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

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COMMENTS

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1. Introduction

On January 29-31, 2008, more than 300 SSL technology leaders gathered in Atlanta, Georgia, to participate in the Fifth Annual Solid-State Lighting (SSL) Program Planning Workshop hosted by the U.S. Department of Energy (DOE). Participants from the lighting industry, research organizations, universities, and national laboratories, along with representatives from efficiency programs, utilities, and the lighting design community, joined DOE to share perspectives on the rapid evolution of SSL technology. The workshop provided a forum for building partnerships and strategies for continuing advances in high efficiency, high-performance SSL technologies.

Chapter 1 of this report covers the opening of the 2008 "Transformations in Lighting" workshop, in which DOE SSL Program Manager James Brodrick highlighted the progress and pace of SSL advances: the New Year's Eve debut of New York City's new Times Square Ball, lit with Philips Luxeon LEDs; the first DOE Gateway demonstration of Beta LED streetlights in Oakland, California; and the LR6 downlight from LED Lighting Fixtures, Inc., (LLF) Grand Prize Winner in the 2007 *Lighting for Tomorrow* design competition.

Chapter 1 also presents DOE's plans to raise the bar, including a new competition for "Bright Tomorrow Lighting Prizes." The Energy Independence and Security Act (EISact 2007) includes provisions for $20 million in prizes for a 60W incandescent replacement technology, a PAR 38 halogen replacement technology, and a 21st Century Lamp. More details will be announced in the coming months.

Chapter 2 of this report details perspectives and strategies from technology, industry, and energy leaders who are helping shape this transformation of lighting. In Chapter 3, DOE provides an overview of the SSL research and development (R&D) portfolio along with reports from selected projects, guidance on preparing a comprehensive application for DOE R&D funding, and an update on the R&D SSL Multi-Year Program plan.

Chapter 4 focuses on lighting design, including insight into what designers and architects need from SSL, and perspectives from the 2007 winners of the *Lighting for Tomorrow* Design Competition. Chapter 5 focuses on DOE efforts to guide market introduction of SSL products. Chapter 6 summarizes results from DOE SSL technology demonstrations and looks specifically at LEDs in outdoor lighting. In Chapter 7, DOE details upcoming program activities and events.

Workshop presentations and materials referenced in this report can be found on the SSL website at http://www.netl.doe.gov/ssl/materials_2008.html.

2. Strategies for "Transformations in Lighting"

2.1 Welcome and Overview

James Brodrick, U.S. Department of Energy

Solid-state lighting rang in 2008 in Times Square

James Brodrick welcomed more than 300 participants to the Fifth Annual DOE SSL R&D Workshop by highlighting several recent signs of the progress and pace of SSL technology advances, starting with the Times Square Ball tradition, which rang in 2008 with over 9,000 high powered Philips Luxeon LED lights surrounded by Waterford crystal. "This moment for me emphasized a turning point—a very public recognition that this transformation in lighting is moving fast, as high quality, energy-efficient SSL products move to market," Brodrick said.

Brodrick noted that DOE recently published a report on the first DOE Gateway demonstration of Beta LED street lighting in Oakland, California. He recognized the LED Lighting Fixtures (LLF) LR6 downlight, grand prize winner of the 2007 *Lighting for Tomorrow* competition, for high performance comparable to today's fluorescent downlights. Brodrick noted that DOE will raise the bar for the 2008 competition, with categories for fixtures meeting ENERGY STAR criteria, decorative fixtures, and a future LED showcase, using the world's highest efficiency LEDs.

Brodrick also announced a new competition, the "Bright Tomorrow Lighting Prizes," designed to raise the bar even higher. The recent energy bill outlines parameters for $20 million in prizes for a 60W incandescent replacement that can deliver 90 lm/W, a PAR 38 halogen replacement that can deliver 123 lm/W, and a 21st Century Lamp that can deliver 150 lm/W. More details will be announced in the coming months, with an RFP expected in May 2008.

In addition, Brodrick highlighted recent laboratory achievements from LLF, Nichia, Cree, and others that signal the next wave of products on the market to offer improved performance and efficiency. He concluded with a wish list of products for 2008, which included commercial downlights for high (10' or 12') ceilings, all-SSL office lighting systems with punch, innovative bathroom or vanity lighting, blazing retail spotlights, and LEDs embedded in kitchen cabinetry and office furniture. The unique attributes of SSL lend themselves to new forms and functions for lighting, and spurred his closing question, "Does a light have to look like a light?"

2.2 Market Perspective – Trends and Timing

Vrinda Bhandarkar, Strategies Unlimited

Vrinda Bhandarkar of Strategies Unlimited presented a "Market Perspective – Trends and Timing." She began by highlighting recent trends in the high brightness LED market segments. "Illumination is only 5% of the global market," Bhandarkar noted, "but it is the fastest growing segment." The market for high-brightness LEDS for lighting was $205 million in 2006.* This number is projected to reach $1 billion by 2011, with white light LEDs dominating the market with a 60% share in 2011.

According to Bhandarkar, the market drivers for SSL include the technology's visual appeal, long lifetime, compact form factor, lack of radiated heat, low-voltage operation, and energy efficiency. She summarized the opportunities for SSL, noting that SSL offers unique lighting solutions, delivers value (on a cost-of-ownership basis), and can be adapted to unique physical environments. In fact, she noted "the vocabulary of lighting is changing with so many form factors."

Bhandarkar described the structure of the lighting fixture industry, noting that LED lighting companies range from start-ups to some of the world's largest corporations (see Figure 2-1 below). Most product development is carried out by the former – small specialized companies with high level LED expertise. The latter are better positioned to introduce new products, with more control and access to sales and distribution channels.

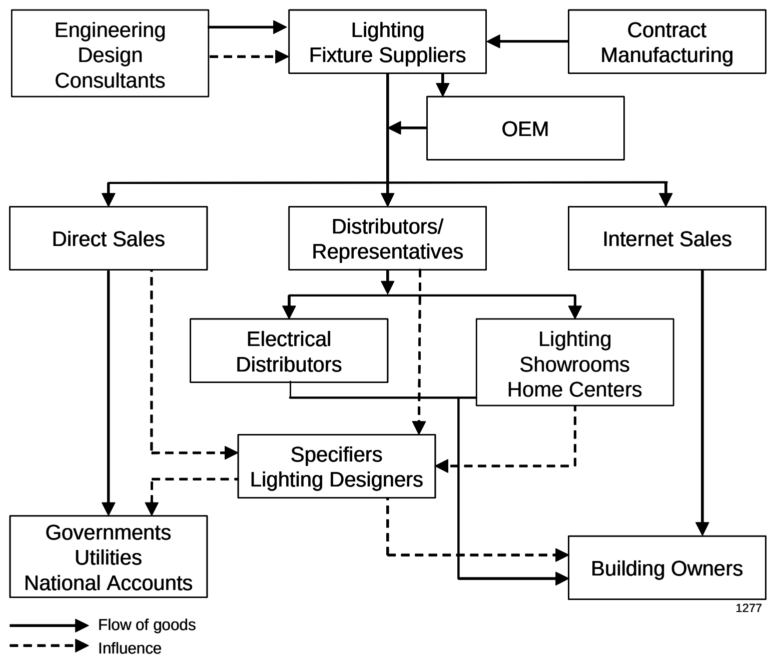

Figure 2-1: Structure of Lighting Fixture Industry

Bhandarkar also highlighted how lighting designers and specifiers impact the structure of the lighting fixture industry, emphasizing that "the whole game changes when you bring in lighting designers and specifiers. If you don't appeal to peoples' design sense, it's not going to sell."

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* Based on 2006 data. The most recent information may be found on Strategies Unlimited website at http://su.pennnet.com/.

Bhandarkar concluded with an LED lighting market outlook, comparing the “best of class” in commercial white LED luminous efficacies today, followed by a comparison of incandescent, CFL, and LED technology (see Figure 2-2 below).

