.pdf

paybacks the forecasts examine savings in both general illumination and niche applications. The most recent edition of the Niche Application study was completed in October of 2008, while the most recent General Illumination study was completed February of 2010[78]

- The LR&D Program may sponsor periodic workshops to better understand research priorities and opportunities. The result of a previous example of a multi-year, private and public interactive activity is the SSL Roadmap.

Implementation of QC&E in the Planning Stage:

- Planning for the coming fiscal year starts in April / May by reviewing the present year's projects:
    - Review progress made in the context of the aforementioned planning tools
    - Assess any new or appropriate alternative technologies and/or approaches
- Determine new or revise existing milestones and performance targets for the next year's projects, based on the broad range of analysis tools available to the DOE for the Planning Stage
- Develop a needs statement to use in a competitive solicitation / evaluation / awards process which ensures applicants are cognizant of and specifically address the LR&D's focus on lighting performance and efficiency in their proposals. Applicants must demonstrate:
    - Technical research
    - Energy savings
    - Resources for research
    - Path to commercialization
- Identify opportunities for Intergovernmental Cooperation / Synergy (e.g., DOD, NIST, other DOE organizations including Basic Energy Science (BES)) – explore opportunities for cost share.
- Internal program reviews by Building Technology (BT) staff
    - FY spend plan review – project by project discussion of suggested funding level: contractors, funding, brief scope, milestones
    - BT Program Review– presentation of program: strategy, R&D preview, technology goals, overall funding, and major program elements in R&D
- Peer program review – DOE periodically organizes external experts to review the LR&D program and its portfolio of projects.
- DOE actively participates in industry workshops and professional conferences applicable to the technologies of interest to the LR&D program. Maintenance of a strong technical level of expertise and visible profile helps keep the LR&D program current and accessible to all interested parties, and it helps to attract new participants.

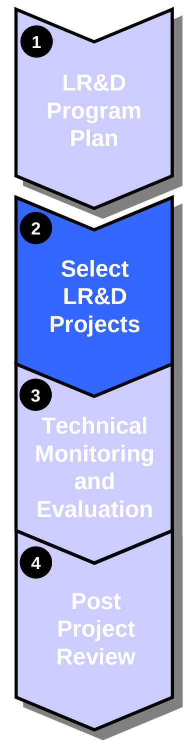
5.5.2 Selection Process for LR&D Projects

Objective of the Selection Stage:

[78] These reports are available at: http://www1.eere.energy.gov/buildings/ssl/tech_reports.html

- Strategically and competitively select projects that offer energy savings, incorporate milestones, and identify the path to market. Projects should be from contractors who have demonstrated technical leadership and have the resources to conduct the research. The resultant portfolio of projects should be balanced and reflect the overarching LR&D program plan and objectives.

Questions in the Selection Stage:



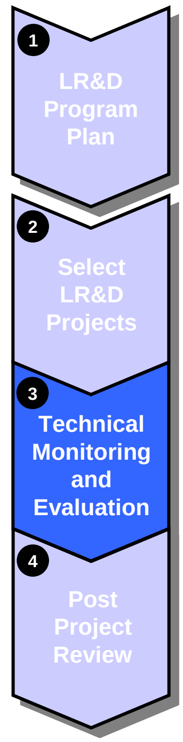
- Will this project help achieve the mission and goals of EERE and the LR&D program?
- Are the lighting energy conservation benefits reasonable?
- Is the project technically and economically feasible?
- How well does this project build on existing technology and is it complementary to related LR&D activities?
- How well does this project incorporate industry involvement? What is the level of industry cost-sharing of the program? Is there other Government investment in this area?
- Does the project offer sound, tangible performance indicators and/or milestones to facilitate monitoring?
- Does the project incorporate "off-ramps" and a clear end-point?
- How far from commercialization will the technology be when the project is complete? What is the commercialization time line (short, medium or long range)?
- What is the extent of technological risk inherent in the research? Is it cost-shared?
- For a project proposal, is there clear consensus among the internal and external reviewers?

Implementing QC&E in the Selection Stage:

- The sequence of technology maturation envisioned by the DOE is illustrated in Figure 5.4. It demonstrates how the overall SSL activity spans four technology maturation stages. The SSL program will conduct a series of actions to complete the levels of the continuum. DOE maintains a number of "open solicitations" that are released at various times during any given fiscal year. "Open" means that any and all stakeholders are invited to apply for cooperative research financial support via these established and well structured solicitations. The solicitations are publicized widely through the DOE's website, media press, and industry trade organizations and at relevant technical conferences. As is shown in the figure below, each solicitation has a specific objective for participation (i.e., academic, small business, manufacturers, etc.) and level of technology maturity.
- Develop new and utilize existing competitive solicitations:
    - Basic Science proposals are solicited throughout the year and are administered by BES according to their own Annual Operating Plan (AOP). However, there is considerable opportunity for technical

collaboration between BES and the LR&D program in the nature of the basic research supported. Since BES does not support applied research, any successful basic research completed must be transitioned to more applied organizations such as BT and the LR&D program. BES also participates in the SBIR program, which tailors some solicitations to focus on lighting related issues.
    - The annual BT/NETL "Energy Efficient Building Equipment and Envelope Technologies" solicitation ensures competition among interested manufacturers, research institutions, and academia for projects that meet defined LR&D program goals and energy conservation requirements.
    - SBIR proposals are issued annually and represent an excellent opportunity to attract small business to the LR&D program. While of modest size, these projects have historically played pivotal roles in establishing the technical viability of novel approaches to overcoming key technology issues.
    - DOD and other Government agencies often solicit proposals for research specifically tailored to their own needs and AOPs. The LR&D program can enjoy a synergistic benefit of this research particularly that which is completed by the DOD. Often the DOD is an early adopter of emerging technology and can be very instrumental in establishing the technical viability of a potential product whose military benefits offset constraints imposed by commercial markets. Many times, expensive technologies are first introduced into military applications and are subsequently reduced (in cost and sometimes technical complexity) to meet civilian applications.
- The LR&D program periodically organizes external technical and programmatic reviews to include internationally renowned expertise. This is utilized especially during the evaluation of proposals submitted to the "open" solicitations. The "evaluation criteria" includes technological risk, energy conservation potential, cost-sharing and other critical elements.
- To facilitate quantitative performance assessment, the LR&D program requires participants to explicitly state the performance targets they expect to achieve for their project during the period of performance along with justification.
- BT/NETL – projects are selected by votes from:
    - Expert (technical) reviewers – usually three
    - Technical managers at Building Technology
    - Merit Review Committee

5.5.3 Concurrent Monitoring and Evaluation



Objective of the Monitoring Stage:

- To manage current projects effectively through good communication and the monitoring of various project progress metrics. Determine appropriate remedial action for projects going off-track. Controls "scope-drift".

Questions in the Monitoring Stage:

- Ongoing Monitoring:
  - Are the projects meeting performance milestones on schedule and within budget?
  - Is reassessment of the project's objectives or milestones required?
  - Are the principal investigators providing sufficient updates on their progress?
  - Does the principal investigator present a logical R&D plan (with milestones) for next budget period?
  - Are required deliverables being satisfied? Are progress reports comprehensive and timely?
  - Should the NETL PMC Project Manager conduct a spot inspection or arrange an interim meeting to assess progress?
  - If the project is failing to achieve its milestones, should it be discontinued or redefined?
  - Are the objectives of the project still relevant to the LR&D goals and the EERE mission?
  - Is the project progressing against a reasonable cost plan?
- Project Completed:
  - Did the contractor complete the project to the satisfaction of DOE?
  - Was the project on time?
  - Was the project within budget?
  - Were the technical objectives met?
  - Do the results encourage further investigation / research into this particular project area? Or, another project area?
  - A "Close Out Questionnaire" is under development and may include some of the following draft suggestions (see Section 5.5.5):

Implementing QC&E in the Monitoring Stage:

- Conduct detailed technical and programmatic reviews of each individual project on a regular basis. Maintain good dialogue with all principal investigators and solicit feedback on progress in accordance with stated milestones and objectives.
- The NETL PMC Project Manager requires comprehensive periodic written progress reports (monthly, quarterly) from principal investigators pertaining to their progress.
    - Review these reports in relation to the stated milestones in the proposals
    - Consider remedial options if project is failing to meet deliverables or milestones (e.g., reprioritization, termination)
    - Re-assess the probability of success of the project
- Anytime spot check reviews – as needed, the NETL PMC Project Manager may select projects (or subtasks of a project) that are experiencing technical or programmatic difficulty. At his discretion, he may ask for a performance reviews at the contractor's facility or invite the contractor to some other location. This process allows the LR&D manager to keep a watchful eye on technical progress and helps ensure that problems are identified early and that deviations from the scope of work are identified quickly to get the project back on course.
- Annually, each project is critically reviewed sometimes with outside expertise. Each participant is expected to present the results of their research in progress and rationale for continued support. Previous milestones are reviewed and a determination of achievement is made. Future milestones are assessed and adjusted if necessary. In this way, research priorities are adjusted annually according to technical merit and relevance.

Milestone QC&E Meetings for FY'10:

The following schedule represents the project review meetings for FY'10 that cover the NETL, SBIR, and other project areas. At these meetings, DOE will be using the QC&E tools described above to assess technical and programmatic performance.

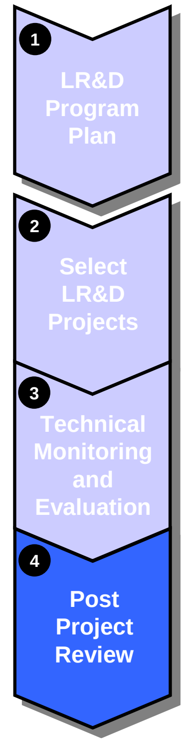
Table 5.1: LR&D Program Project Review Meetings for FY'10

Project	Performer	Objective	Date
AL85000	Sandia National Laboratories	Budget Period 1 Review	Oct-10
DE-EE0003159	KLA Tencor	Kickoff	TBD
DE-EE0003250	GE Global Research	Kickoff	TBD
DE-EE0003292	White Optics	Kickoff	TBD
EE0000611	Osram Sylvania Products Inc.	Budget Period 1 Review	Jul-10
EE0000626	Universal Display Corporation	Budget Period 1 Review	Jun-10
EE0000627	Rensselaer Polytechnic Institute	Budget Period 1 Review	Aug-10
EE0000628	QD Vision, Inc.	Budget Period 1 Review	Sep-10
EE0000641	Cree, Inc.	Budget Period 1 Review	Jun-10
EE0000645	Philips Lighting	Budget Period 1 Review	Jul-10
EE0000979	Eastman Kodak Company	Budget Period 1 Review	Aug-10
EE0000990	University of Florida	Budget Period 1 Review	Aug-10
EE0001269	DuPont Displays, Inc.	Budget Period 1 Review	Sep-10
EE0001292	Army Research Laboratory	Budget Period 1 Review	Nov-10
EE0001522	University of Florida	Budget Period 1 Review	Aug-10
EE0002003	University of California, San Diego	Budget Period 1 Review	Sep-10
EE0002031	Kaai, Inc.	Budget Period 1 Review	Sep-10
EE0003209	PPG	Kickoff	TBD
EE0003210	Philips Lumileds Lighting, LLC	Kickoff	TBD
EE0003232	GE Lumination	Kickoff	TBD
EE0003241	Osram	Kickoff	TBD
EE0003245	Lightscape	Kickoff	TBD
EE0003246	Cree, Inc.	Kickoff	TBD
EE0003249	Philips Lumileds Lighting, LLC	Kickoff	TBD
EE0003251	GE Global Research	Kickoff	TBD
EE0003252	Veeco	Kickoff	TBD
EE0003253	Universal Display Corporation	Kickoff	TBD
EE0003254	Cambrios	Kickoff	TBD
EE0003296	U Rochester	Kickoff	TBD
EE0003302	Ultratech	Kickoff	TBD
EE0003331	Applied Materials	Kickoff	TBD
GO28308	National Renewable Energy Laboratory	Budget Period 1 Review	Oct-10
M6642870	Los Alamos National Laboratory	Final	Mar-10
M6743231	Pacific Northwest National Laboratory	Final	Jul-10
M6743232	Lawrence Berkeley National Laboratory	Final	Sep-10
M68003934	Sandia National Laboratories	Budget Period 2 Review	Mar-10

Table 5.1: LR&D Program Project Review Meetings for FY'10(Continued)

Project	Performer	Objective	Date
M68004043	Pacific Northwest National Laboratory	Budget Period 2 Review	Apr-10
NT01575	Add-Vision Inc.	Budget Period 2 Review	Sep-10
NT01576	Arkema, Inc.	Final	Sep-10
NT01577	Cree, Inc.	Final	Oct-10
NT01578	Crystal IS, Inc.	Final	Jun-10
NT01579	GE Global Research	Final	Sep-10
NT01580	Georgia Institute of Technology	Budget Period 2 Review	Aug-10
NT01581	Lehigh University, Office of Research and Sponsored Programs	Budget Period 2 Review	Oct-10
NT01582	Osram Sylvania Products Inc.	Final	Jun-10
NT01583	Philips Lumileds Lighting, LLC	Final	Oct-10
NT01584	PhosphorTech Corporation	Budget Period 2 Review	Jul-10
NT01585	Universal Display Corporation	Final	Jul-10
NT42857	University of California, Santa Barbara	Final	TBD
NT42859	University of North Texas	Final	Mar-10
NT42861	Research Triangle Institute	Final	Mar-10
NT42934	GE Global Research	Final	Soon
NT43226	GE Global Research	Budget Period 2 Review	Feb-10
NT43227	Yale University	Final	Sep-10
NT43229	Carnegie Mellon University	Final	Sep-10
RL01830	Pacific Northwest National Laboratory	Budget Period 1 Review	Oct-10

5.5.4 Post Project Evaluation and Review



Objective of the Review Stage:

- Review the DOE objective and determine if further work in this area is warranted. Review the process and identify improvements.

Questions in the Review Stage:

- Questions from the draft Close-Out Quiz for Principle Investigators:
  - As a program participant, what are the important lessons you learned?
  - Has the project opportunity helped your organization achieve their strategic goals?
  - Do you have a commercialization plan for the technology you developed under this project?
  - Would you like the DOE to assist your organization to develop such a commercialization plan?
  - Looking back on the project, from solicitation to completion, can you make any specific recommendations to the DOE for improvement?
  - As a program participant, what, if anything, would you do differently?
  - Would you like to see the program continue in the future?

- Questions for DOE
  - What did we learn?
  - What did we accomplish?
  - Does the task completed in that area satisfy the original statement of needs?
  - Do the results encourage further evaluation of this project area? Or, have the target objectives of the DOE been met with the milestones achieved in this project?
  - How could we have improved the process – setting the plan, selecting the project and/or monitoring and evaluating the project?
    - Should there have been higher project goals?
    - Should there have been more interim reviews?
    - Should there have been more reporting (e.g., monthly instead of quarterly)?
  - Tie back to the Planning Stage, how do the results relate to the goals and objectives of the program and the interim milestone for DOE? Has the DOE achieved (completed) research in a particular area?

Implementing QC&E for the Review Stage:

- Recalibrate (if necessary) the LR&D objectives in a particular area based on findings from this research.
- Determine if milestones achieved will "close the chapter" in a particular area of research (e.g., evaluation of tungsten oxide research now determined to be complete).
- Review metrics of "success" for the project:
  - Number of Patents
  - Number of Conference Papers / Citations in Technical Literature
  - Product(s) delivered to market
  - Quantified energy savings impact
- Government Performance Results Act (GPRA) metrics?
- Publish results?

Unplanned Events

Occasionally, an event that is beyond the control of the DOE technical manager may occur which disrupts the normal project management framework. Some examples include:

- Delay in funding from Congress
- Increase or reduction in LR&D budget over planned
- Contractor actions, including: slow progress and funding spend rate; termination of contract; fast progress with need for additional funding; technical concept does not mature / can't meet project goals

These unplanned events will result in additional work by the program manager to alter contracts and/or funding levels for the LR&D program, to achieve original fiscal year goals.

5.5.5 QC&E Closeout Questionnaire

Draft EERE BT/NETL Energy Efficient Building Equipment and Envelope Technologies Competitive Solicitation
Contract Close Out Questionnaire

Overall, how would you rate your experience as a participant in the DOE's Building Envelope Technologies Program in the following categories:

	Good		Medium		Bad
1. Contractual/Administration	☐	☐	☐	☐	☐
2. Technical	☐	☐	☐	☐	☐
3. Financial	☐	☐	☐	☐	☐
4. Level of project success	☐	☐	☐	☐	☐

As a program participant, what are the important lessons you learned?

Has the project opportunity help your organization achieve their strategic goals?

Do you have a commercialization plan for the technology you developed under this project?

Would you like the DOE to assist your organization to develop such a commercialization plan?

Looking back on the project, from solicitation to completion, can you make any specific recommendations to the DOE for improvement?

As a program participant, what, if anything, you do differently?

Would you like to see the program continue in the future?

5.6 Stage-Gate Project Management Plan

The SSL Team developed a white paper to clearly elucidate the stages of Lighting Research and Development, which is intended to provide a management tool for the projects in the SSL portfolio.[79] A stage-gate system[80] tailored to the LR&D program and applied to each project in the portfolio creates a lexicon for discussion, decisions, and planning which is mutually beneficial to the National Energy Technology Laboratory portfolio manager and contractors. This framework was developed as a tool to assist in guiding the research, technical and business actions and decisions that are necessary to move a concept from a scientific phenomenon to a marketable product. As a technical concept advances through the continuum of technology stages, it must demonstrate that it meets the criteria at each gate before it advances to the next stage. By constructing this type of framework, DOE and its contractors will be properly reviewing the R&D projects and asking the right questions to lead to successful commercialization of energy-saving products.

[79] Managing Research and Development: The Technology Continuum of the Lighting Research and Development Portfolio. James R. Brodrick. November 2005.
[80] Robert Cooper, "Winning at New Products, Accelerating the Process from Idea to Launch." 3rd Edition. 2001.

In addition, DOE will be cognizant of where its contractors are located in the overall process of new product development. The stage-gate system also offers management an opportunity to terminate poorly performing projects and allocate resources to better projects. A summary of this method, *The Technology Continuum of the Lighting Research and Development Portfolio* (November 2005*)* is described below.

Cooper's stage-gate system for Industry R&D portfolio management spans the complete spectrum from concept to product development. The stage-gate system divides the development process into discrete, multifunctional stages interspersed with gates that function as potential off-ramps. Gates are decision points where R&D managers review analytical data and make a decision whether to continue developing a project or to terminate it. Stages represent the analytical effort expended by the company to assess research and market analysis on a particular technology or project. Each stage involves a set of parallel activities conducted in different functional areas of a company.

Several of Cooper's stages, shown in the top portion of Figure 5.6, such as preliminary investigation and market launch, fall outside the scope of work supported by the LR&D program. The focus of the LR&D program is primarily on stages 2 through 4 of the industry model, as shown in Figure 5.6. The LR&D model adapts these three generic stages into more specific stages, providing finer differentiation and focus on the activities within each stage. The mapping of the generic industry stages to the more specific LR&D program stages is shown in Figure 5.6.