	Lighting option	**Life expectancy**	**Cost**
	LED R30	50,000 hours	$90
	CFL R30	10,000 hours	$10
	Incandescent R30	2,000 hours	$7

Figure 2-2: LED Competition

A number of challenges remain for LEDs, including high initial costs and the need for high efficiency light engine/fixture design. Bhandarkar emphasized that education remains a key to accelerating the adoption of LEDs in the marketplace. “It took 10 years for LEDs to penetrate the market for traffic lights, but now almost all new traffic lights are LEDs.” Although costs are declining, downward pressure on prices remains essential, along with educating buyers on how efficiency offsets a higher price.

In conclusion, Strategies Unlimited expects niche lighting applications to continue to grow, and general illumination (white light applications) to become increasingly important. Price and performance improvements will continue in white LEDs and luminaires. While substantial marketing efforts will be required to penetrate the conventional lighting market, the overall forecast for high brightness LEDs is $1 billion by 2011.

2.3 LED Cities – Investing in the Future

David Konkle, City of Ann Arbor

David Konkle, Energy Coordinator for the City of Ann Arbor, Michigan, presented an overview of Ann Arbor’s plans for participation in the LED City™ program. LED City is an expanding community of government and industry parties working to promote and deploy LED lighting technology across the full range of municipal infrastructure. The goals of the program are to save energy, protect the environment, reduce maintenance costs, improve light quality for improved visibility and safety, and save tax dollars.

Ann Arbor has long been in the vanguard of environmentally progressive municipalities and belongs to several regional organizations that emphasize environmental issues. The LED initiative has solid support from current Mayor John Hieftje, who has set specific energy and greenhouse gas reduction goals for the city.

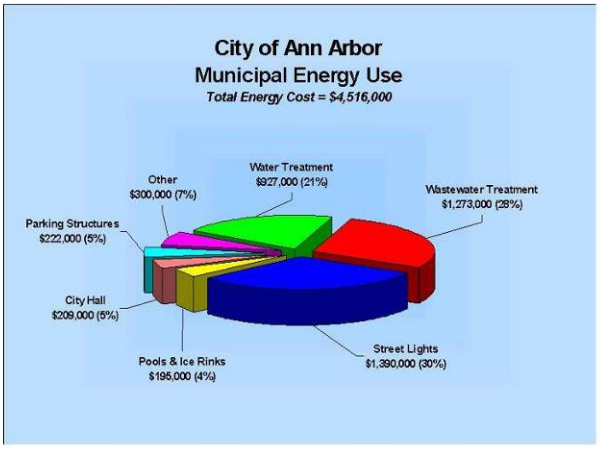


Figure 2-3: City of Ann Arbor Municipal Energy Use

Analysis of the city's outdoor lighting costs revealed they are approaching $1.4 million per year. In 2004, the city started testing LED lighting in traffic lights and pedestrian signals. "It's a no-brainer for municipal governments to do this. It uses less energy, has a longer lifetime and a payback of 3 years or less. The trick is funding it." To address this, Ann Arbor set up a revolving energy fund seeded with $100,000. The city started by replacing the traffic lights and rolled the savings back into the energy fund to finance further investments.

Konkle noted that for municipalities, the question is not whether to convert to LEDs, but choosing the right time. The city started to contact LED manufacturers and offered to test their street lighting products. The staff soon became educated about a variety of ornamental, parking lot, and cobrahead fixtures through a four-point test process, evaluating light output, heat management, energy consumption, and public feedback. The final decision to replace their downtown globe street lights with an LED solution was driven in part by the savings analysis shown in Figure 2-4.

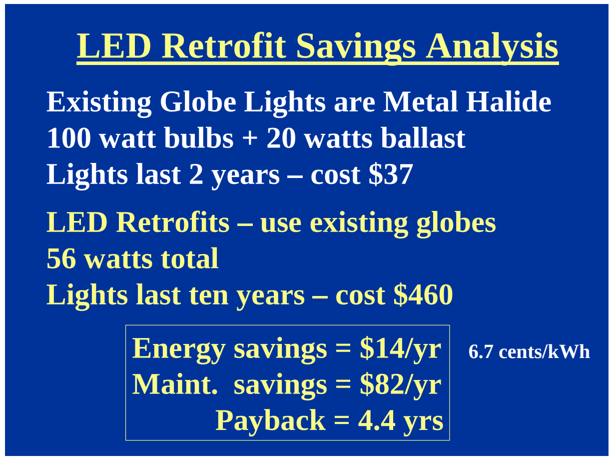


Figure 2-4: Ann Arbor LED Retrofit Savings Analysis

Konkle shared feedback, letters, and emails from other city leaders who are watching and learning from Ann Arbor's experience. He concluded by noting that "the maintenance savings far outstrip the cost at a 4.4-year payback."

2.4 SSL Partnership – Next Generation Lighting Industry Alliance

Ralph Tuttle, Next Generation Lighting Industry Alliance

NGLIA

Ralph Tuttle, Chair of the Next Generation Lighting Alliance (NGLIA), described how the Alliance participates in transformations in lighting. NGLIA is an alliance of for-profit corporations formed to accelerate solid-state lighting development and commercialization through government-industry partnership. Since 2005, DOE and NGLIA have worked under a Memorandum of Agreement (MOA) designed to enhance the manufacturing and commercialization focus of the DOE SSL program and enable DOE to access the expertise of this organization of lighting manufacturers.

The Alliance currently has 15 members, including 3M, Acuity Brands Lighting, Air Products & Chemicals, Inc., CAO Group Inc., Corning, Inc., Cree, Inc., Dow Corning Corporation, Eastman Kodak Company, GE-Lumination, Light Prescriptions Innovators LLC, LSI Industries, OSRAM Sylvania Inc., Philips Solid-State Lighting Solutions, QuNano, Inc. and Ruud Lighting, Inc. The Alliance is administered by the National Electrical Manufacturers Association.

The Alliance supports energy bill directives, identifying SSL technology needs from an industry perspective and assessing the progress of SSL research activities. In addition, it supports the DOE SSL Commercialization Plan by encouraging the development of metrics, codes and standards, by communicating SSL program accomplishments, by promoting demonstrations of SSL technologies for general lighting applications, and by supporting DOE voluntary market-oriented programs such as ENERGY STAR®.

Tuttle noted recent activities of the Alliance, including support for the development of ENERGY STAR criteria for SSL, an update of the DOE SSL Multi-Year Program Plan, and support for provisions in the Energy Independence and Security Act of 2007 related to the Bright Tomorrow Lighting Prizes (described in section 2.1). Alliance task groups also support the DOE CALiPER testing program, standards development, Gateway Demonstrations, the *Lighting for Tomorrow* design competition, and DOE's Product Quality Assurance team (a task group looking to forge more consistent results reporting industry-wide).

Tuttle concluded by emphasizing the Alliance's unique role as "spokespeople for the industry, working with the government." For information on joining the Alliance, visit the NGLIA website at www.nglia.org.

3. DOE Solid-State Lighting Research and Development

3.1 DOE SSL R&D Program Update

James Brodrick, U.S. Department of Energy

James Brodrick presented an annual update of the DOE SSL R&D Program, reviewing mission and progress and detailing budget and investment figures*. Brodrick reported that, in FY2007, the SSL Program received $30 million in congressional appropriations. On the investment side, the total current contract value of DOE SSL R&D projects (including cost-share) is $74.8 million. Figure 3-1 shows the breakdown of funding and cost-share for both LED and OLED projects.

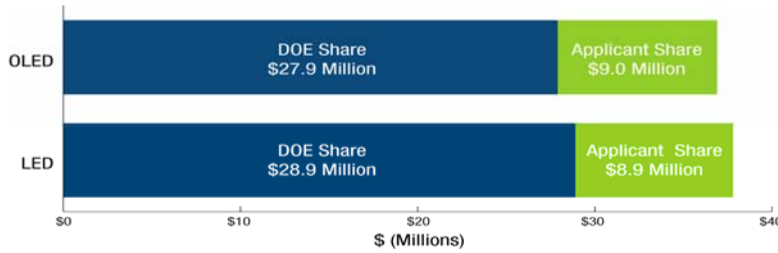


Figure 3-1: SSL R&D Project Funding*

Brodrick reported that 58% of the total portfolio funds 33 projects in Core Technology, while 42% funds 18 Product Development projects. Of the 33 Core Technology research projects, a closer look at the 18 LED projects (Figure 3-2) shows that 6 involve researching the green LED Internal Quantum Efficiency (IQE) gap, 5 are researching substrates and growth, 4 are studying IQE, 2 are studying down conversion materials, and 1 is researching extraction efficiency. Of 15 OLED research projects (Figure 3-3), 5 are studying emitting materials, 5 are researching transparent conductive oxides, 2 are studying charge injection, 2 are researching OLED device structure, and 1 is studying OLED fabrication.

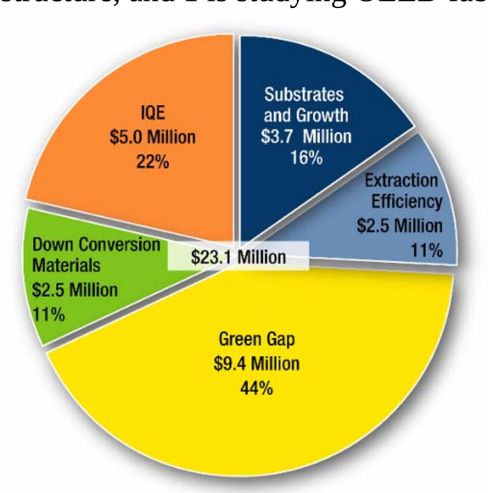


Figure 3-2: LED Core Research*

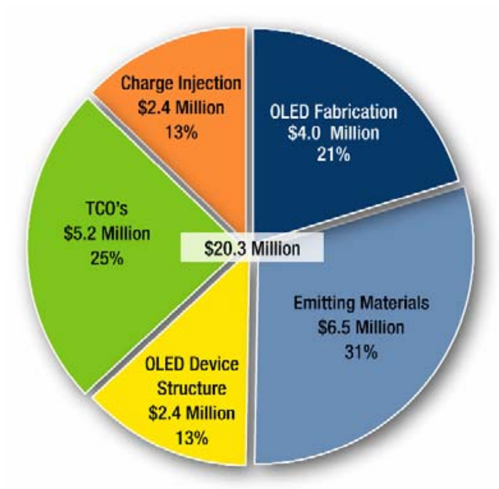


Figure 3-3: OLED Core Research*

* Totals may not equal sums due to independent rounding.

DOE funds SSL research in partnership with industry (39% to corporations, 19% to small businesses), universities (23%), and national labs (19%). Since DOE began funding research projects in 2000, a total of 71 patent applications have been applied for or awarded. See Appendix B for additional information on SSL patents resulting from DOE-funded research.

Brodrick concluded his presentation by highlighting the significant achievements of four project teams, each of which received a special recognition award:

- **Cree, Inc.,** demonstrated a cool-white multi-chip LED component prototype with efficacies of 88-95 lm/W at 350 mA. The LED component consumes approximately 8 watts. This demonstration is based on Cree's EZBright™ chip technology platform combined with prototype packaging technology.
- **Philips Solid-State Lighting Solutions** collaborated with Cree to develop an LED PAR lamp that produces 54 lm/W. This new hybrid-LED source incorporates advanced LED package and system integration technology plus novel, highly efficient driver technology and a unique optical arrangement.
- **National Renewable Energy Laboratory and Pacific Northwest National Laboratory** teams demonstrated OLEDs that use a robust transparent conducting oxide (TCO) based on gallium doped ZnO, instead of more costly indium tin oxide (ITO). This breakthrough achievement reveals the potential for a new generation of designable TCO materials with enhanced performance at reduced cost.
- **Universal Display Corporation** demonstrated an all-phosphorescent white OLED with an efficacy of 45 lm/W at 1,000 cd/m2, with a color rendering index (CRI) of 78. This achievement was enabled by lowering the operating voltage, increasing the outcoupling efficiency, and incorporating highly efficient phosphorescent emitters.

DOE recognized four project teams for significant R&D achievements in 2007. Pictured, left to right: James Ibbetson, Cree, Inc.; Kevin Dowling, Philips Solid-State Lighting Solutions; Joseph Berry, National Renewable Energy Laboratory; Paul Burrows, Pacific Northwest National Laboratory; Brian D'Andrade, Universal Display Corporation; James Brodrick, DOE.

3.2 Reports on Selected DOE-Funded R&D Projects

James Brodrick, U.S. Department of Energy

Brodrick introduced a series of invited talks on significant DOE-funded 2007 project achievements and projects of interest for 2008.

Setting New Benchmarks for LED Efficacy and Brightness

James Ibbetson of Cree, Inc. presented overviews from two projects. The first Cree project focused on *Small-Area Array-Based LED Luminaire Design* (Thomas Yuan, Principal

Investigator). For this effort, the Cree Santa Barbara Technology Center (SBTC) set out to design and develop a compact LED luminaire to demonstrate the feasibility of replacing a significant portion of current incandescent lamps. Specifically, the program developed a BR/PAR-style integrated reflector luminaire suitable for low-cost insertion into existing commercial and residential lighting fixtures. Ibbetson noted that “one of the main tasks was to generate the required amount of light by integrating a large number of chips within a small area.”

The results were noteworthy for this recently completed project. Cree demonstrated a cool white multi-chip LED component prototype with efficacies of 88-95 lm/W at 350 mA. The LED component produces 800 lumens while consuming approximately 8 watts, with a correlated color temperature of 5850°K. This demonstration is based on Cree’s EZBright™ chip technology platform, developed in part with funding support from DOE, combined with prototype packaging technology using improved materials and optimized circuit design layout. Compared to a typical standard 60W incandescent light bulb, which produces 825 lumens with an efficacy of ~14 lm/W, the prototype delivers ~85% reduction of energy consumption.


Cree, Inc. small-area array

The second Cree project was entitled *LED Chips and Packaging for 120 lm/W SSL Component*, (James Ibbetson, Principal Investigator). Initiated in October 2007, the goal of this project is to create a novel warm white lamp module for insertion into high efficiency SSL luminaires. It will use the Cree EZBright™ LED Chip and the XLamp™ 7090 XR-E as baseline technologies; both products were developed in part through prior DOE-funded projects. The project will address LED chip and package efficiency improvements to establish a technology platform that is capable of scaling into low cost, high efficiency commercial luminaires. The ultimate goal will be to replace halogen, fluorescent and metal halide lamps based on the total cost of light.

Currently, the project is achieving 95 lumens or 84 lm/W at 4100K CCT. “The biggest improvement potential is blue chip external quantum efficiency,” Ibbetson said. Part of Cree’s challenge is moving the efficacy curve up at a reasonable cost. There are a number of additional, smaller efficiency losses which add up right now, and Ibbetson commented that Cree researchers view current devices to perform at about half the possible efficiency. “We’re working on getting back the efficiency we’re losing in all the various system components.” Overall, the project seeks to achieve a 40% gain in efficacy from 84 lm/W up to 120 lm/W in the next two years—an aggressive goal.

Solving the “Green Gap” in LED Technology

Christian Wetzel of the Department of Physics, Applied Physics and Astronomy at Rensselaer Polytechnic Institute discussed his team’s efforts to solve “the green performance gap” – that is, to increase the efficiency of green LEDs. According to Wetzel, if green LEDs were more efficient, then the discrete color-mixing approach to white LEDs would also become more efficient.

By growing on non-polar Gallium Nitride substrates, the team is developing processes to double or triple the light output power from green and deep green AlGaInN LED dies in reference to the Lumileds Luxeon II. Lumileds Luxeon II dies and lamps have been identified by DOE as the uniform reference of current performance levels and therefore are being used by the research team.

Since LEDs in this spectral region show the highest potential for significant performance boosts, the project is paying particular attention to all aspects of the internal generation efficiency of light. Anticipated results are high output green and deep green (525 - 555 nm) LED chips as part of high efficacy red-green-blue LED modules. Such modules would perform at and beyond the efficacy target projections for white-light LED systems in DOE's accelerated roadmap.