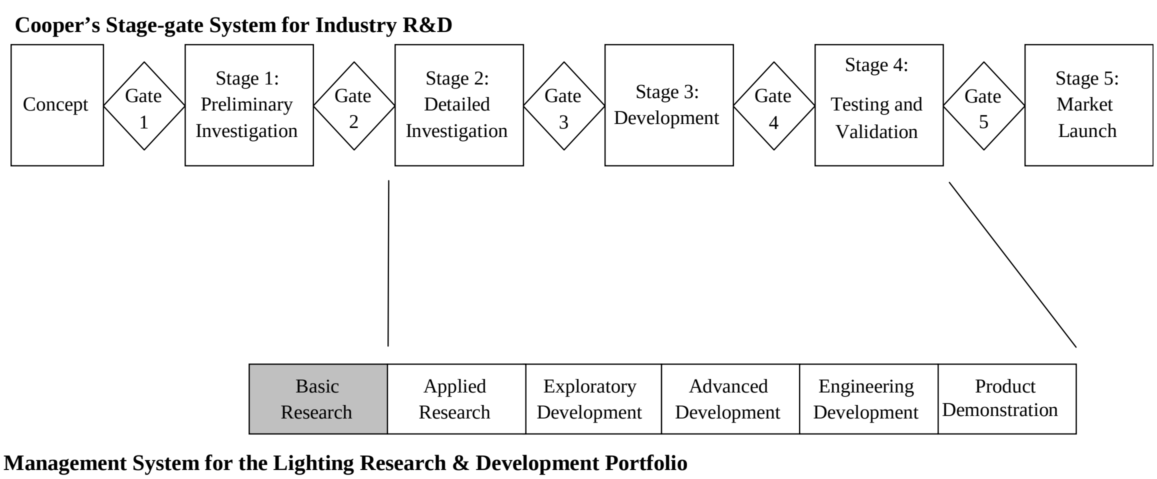


Figure 5.6: Mapping Cooper's Stage-Gate System to the LR&D Portfolio

On the following page, a diagram summarizes the LR&D technology development stages, providing the technical activities, gate expectations and deliverables required at each gate. This stage-gate system was developed primarily as a management system. In addition, it could assist in proposal targeting. For instance, if a solicitation intends to support applied research, a proposal centered on engineering development or product demonstration would be inappropriate. Proposals that are not matched to the solicitation objectives waste the time of stakeholders in their development as well as the DOE in their review.

Figure 5-7: LR&D Technology Development Stages and Gates

Technology Development Stages

	Basic Science Research* 1	Applied Research 2	Exploratory Development 3	Advanced Development 4	Engineering Development 5	Product Demonstration 6	Commercialization and Sales 7
Technical Activities	**Knowledge-Base Expansion** • Scientific principles formulated and proven • Empirical data and/or theoretical derivation	**Idea Generation** • Set performance milestones for Gate 2 • Fundamental lab testing • Create "hard" lab data to support physical principle • Math models of science • Scanning for match of science to application	**Proof of Technology- Product Definition** • Lab bread board of concept • Select technologies that have the best market entry potential • Identify and prioritize alternative approaches for performance/energy savings	**Proof of Technology- Working Model** • Fully functional lab prototypes • Specific application and approach • Testing of prototype on several performance parameters • Proof of "design concept" testing	**Engineering Prototype** • Testing of design features and performance limits, performance mapping • Field ready prototypes • Field testing with customer feedback • Preparation for manufacturing, marketing, certification/code compliance	**Production Prototype** • Validation of performance at owner / operator sites with third party data • Limited size demonstration in the field • Codes/standards certification • Finalize plans for manufacturing/ marketing	**Utilization by End User** • Commercialization • Deployment
Deliverables Required for Gate Decisions	Peer-reviewed paper or journal article Documentation of proof of concept	Correlation with building end use Analytical and/or empirical evidence of technology Performance viability, preferably lab data Written report of above Possible verification testing at another laboratory Set performance milestones for Gate 3	Performance status and expectation for market entry Comparison to available technology baseline Preliminary market assessment • Cost • Performance Estimate of national energy savings potential Attributes and benefits of approach Set performance & cost milestones for Gate 4	Product specifications defined Cost/Benefit analysis for owners/operators Detailed market assessment • Cost • Performance • Market penetration Estimates of national energy savings potential Identification of issues and technology status • Technical performance • Market barriers • Public acceptance • Legal – regulatory • Health and safety Set performance & cost milestones for Gate 5	Partnership agreements • Manufacturing • Licensing Resolution of issues from advanced development stage Field test results and adjustments in design Evaluation of national energy savings potential Update detailed market assessment Cost/Benefit analysis for market Set performance & cost milestones for Gate 6	Partnership agreements Final product specification Cost/Benefit analysis for market Update detailed market assessment Evaluation of national energy savings potential Report on demo performance at owner / operator sites	

Gate Expectations

Gate 1	Gate 2	Gate 3	Gate 4	Gate 5	Gate 6
✓ New concept or principle proven ✓ Theoretical or empirical proof ✓ Met performance milestones	✓ Address priority building end use ✓ Proof of technical performance ✓ Met performance milestones	✓ Prove clear advantage over available technology ✓ Met performance milestones	✓ Meet owner / operator cost/benefit requirements (1-5 yr. payback) ✓ Demonstrate significant end-user demand ✓ Technology status issues defined ✓ Met performance & cost milestones	✓ Ready for owner / operator on multi criteria (economics, safety, etc…)? ✓ Met performance & cost milestones	✓ Ready for production and/or application by owner/operator ✓ Met performance & cost milestones

* Note: The Basic Science Research stage precedes the program mission of the Solid State Lighting Portfolio

Adapted from Robert Cooper, "Winning at New Products, Accelerating the Process from Idea to Launch." Perseus Books Group. 3rd Edition. 2001. ISBN: 0738204633

The LR&D technology development stages consist of seven stages, providing the technical activities, gate expectations and deliverables required at each gate. Each of the seven stages is discussed briefly below.

Technology Maturation Stage 1 – Basic Science Research
Fundamental science exploration is performed to expand the knowledge-base in a given field. Scientific principles (with data-empirical and/or theoretical derivation) are formulated and proven. The output from these projects would generally be peer-reviewed papers published in recognized scientific journals. Specific applications are not necessarily identified in Stage 1.

Technology Maturation Stage 2 - Applied Research
Scientific principles are demonstrated, an application is identified, and the technology shows potential advantages in performance over commercially available technologies. Lab testing and/or math modeling is performed to identify the application(s), or provide the options (technical pathways) to an application. Testing and modeling add to the knowledge base that supports an application and point to performance improvements.

Technology Maturation Stage 3 – Exploratory Development
A product concept addresses an energy efficiency priority. From lab performance testing, down select from alternative technology approaches for best potential performance, via selection of materials, components, processes, cycles, and so on. With lab performance testing data, down select from a number of market applications to the initial market entry ideas. This product concept must exhibit cost and/or performance advantages over commercially available technologies. Technical feasibility should be demonstrated through component bench-scale testing with at least a laboratory breadboard of the concept.

Technology Maturation Stage 4 – Advanced Development
Product concept testing is performed on a fully functional lab prototype – “proof of design concept” testing. Testing is performed on prototypes for a number of performance parameters to address issues of market, legal, health, safety, etc. Through iterative improvements of concept, specific applications and technology approaches are refocused and “down selected.” Product specification (for manufacturing or marketing) is defined. Technology should identify clear advantages over commercially available technologies, and alternative technologies, from detailed assessment.

Technology Maturation Stage 5 – Engineering Development
“Field ready prototype” system is developed to refine product design features and performance limits. Performance mapping is evaluated. Performer conducts testing of a field-ready prototype/system in a representative or actual application with a small number of units in the field. The number of units is a function of unit cost, market influences (such as climate), monitoring costs, owner/operator criteria, etc. Feedback from the owner/operator and technical data gathered from field trials are used to improve prototype design. Further design modifications and re-testing are performed as needed.

Technology Maturation Stage 6 – Product Demonstration
Operational evaluation of the demonstration units in the field is conducted to validate performance as installed. Third party monitoring of the performance data is required, although less data is recorded relative to the "field ready prototype" test in Stage 5. Pre-production units may be used. Size of demo is a function of unit cost, monitoring cost, etc., and involves relatively more visibility. Energy savings are measured, with careful analysis of economic viability and field durability for specific applications.

Technology Maturation Stage 7 – Commercialization and Sales
The final stage of the technology development continuum focuses on commercialization and sales. This stage involves the implementation of the marketing and manufacturing plans, culminating in the successful launch of a new energy saving product.

While the DOE is currently funding SSL projects in the early stages of the technology development spectrum, over the years as the technology evolves and improves, solicitations in the advanced development, engineering development and product demonstration are planned. The expectation is that future projects will build on the foundation of applied research and exploratory development, catalyzing innovations in lamp materials, systems, fixtures, electronics, and device infrastructure. Eventually, demonstration projects in various sectors may also be warranted, to measure and document the beneficial aspects of this revolutionary technology.

5.7 Solid-State Lighting Commercialization Support Plan

The U.S. DOE has developed a comprehensive national strategy to guide SSL technology from lab to market. To leverage DOE's investment in SSL technology research and development, and to increase the likelihood that this R&D investment pays off in commercial success, DOE has developed a commercialization support plan. The plan focuses DOE resources on strategic areas to move the SSL market toward the highest energy efficiency and the highest lighting quality.