Mini LED 100 μm in diameter as seen through microscope (regular fabricated bare die, no light extraction enhancement)

Some key results to date include:

- Growing good quality green emitting epitaxial material on c-plane, a-plane and m-plane Gallium Nitride
- No wavelength shift in non-polar green emitting material with increased excitation density
- Replicating substrate quality throughout the active region
- Low-dislocation density bulk Gallium Nitride substrate

"We are crawling into the chip itself," Wetzel stated. "We have so far been able to double the output with this approach, and we're not at the limits yet, not really comparing it, performance-wise, to the other material. We are continuing to press ahead."

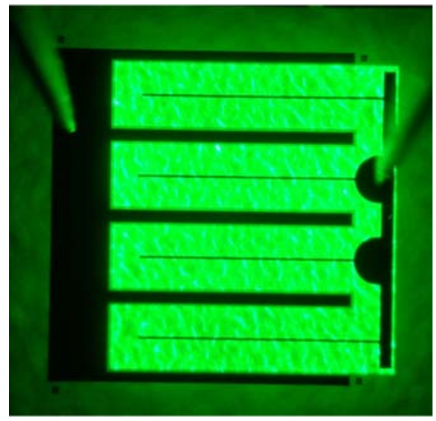
Improving Epitaxial Growth for LEDs

Daniel D. Koleske of Sandia National Laboratories provided an overview of several projects focused on improving the quality and efficiency of underlying materials for LEDs. Funded by both the DOE SSL Program (Office of Energy Efficiency and Renewable Energy) and the Basic Energy Science Program (Office of Science), Sandia is exploring different ways to improve epitaxial growth for LEDs. These projects include:

- *Development of Bulk Gallium Nitride Growth Technique for Low Defect Density Large Area Substrates* addresses how nitrogen's low solubility in liquid gallium makes it difficult to grow bulk gallium nitride, except at extremely high temperatures and pressures. Researchers at Sandia are working to grow bulk GaN crystals at lower temperatures and pressures in molten salt solutions. If successful bulk GaN crystals could be produced faster and reduce the manufacturing cost to grow LEDs. [Karen Waldrip, Principal Investigator]
- *Nanowire Templated Lateral Epitaxial Growth of Low Dislocation Density GaN* seeks to develop inexpensive and low defect density gallium nitride substrates to enable higher efficiency LED devices. In this approach, Principal Investigator George Wang is using vertically-aligned GaN nanowires followed by lateral coalescence to produce a high

quality planar film, with low defects. Higher quality GaN films will increase LED device lifetime and efficiency.

- *Nanostructural Engineering of Nitride Nucleation Layers for GaN Substrate Dislocation Reduction* is working to develop growth methods that reduce defects on a sapphire substrate. Principal Investigator Dan Koleske is investigating methods to reduce nucleation site density while maintaining the ability to fully coalesce the GaN films. GaN nuclei orientation will be improved by improving sapphire smoothness prior to the NL growth. As with the other efforts, reducing defects will help create more efficient LEDs – the ultimate goal of DOE research.
- *Improved InGaN Epitaxial Quality by Optimizing Growth Chemistry* is focused on systematic study of gas-phase parasitic reactions and thermodynamic and surface kinetic effects to improve green LED efficiency. The project addresses improvement of InGaN internal quantum efficiency by systematic study and control of indium incorporation in LED active regions. [Randy Creighton, Principal Investigator]
- *Innovative Strain Engineered InGaN Materials of High Efficiency Green Light Emission* also focuses on green LEDs. Principal Investigator Michael Coltrin seeks to achieve higher internal quantum efficiency for deep green LEDs by developing strain relaxed InGaN templates. The goal of this project is to achieve higher efficiency LEDs at longer wavelengths with fewer defects.



Sandia research on green LEDs

These projects together represent a range of research being conducted today to resolve some of the underlying technological issues in improving epitaxial growth for LEDs. Improvements in epitaxial growth for LEDs have the potential to greatly impact the efficiency and lifetime of blue and green LEDs used in lighting products.

Increasing Efficiency and Stability for White OLEDs

Brian D'Andrade provided an overview of findings and notable progress achieved by researchers at Universal Display Corporation (UDC). UDC's efforts focus on four key elements of research in white OLEDs (WOLEDs) that all must work together to achieve maximum power savings: internal quantum efficiency (IQE), outcoupling efficiency, device voltage, and lifetime.

In the first area – improving IQE – UDC has already achieved 100% IQE. D'Andrade stated that "Phosphorescence is the key. Before we had this breakthrough with phosphorescence, the industry thought OLEDs would top out at about 25% IQE."

Regarding outcoupling efficiency – or external quantum efficiency (EQE) – D'Andrade reported that "OLED luminaires allow light to have a longer travel distance." He highlighted several devices in which outcoupling efficiency was enhanced by using OLED luminaires that significantly reduce the absorption losses incurred when light waveguides in the substrate. "We still have a way to go, however," he added.

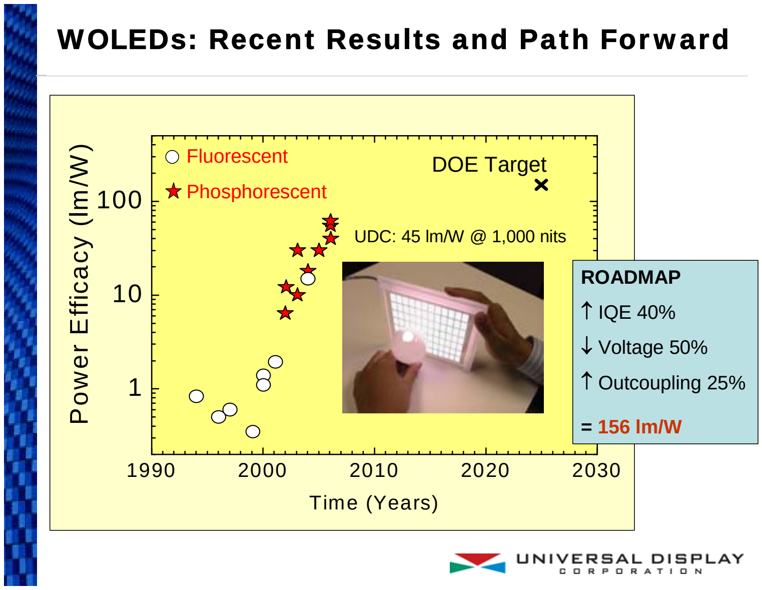


Figure 3-4: UDC WOLEDs Research

Device voltage efforts focus on increasing energy efficiency by driving levels of voltage down. Low voltage operation is obtained by incorporating highly conductive transport layers and by designing devices to improve charge injection and recombination in the emissive layer. D'Andrade observed that "People have demonstrated 2.5V operation at 1,000 cd/m^2 with LEDs, but the best white OLED devices probably operate around 3.2V. The lowest number I've seen is 3-3.1V and that's with a combination of materials and everything optimized. But for the highest possible efficacy, you want to see around 2.4V."

On extending the lifetime of devices, the team has targeted a goal of 50,000 hours, which it is pursuing in tandem with the other key research areas. Pulling all these elements together has enabled UDC to demonstrate an all-phosphorescent WOLED with a power efficacy of 45 lm/W at 1,000 cd/m^2. Building on that success, the team continues to achieve consistent progress in line with DOE targets for WOLED light sources.

Extracting More Light from LEDs

Dr. Yong-Seok Choi of the University of California Santa Barbara (UCSB) presented on behalf of James Speck, Principal Investigator of *High-Efficiency Nitride-Based Photonic Crystal Light Sources.* UCSB proposes to maximize the efficiency of a white LED by enhancing the external quantum efficiency using photonic crystals to extract light that would normally be confined in a conventional structure. Choi stated that ultimate efficiency can only be achieved by looking at the internal structure of light. To do this, UCSB is focusing on maximizing the light extraction efficiency and total light output from light engines driven by Gallium Nitride (GaN)-based LEDs. The challenge is to engineer large overlap (interaction) between modes and photonic crystals. The objectives of this project are focused on achieving high extraction efficiency in LEDs, controlled directionality of emitted light, integrated design of vertical device structure, and nanoscale patterning of lateral structure.

UCSB is using three approaches to address these objectives:

- The **first** uses an AlGaN layer for vertical mode control and confinement. This is relatively easy to fabricate, and provides moderate performance of up to 75%. However, this relies on the quality of the AlGaN layer. Increasing the aluminum composition provides better optical confinement, but thicker layers can result in cracking, which results in a lower IQE.
- The **second** approach uses substrate lift-off and layer thinning. Choi showed extraction efficiency as a factor of cavity thickness and quantum well position, noting the two factors present a tradeoff. This method presents challenges in fabrication, has metal absorption losses, and can result in damage during the fabrication process, but UCSB is pursuing more tests because the performance has the potential to be excellent at 90+%.
- The **third** approach is to use lateral epitaxial overgrowth (LEO). This method is also challenging to fabricate, but because of the thin active layer, it can be patterned before the active region is grown, which achieves vertical mode control. This results in no fabrication damage or material overgrowth, and provides intermediate performance of about 80+%. Researchers at UCSB are encouraged by the coalescence achieved using this method, as it is very important at the nanoscale dimension.

According to Dr. Choi, the "advances being sought in large area patterning and fabrication of devices will pave the pathway to manufacturable processes." The research team has concluded that microcavity and photonic crystal LEDs both require vertical confinement of light and low loss metal mirrors. They also recognize that confinement of the AlGaN layer is a major growth challenge, therefore they will try other materials, such as Aluminum Nitride. They believe thinned LLO layers by selective etching are promising, because the process is scalable to larger sizes. However, this requires better metal contacts to provide the high performance being sought. Finally, the LEO approach puts a major challenge on 2D thin LEO coalescence and growth, but it may provide the ultimate solution if these obstacles are overcome. UCSB will continue to apply vertical mode engineering and photonic crystal technology to extract more light from LEDs.

Figure 3-5 shows the brighter emission with the photonic crystal lattice (left).

	350nm AlGaN	600nm AlGaN
Total increase	1.5x	2.1x

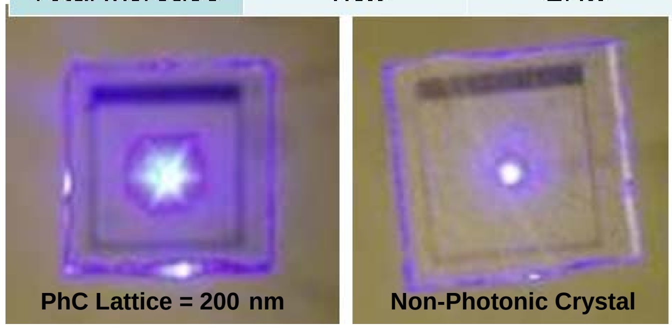


Figure 3-5: Photonic Crystal LED vs. Non-Photonic Crystal LED

Developing Molecular Dopants for Bright, Long-lived OLEDs

The overall objective of the novel molecular dopant research presented by PNNL's Linda Sapochak is to reduce OLED voltage and increase stability, life, and efficiency, at a lower manufacturing cost. Researchers propose to develop a new set of organic anchored molecular dopants for bright, long-lived OLEDs by tethering high electron affinity moieties (functional groups) to stable, vacuum-sublimable anchor molecules, as these anchored molecular dopants will provide "controlled" conductivity doping of charge transport layers in OLEDs.

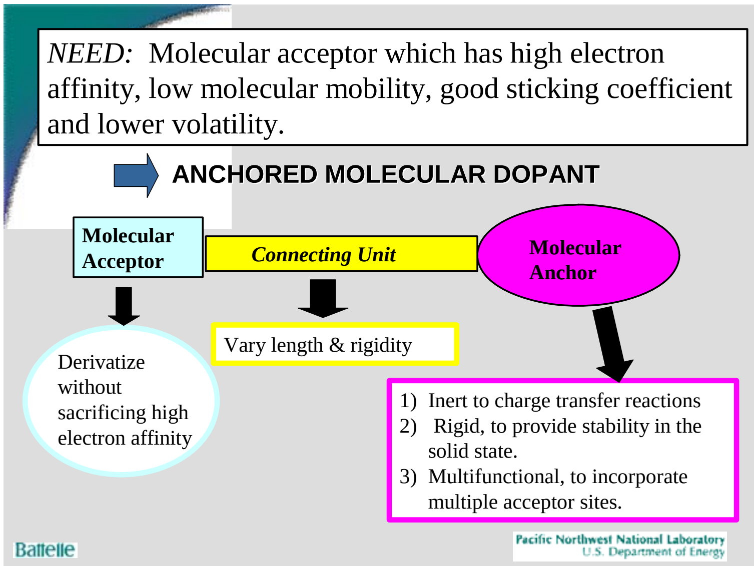


Figure 3-6: PNNL Molecular Dopant Research

In her talk, Sapochak identified objectives for three phases of the project. Phase I is focused on material design and synthetic methodology. Proposed milestones for year one include:

- Synthesize, purify, and characterize four anchored-molecular dopants and demonstrate stability to vacuum sublimation
- Characterize the electrochemical properties of new anchored molecular dopants and demonstrate reduction potentials similar to F4TCNQ
- Demonstrate p-doping of hole transport layer using one anchored molecular dopant in standard Alq3 device and achieve an operating voltage <5 V for 100 cd/m2.

In Phase II, the team will focus on material characterization and optimization, while in Phase III the concentration will be on device fabrication and optimization. The new molecular dopants will lower operating voltage, increase power efficiency, lower manufacturing cost, and allow for a simpler OLED structure. The best performing dopants will be provided to industry, where the anticipated outcome of the project will be achievement of more stable white phosphorescent OLEDs operating near 100% IQE at close to bandgap voltage. Along with improvements in optical outcoupling, these will offer power efficiencies well in excess of 100 lm/W.

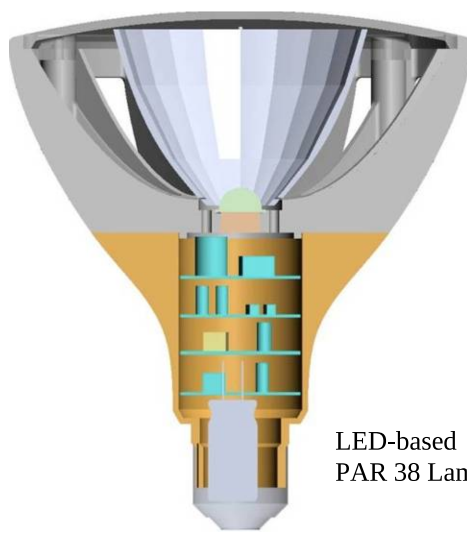
Creating an Integrated Solid-State LED Luminaire for General Lighting

Kevin Dowling of Philips Solid-State Lighting Solutions presented an overview of the collaborative effort between Philips and Cree, Inc. to develop a replacement for a 60W PAR lamp, with comparable form, light output, and color. The companies are aggressively pursuing the goal of a warm white, solid-state luminaire of over 700 lumens and over 70 lm/W at a steady state, with a CRI of 90. The project involves developing a >90% efficient and compact power supply and control elements, as well as thermal management concepts. These elements will be integrated to provide for a form and function fit equivalent to general service lamps, because "lighting designers don't talk in equations." The ultimate goal is to develop a luminaire that lighting designers will specify and use.

Dowling emphasized the importance of analyzing the Total Cost of Ownership (TCO) of an LED system to determine what the cost should be in order to get the adoption rate up in the market. This results in a ripple effect that influences many aspects of the system. For example, the design choices have impact on the electrical delivery system, which relate to the power factor and inductive loads.

The companies also used knowledge gained from previous lighting market experience. They considered the DOE report, *Compact Fluorescent Lighting in America: Lessons Learned on the Way to Market*, to develop a product that overcomes key objections buyers had with CFLs, namely ensuring this new light is instant-on and dimmable. The Philips-Cree collaboration combines this TCO approach and market knowledge with an effort to maximize light output without compromising reliability or lifetime, while keeping the assembly simple.