DOE's plan draws on key partnerships with the SSL industry, research community, standards setting organizations, energy efficiency groups, utilities, and others, as well as lessons learned from the past. Commercialization support activities are closely coordinated with research progress to ensure appropriate application of SSL products, and avoid buyer dissatisfaction and delay of market development. DOE's role is to:

- Help consumers, businesses, and government agencies differentiate good products and applications
- Widely distribute objective technical information
- Coordinate SSL commercialization activities among federal, state, and local organizations
- Communicate performance targets to industry

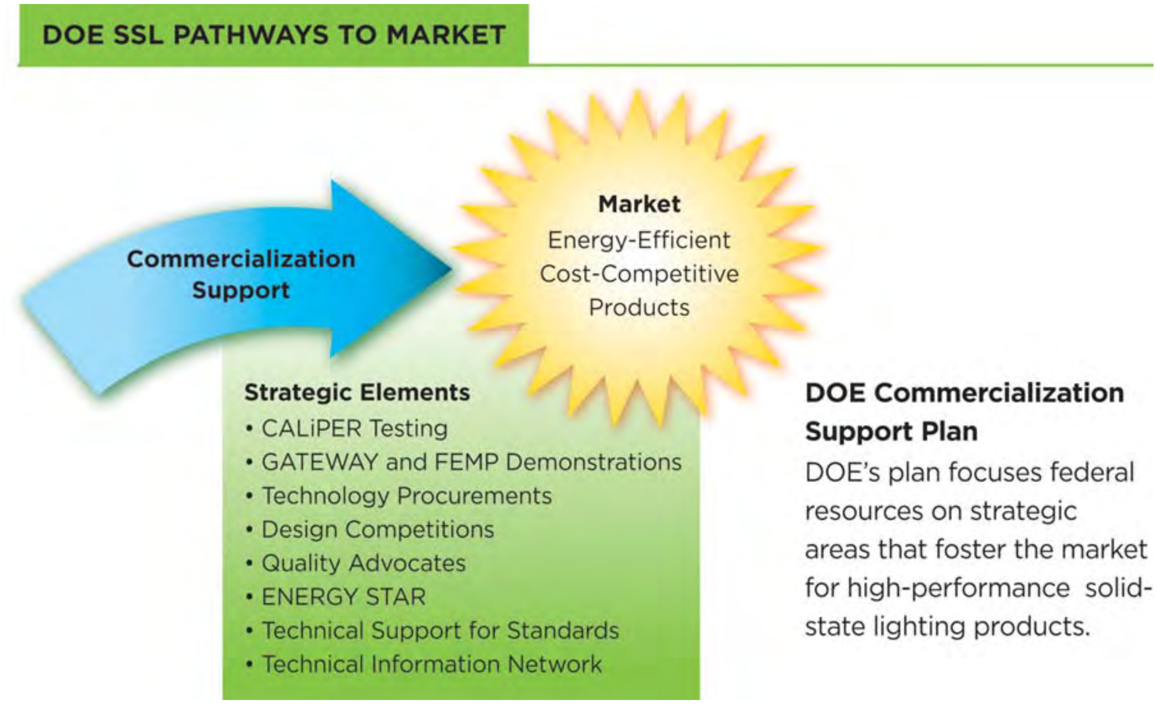


Figure 5.8: DOE SSL Commercialization Support Plan

DOE SSL Pathways to Market

CALiPER. Using test procedures currently under development by standards organizations, DOE's SSL testing program provides unbiased information on the performance of a widely representative array of commercially available SSL products for general illumination. Test results guide DOE planning for R&D, the Lighting for Tomorrow design competition, technology procurement activities, and ENERGY STAR®, in addition to furnishing objective product performance information to the public and informing the development and refinement of standards and test procedures for SSL products. http://www1.eere.energy.gov/buildings/ssl/caliper.html

GATEWAY Technology Demonstrations. Demonstrations showcase high performance LED products for general illumination in a variety of commercial and residential applications. Demonstration results provide real-world experience and data on state-of-the-art SSL product performance and cost effectiveness. Performance measurements include energy consumption, light output, color consistency, and interface/control issues. The results connect DOE technology procurement efforts with large-volume purchasers and provide buyers with reliable data on product performance. To date, GATEWAY demonstration projects include LED roadway and walkway lighting, LED residential lighting, LED parking garage lighting, and LED freezer case lighting. DOE seeks to assemble demonstration teams that match host sites with appropriate products and partners. DOE GATEWAY demonstrations are open to all participants, subject to certain eligibility parameters. Potential participants are encouraged to read more about the GATEWAY Program at: http://www1.eere.energy.gov/buildings/ssl/gatewaydemos.html

FEMP Technology Demonstrations. The DOE Building Technologies program also coordinates with the DOE Federal Energy Management Interagency Task Force, consisting of representatives from 21 agencies, to support demonstrations of LED products throughout the country in federal installations. The Interagency Task Force meets bi-monthly to address and resolve key issues surrounding the implementation of energy savings programs mandated by the Energy Policy Act of 2005.

Technology Procurement. Technology procurement is an established process for encouraging market introduction of new products meeting certain performance criteria. DOE has successfully used this approach with other lighting technologies, including sub-CFLs and reflector CFLs. Technology procurement will encourage adoption of new SSL systems and products that meet established energy efficiency and performance criteria, and link these products to volume buyers and market influencers.

Lighting for Tomorrow. In partnership with the American Lighting Association and the Consortium for Energy Efficiency (CEE), DOE sponsors Lighting for Tomorrow, a design competition that encourages and recognizes excellence in design of energy-efficient residential light fixtures. In the 2007 competition, 24 companies submitted 45 entries in the SSL category, with winning fixtures including a downlight, a desk lamp, an under cabinet fixture, and an outdoor wall lantern. In the 2008 competition, awards were given for an SSL under cabinet light, an SSL recessed can lamp, SSL task lights, an SSL spotlight luminaire, an SSL architectural lay-in, and an SSL module. In the 2009 competition, twenty six companies submitted LED entries, with awards going to an SSL downlight, an SSL task light, and special recognition going to four additional SSL products. http://www.lightingfortomorrow.com

ENERGY STAR for SSL. ENERGY STAR is a voluntary energy efficiency labeling program identifying products that save energy, relative to standard technology. Final ENERGY STAR criteria for SSL luminaires were released in September 2007, and became effective in September 2008..
http://www1.eere.energy.gov/buildings/ssl/energy_star.html

Technical Support for Standards. LEDs differ significantly from traditional light sources, and new test procedures and industry standards are needed to measure their performance. DOE provides national leadership and support for this effort, working closely with the Illuminating Engineering Society of North America, the National Electrical Manufacturers Association, the Next Generation Lighting Industry Alliance, the American National Standards Institute, and other standards setting organizations to accelerate the standards development process, facilitate ongoing collaboration, and offer technical assistance. National standards and rating systems for new SSL products were issued in early 2008. http://www1.eere.energy.gov/buildings/ssl/standards.html

TINSSL. DOE's Technical Information Network for SSL increases awareness of SSL technology, performance, and appropriate applications. Members include representatives from regional energy efficiency organizations and program sponsors, utilities, state and local energy offices, lighting trade groups, and other stakeholders. The Northeast Energy Efficiency Partnerships and the CEE support DOE in this effort, collaborating with DOE to produce SSL information and outreach materials, host meetings and events, and support other outreach activities. http://www.ssl.energy.gov/technetwork.html

SSL Quality Advocates. This program is jointly developed by the DOE and the NGLIA. It is a voluntary program where participants pledge to accurately represent the performance of SSL products in SSL marketing literature. This will encourage market acceptance of SSL lighting systems. Specifically, companies pledge to accurately report lumens, efficacy, watts, CCT, and CRI as measured by the industry standard IESNA LM-79-2008. http://www.lightingfacts.com/

L Prize. The Energy Independence and Security Act of 2007 directed DOE to establish the Bright Tomorrow Lighting Prizes (L Prize) competition to accelerate development and adoption of SSL products to replace the common light bulb. In May 2008, DOE launched the L Prize competition at LIGHTFAIR® International. The competition challenges industry to develop replacement technologies for two of today's most widely used and inefficient products: 60W incandescent lamps and PAR 38 halogen lamps. Winners will be eligible for cash prizes, opportunities for federal purchasing agreements, utility programs, and other incentives.

Four California utilities – Pacific Gas & Electric, Sacramento Municipal Utility District, San Diego Gas & Electric, and Southern California Edison – worked closely with DOE to establish rigorous technical requirements for the competition. These utilities also signed a Memorandum of Understanding with DOE (shown in Appendix H), agreeing to work cooperatively to promote high-efficiency SSL technologies. These L Prize partners will conduct field assessments of proposed products and play an important role in promoting and developing markets for the winning L Prize products. Since the competition's launch, a number of additional partners have signed on. http://www.lightingprize.org/.

Next Generation Luminaires Competition. In May 2008, DOE launched a parallel competition focused on commercial luminaires: the Next Generation Luminaires™ SSL Design Competition. DOE has partnered with IESNA and IALD to organize this new competition, which 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 the high lighting quality and consistency, glare control, lumen maintenance, and luminaire appearance needed to meet specification lighting requirements. Winners of the 2009 competition were announced at Strategies in Light in February 2010. http://www.ngldc.org/. The Memorandum of Understanding between DOE and IESNA is located in Appendix E, and the Memorandum of Understanding between DOE and the IALD is located in Appendix F.

Table 5.2 shows the DOE meetings related to SSL commercialization.

Table 5.2: DOE SSL Commercialization Support Meetings

Meeting	Topic	Date
DOE SSL Market Introduction Workshop	SSL Commercialization	July 2009
CALiPER Roundtable	SSL Testing and Standards	March 2009
DOE SSL Market Introduction Workshop	SSL Commercialization	July 2008
Lighting Designer Roundtable	SSL Commercialization	March 2008
CALiPER Roundtable	SSL Testing	November 2007
DOE LED Industry Standards Workshop	SSL Standards	November 2007
DOE SSL Market Introduction Workshop	SSL Commercialization	July 2007
DOE SSL Market Introduction Workshop	SSL Commercialization	April 2007
DOE SSL Commercial Product Testing Program Workshop	SSL Testing	January 2007
DOE LED Industry Standards Workshop	SSL Standards	March 2006

6.0 Solid-State Lighting Portfolio Evaluation Plan

6.1 Internal DOE Evaluation

6.1.1 Government Performance and Results Act (GPRA)

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

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

The BTS GPRA estimates are calculated using the National Energy Modeling System (NEMS). NEMS can link the costs and benefit characteristics of a technology and its market penetration. The NEMS commercial and residential demand modules generate forecasts of energy demand (energy consumption) for those sectors. The commercial demand module generates fuel consumption forecasts for electricity, natural gas, and distillate fuel oil. These forecasts are based on energy prices and macroeconomic variables from the NEMS system, combined with external data sources. The residential model uses energy prices and macroeconomic indicators to generate energy consumption by fuel type and census division in the residential sector. NEMS selects specific technologies to meet the energy services demands by choosing among a discrete set of technologies that are exogenously characterized by commercial availability, capital costs, operating and maintenance costs, efficiencies, and lifetime. NEMS is coded to allow several possible assumptions to be used about consumer behavior to model this selection process. For the GPRA effort, the menu of equipment was changed to include relevant BTS program equipment, technological innovations, and standards.[81]

6.1.2 Peer Review

A formal review of the seventeen FY 2009 funded projects was conducted in the summer of 2009, the fourth in an annual series since 2005. These reviews are conducted by panels of highly qualified scientists, engineers, and independent technical consultants who evaluate each project based on technical approach, accomplishments, productivity, and relevance of the work to DOE goals. The panels identify areas of concern and areas

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

to be commended, and the results of the peer review process are shared with the project team and DOE.

6.2 External Evaluation

6.2.1 National Academies of Science Review

EPACT 2005, passed in August 2005, requires the SSL program enter into an agreement with the National Academy of Sciences to conduct periodic reviews of the Solid-State Lighting Initiative. However, even before the passage of EPACT 2005, the National Research Council (NRC) was tasked by Congress to develop a methodology for the prospective assessment of DOE program impacts. Starting in December of 2003, the NRC developed a conceptual framework and applied it to a review of three DOE programs as the first step in developing a recommendation for a methodology for future program reviews. The committee appointed expert panels to apply the methodology to these programs as case studies.

One of these programs was the LR&D program, and in particular the SSL program. Although the intent of the NRC study was not specifically to review these programs, some of the reported findings point to the benefits of investing in SSL R&D. The NRC published a report, *Prospective Evaluation if Applied Research and Development at DOE (PHASE ONE): A First Look Forward* [82]

- The committee found that, if successful, the program would yield a projected national economic benefit of $84 billion through 2050, discounted to 2005 dollars. This is for annual DOE funding of $25 million for 20 years ($500 million, undiscounted). Even allowing for program risk, the projected risk-adjusted benefit is $50 billion (p. 151). This benefit is over and above that to be realized by the private and foreign R&D funding during these years, which is twice the assumed DOE funding.

- The NRC noted that the potential benefits associated with full funding are large, even if the stretch performance goals are not achieved.

- The panel noted that the large projected benefits were for a relatively conservative reference scenario, and the other scenarios not analyzed would have shown even larger benefits (p. 64). It noted that the projected benefits even under baseline conditions are high enough to justify the authorized $500 million SSL DOE program.

- The panel concluded that the achievement of DOE's technical goal depends on an increase in funding from $10 million per year at the time of the study to $50 million per year. Without DOE funding, the panel believed the technical goals will not be achieved.

- Even if the R&D results were to be considerably less than the stretch goal, the

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

panel estimated that the benefits would substantially exceed the cost of the program.

The panel believed that DOE funding is an important catalyst to other R&D funding, and is a catalyst to spur such non-DOE funding. Huge environmental benefits would also flow from the program results, once implemented. Estimates of these benefits are given in the report, though they were not the focus of the study, and they are not included in the $50 billion economic benefits cited above.

Section 321(h)(3) of EISA 2007 requires the SSL program to enter into an agreement with the National Academy of Sciences to conduct two additional peer reviews of the Solid-State Lighting Initiative to be completed by December 31, 2013 and July 31, 2015. The report should include the following:

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

Appendix A List of Patents Awarded Through DOE-Funded Projects

As of August 2009, a total of twenty four SSL patents have been granted as a result of DOE-funded research projects. This demonstrates the value of DOE SSL projects to private companies and notable progress toward commercialization. Since DOE began funding SSL research projects in 2000, a total of 94 patents applications have been applied for as follows: large businesses - 44, small businesses - 20, universities - 26, and national laboratories - 4.

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

Primary Research Organization	Title of Patent Application (Bolded titles indicates granted patents)
Light Prescriptions Innovators	**Optical Manifold for Light-Emitting Diodes** **Optical Manifold for Light-Emitting Diodes** Two other patent applications filed.
Maxdem Incorporated	Polymer Matrix Electroluminescent Materials and Devices
Nanosys	Nanocrystal Doped Matrices
OSRAM Opto Semiconductors, Inc.	**Integrated Fuses for OLED Lighting Device** **Novel Method to Generate High Efficient Devices, which Emit High Quality Light for Illumination** Novel Method to Generate High Efficient Devices, which Emit High Quality Light for Illumination OLED with Phosphors Polymer and Small Molecule Based Hybrid Light Source Polymer Small Molecule Based Hybrid Light Source
Pacific Northwest National Laboratory	Organic Materials with Phosphine Sulphide Moieties having Tunable Electric and Electroluminescent Properties Organic Materials with Tunable Electric and Electroluminescent Properties
Philips Electronics North America	High Color-Rendering-Index LED Lighting Source using LEDs from Multiple Wavelength Bins Three other patent applications filed.
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**
Sandia National Laboratory	**Cantilever Epitaxial Process** One additional patent application filed.
Universal Display Corporation	**Binuclear Compounds** **Organic Light Emitting Device Structure for Obtaining Chromaticity Stability** **Organic Light Emitting Device Structure for Obtaining Chromaticity Stability** Stacked OLEDs with a Reflective Conductive Layer One other patent application filed.
University of California, San Diego	Rare-earth activated nitrides for solid state lighting applications Two additional patent applications filed.
University of California, Santa Barbara	**Plasmon Assisted Enhancement of Organic Optoelectronic Devices** Silicone Resin Encapsulants for Light Emitting Diodes Five other patent applications filed.
University of North Texas	One patent application filed.

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

Appendix B 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 solid state lighting research, development, infrastructure, and manufacturing expertise as a whole.

(e) Research. –
  (1) Grants. – The Secretary shall carry out the research activities of the Initiative through competitively awarded grants to –
    (A) researchers, including Industry Alliance participants;

(B) National Laboratories; and
(C) institutions of higher education.

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

(A) comments to identify solid-state lighting technology needs;
(B) an assessment of the progress of the research activities of the Initiative; and
(C) assistance in annually updating solid-state lighting technology roadmaps.

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

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

(1) In General. – The Secretary shall carry out a development, demonstration, and commercial application program for the Initiative through competitively selected awards.
(2) Preference. – In making the awards, the Secretary may give preference to participants in the Industry Alliance.

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

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

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

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

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

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

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

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

[APPENDIX STARTS ON NEXT PAGE]

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

ARTICLE I – PURPOSE

This Memorandum of Agreement (MOA) is entered into by and between the Next Generation Lighting Industry Alliance (NGLIA) and the U.S. Department of Energy (DOE) ("the Parties") for the purpose of establishing a mutual framework governing the respective responsibilities of the Parties. The Parties will conduct activities in support of research, development, demonstration and deployment of solid state lighting (SSL) technologies for general lighting applications.

ARTICLE II - AUTHORITY

DOE enters into this MOA under the authority of, among others, the Department of Energy Organization Act (Pub. L. 95-91) section 301, 42 U.S.C. § 7151; and the Energy Reorganization Act of 1974 (Pub. L. 93-438) section 103, 42 U.S.C. § 5813.

ARTICLE III - OBJECTIVE

The objective of this MOA is to provide a partnership to conduct various activities in support of core technology research, development, demonstration and deployment activities targeted to the application of SSL technologies in energy efficient general lighting applications. In particular, this collaboration will 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 cooperation will provide DOE with a manufacturing and commercialization focus in the development of research needs and goals for the DOE SSL Program. The quality of the SSL Program will be enhanced through the NGLIA's willingness, at DOE's discretion, to provide technical expertise for proposal and project reviews. The Parties further believe that the cooperation 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. The partnership will stimulate the implementation of SSL technologies through the Parties' efforts to promote demonstrations of SSL technologies for general lighting applications.

ARTICLE IV – SCOPE OF COLLABORATIVE ACTIVITIES

Collaboration under this MOA includes, but is not limited to, SSL activities in support of:

- Core Technology Research;
- Product Development and Systems Integration;
- Demonstration; and
- Market Conditioning

The SSL technologies that are the subject of this MOA 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 MOA may include, but is not limited to, the following forms of joint activities:

- Conducting workshops related to SSL technology and annual program reviews for projects in DOE's SSL Program. These workshops and program reviews will be open to the public;
- At DOE's discretion, participating in proposal reviews and individual project reviews for research projects in DOE's SSL Core Technology Program;
- Encouraging the development of metrics, codes, standards for measurement and utilization of SSL products for general illumination, and criteria for voluntary DOE deployment programs; and
- Planning and promoting demonstrations by NGLIA members of 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 MOA.