The two companies leveraged previous research to develop a new hybrid-LED PAR lamp that incorporates advanced LED package and system integration technology plus novel, highly efficient driver technology, a unique optical arrangement, and a chimney effect for thermal management. "We wanted to extract every photon from the system possible – to leave no photon behind." As of the fall 2007, the team has achieved 600 lumens, 86 CRI, CCT at 2900K, power factor around 90%, and efficacy of 56 lm/W – all in a narrow flood beam at steady state. This is significantly more efficient than comparable LED PAR 38 lamps on the market, and 4-5 times more efficient than incandescent PAR 38 lamps. In the coming months, a third generation will evolve based on what has been learned thus far.



LED-based PAR 38 Lamp

In the question-and-answer session, Dowling addressed the issue of dimmability. He acknowledged one of the obstacles facing the SSL industry is that most dimmers today are not compatible with LED systems, because most require minimum loads. (LEDs are so low-powered, they don't trip the dimmer.) This is among the challenges SSL companies are working hard to overcome.

3.3. Poster Session for All DOE-Funded R&D Projects

In the evening, a Poster Session and Reception for all DOE SSL projects provided additional opportunities to share research results, identify needs, and build relationships. The following list gives the poster topics and presenters.

LED Project Posters

Multicolor, High Efficiency, Nanotextured LEDs
Jung Han, Yale University

Quantum-Dot Light Emitting Diode
Keith Kahen, Eastman Kodak Company

Epitaxial Growth of GaN Based LED Structures on Sacrificial Substrates
Ian Ferguson, Georgia Tech Research Corporation

Low-Cost Substrates for High-Performance Nanorod Array LEDs
Timothy Sands, Purdue University

High Performance Green LEDs by Homoepitaxial MOVPE
Christian Wetzel, Rensselaer Polytechnic Institute

Photoluminescent Nanofibers for High Efficiency Solid-State Lighting Phosphors
Lynn Davis, Research Triangle Institute

High-Efficiency Nitride-Based Photonic Crystal Light Sources
James Speck, University of California, Santa Barbara

Innovative Strain-Engineered InGaN Materials for High-Efficiency Deep-Green Light Emission
Michael Coltrin, SNL

Novel ScGaN and YGaN Alloys for High Efficiency Light Emitters
Daniel Koleske, SNL

Nanostructural Engineering of Nitride Nucleation Layers for GaN Substrate Dislocation Reduction
Daniel Koleske, SNL

Development of a Bulk Gallium Nitride Growth Technique for Low Defect Density Large-Area Native Substrates
Karen Waldrip, SNL

Improved InGaN Epitaxial Quality by Optimizing Growth Chemistry
J. Randall Creighton, SNL

Novel Heterostructure Designs for Increased Internal Quantum Efficiencies in Nitride LEDs
Robert Davis, Carnegie Mellon University

High-Efficiency Non-Polar GaN-Based LEDs
Paul Fini, Inlustra Technologies, LLC

Development of White LEDs Using Nanophosphor-InP Blends
Lauren Rohwer, SNL

Nanowire Templated Lateral Epitaxial Growth of Low Dislocation Density GaN
George Wang, SNL

Investigation of Surface Plasmon Mediated Emission from InGaN LEDs Using Nano-Patterned Films
Arthur Fischer, SNL

An Efficient LED System-in-Module for General Lighting Applications
James Gaines, Philips Lighting

An Integrated Solid-State LED Luminaire for General Lighting
Kevin Dowling, Color Kinetics

Phosphor Systems for Illumination Quality Solid State Lighting Products
Anant Setlur, GE Global Research

White LED With High Package Extraction Efficiency
Matt Stough and Yi Zheng, Osram Sylvania

LED Chips and Packaging For 120 LPW SSL Component
James Ibbetson, Cree, Inc.

Small-Area Array-Based LED Luminaire Design
Monica Hansen, Cree, Inc.

Novel Growth Technique for Large Diameter AlN Single Crystal Substrates
Shaoping Wang, Fairfield Crystal Technology, LLC

OLED Project Posters

Surface Plasmon Enhanced Phosphorescent Organic Light Emitting Diodes
Guillermo Bazan, University of California, Santa Barbara

New Approaches to High Efficiency Organic Electroluminescence
Chao Wu, University of Southern California

High Efficiency Microcavity OLED Devices With Down-Conversion Phosphors
Franky So, University of Florida

Multi-Faceted Scientific Strategies Towards Better Solid-State Lighting of Phosphorescent OLEDs Phosphors
Mohammad Omary, University of North Texas

High Efficiency Long Lifetime OLEDs With Stable Cathode Nanostructures
Samuel Mao, LBNL

High Quality Low Cost TCOs
Anthony Burrell, LANL

Investigation of Long-Term OLED Device Stability via Transmission Electron Microscopy Imaging of Cross-Sectioned OLED Devices
Gao Liu, LBNL

High Stability Organic Molecular Dopants for Maximum Power
Linda Sapochak, PNNL

Low-Cost Transparent Conducting Nanoparticle Networks for OLED Electrodes
Jeffrey Elam, ANL

Hybrid Nanoparticle/Organic Semiconductors for Efficient Solid State Lighting
Darryl Smith, LANL

Low-Cost Nano-Engineered Transparent Electrodes for Highly Efficient OLED Lighting
David Geohegan, ORNL

Thin Film Packaging Solutions for High Efficiency OLED Lighting Products
Ken Weidner, Dow Corning Corporation

OLED Lighting Device Architecture
Yaun-Sheng Tyan, Eastman Kodak Company

High Efficiency, Illumination Quality White OLEDs for Lighting
Joe Shiang, GE Global Research

High Quantum Efficiency OLED Lighting Systems
Joe Shiang, GE Global Research

Zinc Oxide Based Light Emitting Diodes
Ramachandran Radhakrishnan, Materials Modification Inc.

High Efficiency Organic Light Emitting Devices for General Illumination
Paul Shnitser, Physical Optics Corporation

High Recombination Efficiency White Phosphorescent Organic Light Emitting Diodes
Brian D'Andrade, Universal Display Corporation

WOLEDs Containing Two Broad Emitters
Brian D'Andrade, Universal Display Corporation

Novel Low Cost Organic Vapor Jet Printing of Striped High Efficiency Phosphorescent OLEDs for White Lighting
Theodore (Teddy) Zhou, Universal Display Corporation

Novel Organic Molecules for High Efficiency Blue Organic Electroluminescence
Asanga Padmaperuma, PNNL

Novel High Work Function Transparent Conductive Oxides for Organic Solid State Lighting Using Combinatorial Techniques
Paul Burrows, PNNL and Joe Berry, NREL

For an overview of all current DOE-funded SSL R&D projects, including a brief description, partners, funding level, and proposed timeline, see the 2008 SSL Project Portfolio on the DOE SSL website at http://www.netl.doe.gov/ssl/materials_2008.html.

3.4 DOE SSL Funding Opportunities – Preparing a Comprehensive Application

Joel Chaddock, National Energy Technology Laboratory

Joel Chaddock from NETL presented an overview of the DOE SSL proposal review process and offered insights on preparing successful applications. Chaddock began by detailing the steps in the proposal evaluation process. All applications receive three-to-four evaluations, performed by external technical experts. Technical reviewers sign a non-disclosure agreement and judge against technical criteria only – they neither score applications nor evaluate budgets.

Next, the Merit Review Committee looks at each proposal to assess external evaluator input and rate individual criterion as they develop an overall weighed score and ranking. The Committee produces a report on its findings and makes recommendations for selection. At this point, the source selection official – a high-level DOE manager – makes the actual selections for negotiation, weighing recommendations, program policy factors such as portfolio mix and gaps, and assessment of best use of federal funds between, for example, applications proposing similar research at varying costs.

Chaddock next offered specific, common-sense guidance and tips on creating successful applications. "Make sure your applications are complete and submitted on time," he advised, noting that a common cost-share error is made when applicants calculate performer share solely as a percentage of government share, rather than as a percentage of the total cost, equaling government share *plus* performer share. He further reminded his listeners that the minimum required cost-share is 20%.