All representatives of the NGLIA and its members must agree to non-disclosure of all confidential or proprietary information prior to participation in partnership activities such as proposal or project reviews 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 VI – RESPONSIBILITES OF THE PARTIES

A. Responsibilities of the Department of Energy:

- 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 collaborative activities conducted under this MOA 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 MOA and as available from DOE's SSL projects.
- As set forth in the document titled "Statement of Analysis of Determination of Exception 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 demonstrations by their members, and create criteria for voluntary market conditioning programs, such as Energy Star.

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 collaborative activities conducted under this MOA 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, provide technical expertise to review SSL Core Technology Program proposals, 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 technically and financially support demonstrations of SSL technologies, emphasizing those technologies developed in the DOE SSL Program.

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

C. NGLIA and DOE mutually agree to 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 of the partnership. 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.

ARTICLE VII – PUBLICATIONS

Each Party agrees to seek pre-publication review and comment from the other Party prior to any planned publication under this MOA by the Parties to this MOA. The Parties agree that any such publications shall not include Confidential Information designated confidential by a third party. Failure to receive a written response within thirty (30) calendar days from the date the document is provided for review shall be considered as concurrence with the publication. 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 seek to execute a 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 seek to include comparable provisions in any patent waivers granted to entities such as large businesses that do not qualify for a statutory patent waiver under the Bayh-Dole

Act. DOE will use its best efforts to ensure that information is provided to the NGLIA concerning inventions and other intellectual property developed by SSL Core Technology Program participants.

The Parties understand that:

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

All representatives of the NGLIA and its members must agree to non-disclosure of any and all confidential or proprietary information prior to participation in partnership activities such as proposal or project reviews 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 – FUNDING AND IMPLEMENTATION

The Parties shall each bear the costs they incur for performing, managing, and administering their activities under this MOA. These costs include salaries, travel, and per diem for personnel, as well as any contract costs. This MOA shall not be used to obligate or commit funds or as the basis for the transfer of funds.

ARTICLE X – MISCELLANEOUS

A. Other Relationships or Obligations

This MOA shall not affect any pre-existing or independent relationships or obligations between the DOE and the NGLIA.

B. Survival

The provisions of this MOA which require performance after the expiration or termination of this MOA shall remain in force notwithstanding the expiration or termination of this MOA.

C. Severability

Nothing in this MOA is intended to conflict with current law or regulation or the directives of the Department of Energy. If any provision of this MOA is determined to be invalid or unenforceable, the remaining provisions shall remain in force and unaffected to the fullest extent performed by law and regulation.

D. Compliance with Laws

The Parties shall each be responsible for their own compliance with applicable laws and regulations, including export control laws, in performing the work scope of this MOA. The construction, validity, performance, and effect of this MOA for all purposes shall be governed by the laws applicable to the Government of the United States.

E. Effect on Third Parties

This MOA does not direct or apply to any person outside DOE and the Next Generation Lighting Industry Alliance. It shall not be construed to provide a right, benefit, or cause of action for or by any person or entity not a party to this MOA, enforceable by law or equity against DOE or the Next Generation Lighting Industry Alliance, their officers, or employees.

ARTICLE XI – AMENDMENT, MODIFICATION, AND TERMINATION

This MOA 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 MOA may be modified or amended only by written agreement of the Parties. Either Party may terminate this MOA 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 MOA will become effective upon the latter date of signature of the Parties.

Executed in duplicate on the dates indicated below:

By: ______________________ Date: 2/2/2005

Michael J. McCabe
Building Technologies Program Manager
U.S. Department of Energy
Office of Energy Efficiency and Renewable Energy

By: ______________________ Date: 2 Feb 05

Dale Work
Chair
Next Generation Lighting Industry Alliance

for Susan Beard 1/28/05
Concurring for the Office of
General Counsel

Appendix D Approval of Exceptional Circumstances Determination for Inventions Arising Under the Solid State Lighting (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

STATEMENT OF ANALYSIS OF DETERMINATION
OF EXCEPTIONAL CIRCUMSTANCES FOR WORK PROPOSED
UNDER THE SOLID STATE LIGHTING PROGRAM

For the reasons set forth below, the Department of Energy (DOE) has determined, pursuant to 35 U.S.C. § 202 (a)(ii), that the circumstances surrounding the DOE's Solid State Lighting (SSL) Program being implemented by DOE's Energy Efficiency and Renewable Energy's (EERE's) Office of Building Technologies and the National Energy Technology Laboratory (NETL), to develop improved lighting products described within various solicitations and National Laboratory funding calls implemented under the SSL program, are exceptional. Accordingly, a disposition of patent rights different from that generally available under Public Law 96-517 and Public Law 98-620 for funding agreements with small businesses, universities and other nonprofit organizations, and work done by DOE government-owned, contractor-operated (GOCO) National Laboratories, whether operated by nonprofit or for profit organizations, is warranted. These laws generally entitle such entities to retain title to inventions made under Government sponsorship, with minimal licensing obligations. The disposition of patent rights specified below will better promote the policies and objectives set out in 35 U.S.C. § 200, as described in detail below.

The goal of the SSL Program is to, by 2025, develop advanced solid state lighting technologies that, compared to conventional lighting technologies, are much more energy efficient, longer lasting, and cost-competitive, by targeting a product system efficiency of 50 percent with lighting that accurately reproduces sunlight spectrum. It is envisioned that SSL products of this quality would 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 focus on finding solutions to the more difficult shared technical barriers identified by the SSL Partnership.

In order for the link between the SSL Partnership and the Core Technology Program to succeed, 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 (35 U.S.C. § 200 *et seq.*), or their laboratory operating contracts, to retain title to any inventions they conceive or first actually reduce to practice under their Government-funded awards.

It is anticipated that the Government share of the budget for this 20-year program will be over 200 million dollars. Except for the DOE GOCO National Laboratories, the organizations participating in the Core Technology Program will provide 20% cost-share. 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.

Exceptional circumstances determinations are authorized by 35 U.S.C. § 202(a) when the agency determines that restriction of the right to retain title to an invention resulting from federally sponsored research and development "will better promote the policy and objectives of this chapter." This exceptional circumstances determination will better promote the following policy and objectives of the Congress as described in 35 U.S.C. § 200: to use the patent system to promote the utilization of inventions arising from federally supported research or development; to promote collaboration between commercial concerns and nonprofit organizations, including universities; to ensure that inventions made by nonprofit organizations and small business firms are used in a manner to promote free competition and enterprise; and to promote the commercialization and public availability of inventions made in the United States by United States industry and labor.

In addition, this determination is being made in accordance with 37 CFR 401.3(a)(2), 401.3(b), and 401.3(e). In particular, 37 CFR 401.3(b) requires that when an agency exercises an exception, it shall use a standard prescribed clause "with only such modifications as are necessary to address the exceptional circumstances or concerns which led to the use of the exception." Also, 37 CFR 401.3(e) specifies that "the agency shall prepare a written determination, including a statement of facts supporting the determination, that the conditions identified in the exception exist."

The exception to the disposition of patent rights from that generally available under Public Law 96-517 and Public Law 98-620 for funding agreements between small businesses, universities and other nonprofit organizations and for work done by DOE GOCO National Laboratories will have several components. First, it will involve requiring the participants in the SSL Core Technology Program 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 subject inventions developed under the Core Technology Program. The 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. Any waiver of this requirement must be approved in writing by the Department of Energy in advance of foreign manufacture.

The Core Technology Program participant's licensing offer must be held open for at least one year after the U.S. patent issues and the invention owner must agree to negotiate in good faith with any and all SSL Partnership members that indicate a desire to obtain at least a non-exclusive license. During this one year period, the invention owner can enter into licensing negotiations for solid state lighting applications only with members of the Partnership.

Exclusive licensing may be considered if only one SSL Partnership member expresses an interest in licensing the invention. Partially exclusive licenses in a defined field of use may be granted to a Partnership member, as long as doing so would not preclude any other Partnership member that indicates a desire to license the invention from being granted at least a non-exclusive license. However, the Government will not require the patent owner to grant any exclusive or partially exclusive licenses. The Core Technology Program participant that owns or controls the invention must enter into good faith negotiations with each individual Partnership member that has indicated a desire to license the invention. Because the submission by a potential licensee of a satisfactory business plan is accepted licensing practice, DOE expects that good faith negotiations will include the invention owner requiring a satisfactory business plan from each individual Partnership member with which it is negotiating.

In the event the parties to the negotiation cannot reach agreement on the terms of the license, as set forth above, within nine months of initiating good faith negotiations, each individual SSL Partnership member shall have the right of a third party beneficiary to maintain an action in a court of competent jurisdiction to force licensing on reasonable terms and conditions. Any assignment of the invention must be made subject to these requirements.

The above described licensing option is believed to result in the minimum rights that the SSL Partnership members need to ensure that the technology developed by the Core Technology Program participants is available to promote commercialization of the solid state lighting technology. The Core Technology Program participants will retain title to the inventions and will be entirely free to negotiate and enter into additional licenses with entities other than the members of the SSL Partnership in other fields of use. This licensing for outfield uses could accelerate the SSL program because commercialization of outfield uses often benefits the commercialization of infield uses. In a similar manner, licensing leading to the commercialization of infield uses could benefit the commercialization of outfield uses. For example, SSL technology could be applied to non-lighting fields such as biological agent detection, power transistors, night vision systems, and photovoltaics. The DOE believes that this approach would ensure the most broad-based applications for the technology developed under the SSL program. To further demonstrate the fact that this licensing option minimizes the rights being extracted, the Core Technology Program participants will not be required to license their background patents. However, we would expect that a further positive outcome of this Determination will be the voluntary licensing of background technology to foster commercialization. Finally, in the event that an affected awardee may have an existing licensing arrangement or commitment that might conflict with this Determination, the DOE will seek to accommodate any such arrangement.

Based on discussions with a group of people associated with small businesses, DOE understands that some small businesses may object to this Determination because they want to reserve the right to practice their inventions themselves, rather than to license them to the SSL Partnership members. While DOE appreciates their concerns, 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.

Because of the nature of this program, without this exceptional circumstances determination, the small businesses, universities, other nonprofits and DOE GOCO National Laboratories participating in the Core Technology Program would automatically be entitled, pursuant to Public Law 98-620 and Public Law 96-517 or advance patent waivers, to elect to retain title to their inventions. Should this occur, the Core Technology Program participants described above will be under no obligation to share the technology/innovations developed with the members of the SSL Partnership, or in the alternative, could choose to share the developed technology with only certain members. This would create a situation where some Partnership members would not have assurance of licensing rights to use the new technology developed. Such a situation, if allowed to occur, might stifle the ability of the Government to work with a broad base of participants in the SSL Program and would stifle the widest application of the developed technology, the very intent of the proposed Core Technology Program.

The SSL Program exceptional circumstances determination is justified for several additional reasons including the following:

- If Core Technology Program participants could exclusively license to anyone they choose, including non-members of the SSL Partnership, or could choose to not license anyone, then it would be unlikely that the SSL Partnership would be willing to, at no cost to the Government, support the SSL Program, including collaboratively defining the Core Technology Program objectives. This could seriously impede the SSL program goal of leveraging Government funds to address the most difficult problems in an effort to accelerate commercialization of this nationally important technology.

- A market for the intellectual property is being created. The Core Technology Program participants will have a ready set of potential licensees to which to license their invention(s), and, if the SSL Partnership members are successful in commercializing their lighting systems, reap income in the form of royalties.

- If the intellectual property was held by a small company, university, or DOE GOCO National Laboratory that is unwilling to negotiate in good faith, that technology could be unavailable for an extended period of time. This would be detrimental to U.S. national interests.

As further support for this Determination, the Conference Report for the FY 2005

Department of Interior and Related Agencies Appropriation Bill states in Note 8:

> The managers understand that the Department will soon issue an Exceptional Circumstances Determination with regard to solid state lighting core technology research, with the purpose of facilitating favorable access to the resulting intellectual property by members of the Next Generation Lighting Industry Alliance [the "SSL Partnership" in this Determination]. This access is in exchange for the active work for the Alliance in using its experience and expertise to bring a manufacturing and commercial focus to the solid state lighting project portfolio, as stipulated in the competitive solicitation by which the Alliance was selected. The managers support this arrangement and believe it will facilitate the deployment of solid state lighting technologies and accelerate reductions in electrical energy consumption.

The duration of this 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 occur and DOE subsequently enters into a similar agreement with another partnership, DOE reserves the unilateral right to continue the Determination, with the benefits accruing to the successor partnership.

The membership of the SSL Partnership may change as companies join and drop out. Individual companies will receive the benefits of this determination commencing on the date they become a member of the Partnership group. An individual company will be entitled to the licensing benefits described above for subject inventions made under Core Technology Program projects that have been selected for award after the time the company's membership in the Partnership 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. The Partnership group shall maintain a log of membership, including the effective date of each company's membership. If an individual company elects to discontinue its membership in the Partnership, it will receive licensing benefits under this determination only for patent applications filed prior to the date when the company's membership ends.

Separately, under the SSL Program, a number of product developers will receive cost shared cooperative agreements from NETL as a result of competitive product development solicitations. This 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. Any waiver of this requirement must be approved in writing by the Department of Energy in advance of foreign manufacture.

For the foregoing reasons, the Department of Energy has determined that exceptional circumstances exist as provided in 35 U.S.C. § 202(a)(ii) in any agreement with a small business, university or other nonprofit organization, or GOCO National Laboratory selected as a Core Technology Program participant under SSL, such as to give rise to the need for the licensing provisions described herein.

Under 35 U.S.C. § 203(2), a contractor has a right to appeal any agency's determination of exceptional circumstances. Accordingly, each Core Technology Program and product developer participant to which this determination applies will be provided with notice of this determination and a right to appeal.

Appendix E 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

Final version: 6/5/06

MEMORANDUM OF UNDERSTANDING

By this Memorandum of Understanding (MOU), the U.S. Department of Energy (DOE) and the Illuminating Engineering Society of North America (IESNA) agree to work cooperatively to improve the efficient use of energy and to minimize the impact of energy use on the environment.

DOE and IESNA 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 IESNA 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, including development of ENERGY STAR® criteria for solid state lighting, 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 IESNA technical committee activities and provide the opportunity for dissemination/publication of related research.

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

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 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.

This MOU is strictly for the internal 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.

This MOU will become effective upon signature by DAS of EERE, DOE and the Executive Vice President of the Illuminating Engineering Society of North America. It may be modified or amended by written agreement between both parties, and such amendments shall become part of, and shall be attached to this MOU. This MOU shall terminate at the end of 5 years unless revised or extended at that time by written agreement of the parties. It may be terminated at any time by either party, upon 90 days written notice to the other. Its provisions will be reviewed annually and amended/supplemented if mutually agreed upon in writing.

[signature]	Date 7/17/06	[signature]	6/05/06 Date
David E. Rodgers Deputy Assistant Secretary (Acting) Office of Technology Development US Department of Energy		William Hanley Executive Vice President Illuminating Engineering Society of North America	

Appendix F Memorandum of Understanding between the U.S. Department of Energy and the International Association of Lighting Designers

[APPENDIX STARTS ON NEXT PAGE]

MEMORANDUM OF UNDERSTANDING
Between
The United States Department of Energy
and
The International Association of Lighting Designers

By this Memorandum of Understanding (MOU), the U.S. Department of Energy (DOE) and the International Association of Lighting Designers (IALD) agree to work cooperatively to improve the efficient use of energy by lighting equipment and systems, thereby minimizing the impact of energy use on the environment.

DOE and IALD agree to work together in the following areas:

1) Promoting lighting design principles and lighting technologies that improve lighting quality, energy efficiency, and environmental sustainability.

2) Developing and disseminating technical information to assist the lighting design community in the assessment and specification of solid state lighting (SSL) and other efficient lighting technologies, to support DOE programs on lighting quality such as ENERGY STAR and SSL Quality Advocates.

3) Jointly facilitating forums in which lighting designers can exchange ideas and information with DOE, and provide input to DOE lighting program planning.

4) Encouraging professional lighting designers to participate in DOE lighting projects, such as DOE's Gateway SSL Demonstrations, with particular attention to helping DOE assess lighting quality.

The Department of Energy enters into this agreement under the authority of Section 646 of the Department of Energy Organization Act (Pub. L. 95-91, as amended, 42 U.S.C. § 725 6).

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 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.

This MOU is strictly for the internal 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.

This MOU will become effective upon signature by the Deputy Assistant Secretary for Energy Efficiency, DOE and the Executive Vice President of the International Association of Lighting Designers. It may be modified or amended by written agreement between both parties, and such amendments shall become part of, and shall be attached to this MOU. This MOU shall terminate at the end of five (5) years unless revised or extended at that time by written agreement of the parties. It may be terminated at any time by either party, upon 90 days written notice to the other. Its provisions will be reviewed annually and amended/supplemented if mutually agreed upon in writing.

	10-28-08		10 November 08
David E. Rodgers Deputy Assistant Secretary for Energy Efficiency Office of Technology Development Energy Efficiency and Renewable Energy U.S. Department of Energy	Date	Marsha L. Turner Executive Vice President International Association of Lighting Designers	Date

Appendix G MYPP Task Structure

Priority tasks for 2010 shown in red.

LED Core Research Tasks

A.1.0 Emitter Materials
- A.1.1 Alternative substrates
- **A.1.2 Emitter materials research**
- **A.1.3 Down converters**

A.2.0 Device Materials and Architectures
- A.2.1 Light extraction approaches
- **A.2.2 Novel emitter materials and architectures**

A.3.0 Device Packaging
- A.3.4 Thermal control research

A.4.0 LED Fabrication
- A.4.4 Manufacturing simulation

A.5.0 Optical Components
- A.5.1 Optical component materials

A.6.0 Luminaire Integration
- A.6.2 Thermal components research
- **A.6.3 System reliability methods**

A.7.0 Electronic Components
- A.7.4 Driver electronics
- **A.7.5 Electronics reliability research**

LED Product Development Tasks

B.1.0 Emitter Materials
- **B.1.1 Substrate development**
- **B.1.2 Semiconductor materials**
- **B.1.3 Phosphors**

B.2.0 Device Materials and Architectures
- B.2.3 Electrical

B.3.0 Device Packaging
- B.3.1 LED package optics
- B.3.2 Encapsulation
- B.3.4 Emitter thermal control
- B.3.5 Environmental sensitivity
- **B.3.6 Package architecture**

B.4.0 LED Fabrication
- B.4.1 Yield and manufacturability
- B.4.2 Epitaxial growth
- B.4.3 Manufacturing tools

B.5.0 Optical Components
- B.5.1 Light utilization
- **B.5.2 Color maintenance**
- B.5.3 Diffusion and beam shaping

B.6.0 Luminaire Integration
- B.6.1 Luminaire mechanical design
- B.6.2 Luminaire thermal management
- **B.6.3 Optimizing system reliability**

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

OLED Core Research Tasks

C.1.0 Materials and Device Architectures
- C.1.1 Novel device architectures
- **C.1.2 Novel materials**
- C.1.3 Material and device architecture modeling
- C.1.4 Material degradation
- C.1.5 Thermal characterization of materials and devices

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

C.3.0 Fabrication
- **C.3.1 Fabrication technology research**

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

C.5.0 Electronic Components

C.6.0 Panel Architecture
- **C.6.3 Light extraction approaches**

OLED Product Development Tasks

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

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

D.3.0 Fabrication
- D.3.1 Panel manufacturing technology
- D.3.2 Quality control

D.4.0 Luminaire Integration
- D.4.1 Light utilization
- D.4.2 Luminaire integration
- D.4.3 System reliability methods
- D.4.4 Luminaire thermal management
- D.4.5 Electrical interconnects

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

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

Non-Prioritized Tasks

LED Core Research Tasks

	Task	Description
A.1.1	Alternative substrates	Explore alternative practical substrate materials and growth for high-quality epitaxy so that device quality can be improved.
A.2.1	Light extraction approaches	Devise improved methods for raising chip-level extraction efficiency and LED system optical efficiency. Photonic crystal structures or resonant cavity approaches would be included.
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.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.