"The application should stand on its own," Chaddock stated. "You're responsible to convince the evaluators of your merit, knowledge, and plan. We look for thorough descriptions and explanations. Nothing is assumed." Ultimately, an application should clearly answer the questions: "What is the Government buying? What is the end result of the research?" Chaddock also advised teams to focus on a single "area of interest" and keep in mind the solicitation performance objectives and DOE Multi-Year Plan goals and objectives. "Write the application toward the evaluation criteria," he advised, "and detail why your approach is better, then provide findings and support to back up your statements."

In summary, Chaddock offered tentative dates for upcoming solicitations – April 2008 for Core Research and May 2008 for Product Development. He emphasized the importance of reading the complete solicitation document and submitting on-time – even ahead of time – to avoid unexpected last-minute complications that could cause a proposal to be eliminated from consideration.

3.5 Moving Targets – Updates to the DOE SSL R&D Multi-Year Program Plan

Fred Welsh, Radcliffe Advisors

Fred Welsh provided an overview of draft updates to Chapter 4 (see Appendix C) of the DOE SSL Multi-Year Program Plan (MYPP). "Chapter 4 contains the technical content of the DOE roadmap – the R&D agenda – for solid-state lighting for the coming year," Welsh noted. "We realize that people sell LEDs for lots of other reasons, but DOE's focus is on energy savings and the MYPP spells out, step-by-step, the goals that we have along the way."

The MYPP is updated annually, with close participation from many partners, including NGLIA, NETL, and attendees from the annual R&D Workshop. Chapter 4 specifies performance targets for conversion efficiencies (independent of spectrum); overarching device targets for efficacy, lifetime, and cost; luminaire targets (newly added this year); and detailed, specific task and subtask metrics and targets.

A number of key events in 2007 guided the Chapter 4 updates. LED efficacies far surpassed projections, and several high-quality LED luminaires appeared in the market. Product costs appear to be coming down. At the same time, OLED efficacies have improved exponentially. As a result, the draft updates for Chapter 4 include higher near-term efficacy targets for LEDs and a new emphasis on luminaire performance. New milestones for LEDs have been established and some task priorities have shifted.

Metric	2007	2010	2012	2015
Efficacy- Lab (lm/W)	120	160	176	200
Efficacy- Commercial Cool White (lm/W)	84	147	164	188
Efficacy- Commercial Warm White (lm/W)	54	117	134	158
OEM Device Price- Product ($/klm)	25	10	5	2

Figure 3-7: LED Device Performance Track

The OLED device performance track remains essentially the same for efficacy, but reflects an additional cost and reliability effort for OLEDs.

Metric	2007	2009	2012	2015
Efficacy- Lab (lm/W)	44	76	150	150
Efficacy- Commercial (lm/W)	N/A	34	76	150
OEM Device Price- ($/klm)	N/A	72	27	10
OEM Device Price- ($/m^2)	N/A	216	80	30
Device Life- Commercial Product (1000 hours)	N/A	11	25	40

Figure 3-8: OLED Device Performance Track

Welsh concluded by asking attendees for feedback on the draft updates detailed in his presentation and the handout provided in the workshop materials. In the interval since the workshop, DOE has incorporated comments and feedback into a final MYPP, published in March 2008 on the SSL website at http://www.netl.doe.gov/ssl/PDFs/SSLMYPP2008_web.pdf.

4. Designing SSL for Market

4.1 What Architects and Lighting Designers Want from SSL

Samantha LaFleur, Atelier Ten

Samantha LaFleur, Lighting Designer for Atelier Ten, an environmental design and engineering firm, offered her perspective on "What Architects and Lighting Designers Want from SSL." Atelier Ten projects cover a range of commercial buildings, including university buildings that sometimes have a life span of 100 years. LaFleur defined her role as a hybrid between the designer and engineer, with "a quest to use less energy to get the job done beautifully." She emphasized the importance of developing relationships with lighting designers, as they are "a shortcut to their clients, and to a network of other lighting designers who talk regularly."

LaFleur stated that a lighting designer's biggest challenge is learning about new fixtures and technologies so she can represent them honestly to clients. "Most of my projects now include LEDs as a light source for one application or another. I wouldn't have said that five years ago. I wouldn't have said that a year and a half ago." She emphasized a significant turning of the tide, that "[SSL] is finally coming mainstream."

LaFleur acknowledged what is going right with LEDs: Light output is "getting there," and color temperature and consistency are no longer sticking points. In her use of white lights, she finds increasing numbers of fixture options and manufacturers, and a decline in costs. Needed improvements, said La Fleur, include making the technology less proprietary, and increasing manufacturer loyalty to specifiers. LaFleur emphasized "specify-ability," because the lighting designer ends up representing lighting products. "Without three items to specify, I can't use a product."

LaFleur offered advice on how to work with designers:

- **Inform** the 500 or so lighting designers across the U.S. by going to shows, especially in cities like New York, Chicago, Los Angeles, and Washington, where large concentrations of designers gather. Bring a sample kit and make a small investment in a trade show, and provide this critical group with a hands-on opportunity to learn about products.
- Provide **samples**.
- Keep working to **bring first costs down**.
- Provide a **complete system—**with the power, the mounting, lens, all figured out.
- **Pre-solve installation details** and **stand by the products** until they work and keep working (warranty).
- Provide **technical support** during business hours. Designers typically only have a day or two to get details from a manufacturer, or the designer must move on to another product.
- Provide a thorough **website** and solid specification documents via PDF online, so a lighting designer can walk into a meeting with a kit of specs.
- Encourage your reps to **talk about pricing**. The market opinion of SSL prices is likely to be higher than the reality. Talking about this makes it easier for designers to test the feasibility of different products sooner.
- Provide lighting designers with **feedback**. Chances are, if a designer specifies your product once for a desired effect, it will be chosen again. "If we've done it wrong, it'd be

great if someone would say 'You know, you're going to totally torch the fixture' before we do it five times."

- **Talk to distributors** during construction. "It'd be great to have serious submittals that think through the power and installation details. We all want the lights to still work in 15 years. Once it's in, any help you give to a specifier will come back to you – absolutely."

LaFleur then outlined her "wish list" for LEDs. "The market potential for LED-based task fixtures cannot be understated," said LaFleur. "Every pantry, residential kitchen, hospitality bathroom – tasks are a huge market. LEDs are an ideal source for them. Please give us lots more choices, and bring the cost way down." LaFleur noted that she designs for vertical tasks—for walls, not floors. She encouraged the development of recessed and asymmetrical lighting, to graze or accent different wall materials. LaFleur also shared her hope that LEDs take over exterior lighting, because current sources have too much light output, which has a ripple effect when adjacent structures or communities are built. "The sooner we can fix this, the better our countryside will be in 10 years." She also noted that LEDs dim as they age, causing a potential hazard or liability in an egress or circulation application. She challenged attendees to find a way to deal with this unique behavior, perhaps having lights shut down when the output has fallen to an unsafe level.

During the question and answer period, LaFleur stated that because LEDs will be mixed with incandescent and fluorescent, they need to be in ~3000 Kelvin range, with color rendering >80 for most interior spaces. Addressing the cost concerns with LEDs, LaFleur observed, "My clients want to know if they can afford [LEDs] today. The comparison that most frequently gets drawn today is versus fluorescents. Some [cost] increase is tolerable, but when it's 2 or 3 times the cost, it's not going to work." An attendee asked about customer objections to LEDs, and LaFleur frankly noted one of the important technical issues with LEDs is what do you do when the light becomes too dim? "I don't always know what to tell them. Some fixtures you replace entirely, some just the board – it's not always clear from the cut sheets."

4.2 2007 *Lighting for Tomorrow* Competition

Ruth Taylor, Pacific Northwest National Laboratory

Ruth Taylor of PNNL presented the winners of the 2007 *Lighting for Tomorrow* (LFT) SSL Competition. Organized by the American Lighting Association (ALA), the Consortium for Energy Efficiency, and DOE, the competition is designed to encourage and recognize attractive, energy-efficient residential lighting fixtures, to build demand for these fixtures by highlighting their functionality and beauty, and to encourage technical innovation in energy-efficient lighting.