LED Product Development Tasks

	Task	Description
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-mixing 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.4.1	Yield and manufacturability	Devise methods to improve epitaxial growth uniformity of wavelength and other parameters so as to reduce binning yield losses. Solutions may include in-situ monitoring and should be scalable to high volume manufacture.
B.4.2	Epitaxial growth	Develop and demonstrate growth reactors and monitoring tools or other methods capable of growing state of the art LED materials at low-cost and high reproducibility and uniformity with improved materials-use efficiency.
B.4.3	Manufacturing tools	Develop improved tools and methods for die separation, chip shaping, and wafer bonding, and testing equipment for manufacturability at lower cost.
B.5.1	Light utilization	Maximize the ratio of useful light exiting the luminaire to total light from the LED source. This includes all optical losses in the luminaire; including luminaire housing as well as optical losses from diffusing, beam shaping, and color mixing optics. Minimize artifacts such as multishadowing or color rings.

LED Product Development Tasks (Cont)

	Task	Description
B.5.3	Diffusion and beam shaping	Develop optical components that diffuse and/or shape the light output from the LED source(s) into a desirable beam pattern and develop optical components that mix the colored outputs from the LED sources evenly across the beam pattern.
B.6.1	Luminaire mechanical design	Integrate all aspects of LED based luminaire design: thermal, mechanical, optical, and electrical. Design must be cost effective, energy efficient and reliable.
B.6.2	Luminaire thermal management	Design low-cost integrated thermal management techniques to protect the LED source, maintain the luminaire efficiency and color quality.
B.7.1	Color maintenance	Develop LED driver electronics that maintain a color setpoint over the life of the luminaire by compensating for changes in LED output over time and temperature, and degradation of luminaire components.
B.7.2	Color tuning	Develop efficient electronic controls that allow a user to set the color point of the luminaire.
B.7.3	Smart controls	Develop integrated lighting controls that save energy over the life of the luminaire. May include methods to maximize dimmer efficiency. May include sensing occupancy or daylight, or include communications to minimize energy use, for example.
B.7.4	Electronics component research	Develop compact, long-life LED driver electronics and power converters that efficiently convert line power to acceptable input power of the LED source(s) while maintaining an acceptable power factor; encourage standardization in the long term.

OLED Core Technology Tasks

	Task	Description
C.1.1	Novel device architectures	Device architectures to increase EQE, reduce voltage, and improve device lifetime that are compatible with the goal of stable white light. Explores novel structures like those that use multi-function components, cavities or other outcoupling strategies to optimize light extraction. Could include studying material interfaces.
C.1.3	Material and device architecture modeling	Developing software simulation tools to model the performance of OLED devices using detailed material characteristics.
C.1.4	Material degradation	Understand and evaluate the degradation of materials during device operation.
C.1.5	Thermal characterization of materials and devices	Involves modeling and/or optimizing the thermal characteristics of OLED materials and device architectures with the goal of developing less thermally sensitive and hydrolytically more stable materials and devices.
C.4.3	Optimizing system reliability	Research techniques to optimize and verify overall luminaire reliability. Develop system reliability measurement methods and accelerated lifetime testing methods to determine the reliability and lifetime of an OLED device, panel, or luminaire through statistical assessment of luminaire component reliabilities and lifetimes.

OLED Product Development Tasks		
	Task	**Description**
D.1.1	Implementation of materials and device architectures	Develop materials and device architectures that can concurrently improve robustness, lifetime, efficiency, and color quality with the goal of stable white light over its lifetime. The device should be pixel-sized, demonstrate scalability, and have a lumen output of at least 50 lumens.
D.1.5	Device failure	Understand the failure modes of an OLED at the device level.
D.2.1	Substrate materials	Demonstrate an OLED with reasonable performance and low degradation using a substrate material that is low-cost and shows reduced water and oxygen permeability. Other considerations may include processing and operational stability, weight, cost, optical and barrier properties, and flexibility.
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	Maximize the ratio of useful light exiting the luminaire to total light from the OLED sources. This includes all optical losses in the luminaire; including optical losses from beam distribution and color mixing optics.
D.4.2	Luminaire integration	Integrate one or more OLED panels into a luminaire, with thermal, mechanical, optical, and electrical design to achieve a cost-effective, long-life, energy-saving, and marketable luminaire suitable for general lighting applications. All components should be as robust as the OLED. This task is to include maximizing light output, thermal management to limit OLED source temperature, and electrical interconnections with driver and among OLED panels.
D.4.3	System reliability methods	Develop models, methodology, and experimentation to determine the lifetime of the integrated OLED luminaire and all of the components.
D.4.4	Luminaire thermal management	Design integrated thermal management techniques to extract heat from the luminaire in a variety of environments and operating conditions. Thermal management should maintain the OLED source temperature as well as enhance the luminaire color and efficiency performance.
D.4.5	Electrical interconnects	Develop standard connections for integration of OLED panels into the luminaire.
D.5.1	Color maintenance	Develop OLED driver electronics that maintain a color setpoint over the life of the luminaire by compensating for changes in OLED output over time and temperature, and degradation of luminaire components.
D.5.2	Smart controls	Develop integrated lighting controls and sensors that save energy over the life of the luminaire.
D.5.3	Driver electronics	Develop efficient, long-life OLED driver electronics and power converters that efficiently convert line power to acceptable input power of the OLED source(s) and maintain their performance over the life of the fixture. These can include energy-saving functionality such as daylight and occupancy sensors and communication protocols for external lighting control systems.
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 H Memorandum of Understanding between the U.S. Department of Energy and L-Prize Partners

The following document contains a template Memorandum of Understanding that has been signed by all partners currently collaborating with the Department of Energy on the L-Prize. The list of partners as of March 2010 is below.

West

- BC Hydro
- California Public Utilities Commission
- Energy Trust of Oregon
- Eugene Water & Electric Board
- National Resources Defense Council
- NV Energy
- Pacific Gas & Electric
- Puget Sound Energy
- Sacramento Municipal Utility District
- San Diego Gas & Electric
- Seattle City Light
- Southern California Edison

Mountain / Central

- Ameren Illinois Utilities
- Commonwealth Edison
- DTE Energy
- Midwest Energy Efficiency Alliance
- Platte River Power Authority
- Southern Minnesota Municipal Power Agency
- Wisconsin Energy Conservation Corporation
- Xcel Energy

East

- Cape Light Compact
- Connecticut Energy Efficiency Fund
- Connecticut Light & Power
- Efficiency Vermont
- greenTbiz, Toronto Association of Business Improvement Areas
- Long Island Power Authority
- National Grid
- New York State Energy Research and Development Authority
- Northeast Energy Efficiency Partnerships
- NSTAR Electric
- Progress Energy
- United Illuminating Company

The United States Department of Energy
and
____

MEMORANDUM OF UNDERSTANDING
DOE Bright Tomorrow Lighting Prizes

By this Memorandum of Understanding (MOU), the U.S. Department of Energy (DOE) and ____________________ (company) agree to work cooperatively to improve the efficient use of energy and to minimize the impact of energy use on the environment.

DOE and ____________________ (company) intend to work together toward the following objectives:

1) Encourage the development of solid-state lighting (SSL) products to significantly decrease lighting energy use and maintain or improve lighting service, compared to traditional light sources through support of the Bright Tomorrow Lighting Prize.
2) Coordinate information-sharing regarding the evaluation of SSL products to the extent permissible.
3) Develop and implement cooperative programs to speed the market introduction, retail availability, and consumer acceptance of the selected SSL products. Such programs may include cooperative marketing, consumer education, distribution chain incentives, and/or field testing, among other possible strategies.

In conducting activities pursuant to this MOU, the parties understand and agree that DOE will not endorse any particular company or its products. The parties further understand and agree that the DOE logo shall not be used without the prior written authorization of DOE.

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.

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

This MOU will become effective upon signature by the Assistant Secretary of EERE, DOE and ____________________ (representative), ____________________ (company). It may be modified or amended by written agreement between both parties, and such amendments shall become part of, and shall be attached to this MOU.

This MOU shall terminate at the end of three (3) years from the later of the dates indicated below, unless revised or extended at that time by written agreement of the parties. It may be terminated at any time by either party, upon 90 days written notice to the other. Its provisions will be reviewed annually and amended/supplemented if mutually agreed upon in writing.

The Department of Energy enters into this MOU under the authority of section 646 of the Department of Energy Organization Act (Pub. L. No. 95-91, as amended; 42 U.S.C. 7256).

___________________________	__________	_________________________	__________
John Mizroch	Date	Signature	Date
		_________________________	
Acting Assistant Secretary Office of Energy Efficiency and Renewable Energy US Department of Energy		Name	
		_________________________	
		Title	
		_________________________	
		Company	

Appendix I 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 solid state lighting. Within Core Technology research areas, scientific principles are demonstrated, technical pathways to solid-state lighting (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 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