Initially, the competition focused on compact fluorescent lighting; in 2006, the SSL category was added. The 2007 SSL competition objectives included:

- Exploring the use of LEDs in niche applications
- Evaluating fixtures employing LEDs
- Facilitating learning within the lighting fixture industry

2007 *Lighting for Tomorrow* Winners – SSL Category

Grand Prize

LR6 Downlight by LED Lighting Fixtures (LLF)
- 12 watts
- 650 lumens
- 61 lm/W
- 2700 K, 92 CRI

Portable Desk/Task

PLS Task by Finelite, Inc.
- 10 watts
- 430 lumens
- 43 lm/W
- 3500 K
- 71 CRI

Undercabinet

PLS Undercabinet by Finelite, Inc.
- 8 Watts
- 344 lumens
- 43 lm/W
- 8500 K
- 71 CRI

Outdoor

Strata by Progress Lighting
- 5 watts
- 125 lumens
- 25 lm/W
- 3200 K
- 70 CRI

4.3 SSL Grand Prize Winner – LLF LR6 Downlight

Gary Trott, LED Lighting Fixtures

Gary Trott, from LED Lighting Fixtures Inc. (LLF), began his presentation by describing the competition itself. "*Lighting for Tomorrow* is not just a beauty contest," he asserted. "It is a balanced evaluation of the luminaire on performance, aesthetics, and energy efficiency." Trott emphasized the value of participating in the competition, particularly the testing and validation of the LR6 product performance.

The technology behind the winner, Trott stated, "involves a unique and patented way to generate white light with LEDs. It is not RGB mixed, not a white phosphor converted LED, but a novel approach. Second, it is a fully integrated design from a team using an unprecedented breadth of experience, a bottom-up approach from material science through architecture, and significant breakthroughs in mechanical, optical, thermal, and electrical engineering."

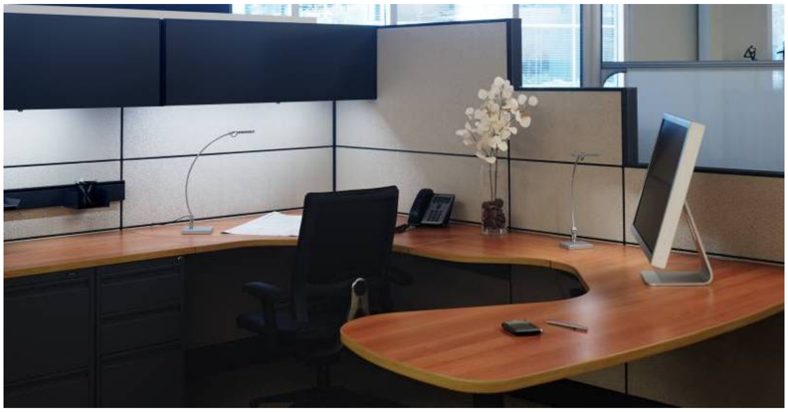
LR6 downlights by LLF in kitchen ceiling application

Trott detailed end-user benefits that include saving energy and reducing maintenance issues and environmental impact. He concluded by illustrating several before-and-after installations of the LR6 downlight, demonstrating the enhanced brightness and reduced power draw in each application.

4.4 Task/Low Ambient Lighting for Today's Offices

Terry Clark, Finelite, Inc.

Terry Clark of Finelite, Inc., began his presentation with an overview of the research behind the products. "We developed our product through research with the California Energy Commission," Clark noted. "The State of California matches dollars with manufacturers for research into better lighting solutions through the PIER (Public Interest Energy Research) program."



Personal Lighting System desk lamp and undercabinet lighting by Finelite, Inc.

Clark presented key findings from PIER/Finelite research into office lighting, noting that more than 80% of workers choose “uncomfortable” lighting (under-lighting) over “unbearable” lighting (over-lighting). “Task lighting in the ‘goal’ zone is the key to significant energy savings and user acceptance. Better lighting is the *right amount* of light – eliminating shadows and glare.”

Through its research with PIER, Finelite developed a new LED-based solution that combines task lighting with low ambient lighting. The task lighting is accomplished with Finelite’s Personal Lighting System (PLS) desk lamp and undercabinet lighting. When task lighting is right, says Clark, ambient lighting takes only 0.5 to 0.65 W/sf. Clark concluded by highlighting the affordability of task/low ambient lighting.

4.5 SSL Technology and Innovations for Residential Lighting

Jim Decker, Progress Lighting

Progress Lighting does business with 19 of the 25 top builders in the U.S., according to Jim Decker. “They’ve pushed us a lot to come up with energy efficient solutions – and this is being driven by consumers,” Decker stated. “Last year for the first time, spending on ‘green’ options exceeded spending for luxury options in homes.”

Strata Outdoor Lantern by Progress Lighting

Decker described the development of several fixtures in the Progress LED line, pointing out key advantages from LED sources, including the ability to function in cold environments and lack of mercury. The Strata Outdoor Lantern design is also full cutoff, dark sky compliant.

Decker offered his perspective on what DOE and LED manufacturers need to do to facilitate market acceptance of LED products. “Consistency will be key,” he stated, noting that LM79 and LM80 standards will set a context for this. Decker asked LED manufacturers to ensure that “data on LEDs – such as lumen output and performance characteristics – are presented in a consistent manner,” and he recommended “showing how life is affected at different temperatures, instead of only the temperature that gives you 50,000 hours.”

And consistent, clear information is equally relevant for the public, Decker cautioned. “Consumer education is key,” he concluded. “As we move forward, comparative information is going to very important for all of us. The typical shopper does not have a clue about LEDs. They may think it’s a great idea, but to walk into a store and see a fixture that’s 5 watts? The questions are: ‘What does that mean? How does that compare with 100 watts? Is it enough light?’ So, as an industry, we have to address not just ‘better,’ and ‘best,’ but ‘how do we get this technology out into the world?’”

4.6 2008 *Lighting for Tomorrow* Competition

Ruth Taylor, Pacific Northwest National Laboratory

Ruth Taylor provided a preview of the 2008 SSL competition, outlining this year's three categories:

- **Near-term applications –** Undercabinet, portable desk/task, downlights, and outdoor porch/path/step lighting capable of meeting ENERGY STAR® criteria for SSL, Category A
- **Other applications –** Additional fixture types including wall sconces, table/floor lamps, pendants, and chandeliers, among others
- **Future LED showcase –** Fixtures that use the most energy-efficient, pre-production LED devices

"The 'future LED showcase' category is new this year, and that's where we're pushing the envelope," Taylor observed. "We are really promoting innovation – to not only show the world what's out there now, but also to say: 'Here's what's coming next.'"

Judging criteria, Taylor noted, will be based on lighting quality factors of color appearance, color rendering, and illuminance levels and distribution, as well as application efficiency, thermal management, and aesthetic appearance. In addition, bonus points will be given for innovative designs that take advantage of unique LED attributes, dimmability, no off-state power consumption, and outdoor/dark sky friendliness.

"A very important part of the competition," Taylor commented in conclusion, "is the testing. Today, we're at a stage where people look at products but question the claims. All our finalists are sent through the CALiPER program for verifying – *before* any announcements come. An added benefit is that finalists can use their CALiPER results for ENERGY STAR compliance."

The 2008 timeline is:

- January 2008 – Competition announced
- February 29, 2008 – Intent to Submit forms due
- April 30, 2008 – Entries due
- May 2008 – Judging
- September 14, 2008 – Winners announced at ALA Annual Conference in Washington, D.C.

For complete guidelines, minimum requirements, and rules for the 2008 competition, visit www.lightingfortomorrow.com.

5. Guiding Market Introduction of Energy-Efficient Solid-State Lighting Products

5.1 DOE's SSL Commercialization Support Update

Marc Ledbetter, Pacific Northwest National Laboratory

Marc Ledbetter of PNNL presented an update on DOE's five-year commercialization support plan, highlighting significant changes for 2008. Strategic elements of the plan include:

- Buyer guidance, such as ENERGY STAR and lighting design guidance
- Design competitions, including *Lighting for Tomorrow* and a future commercial fixture design competition
- Technology demonstrations/procurements
- CALiPER testing
- Technical information development/dissemination
- Standards and test procedure support
- Market studies and technology evaluations.

Significant updates for 2008 (not covered in other sections of this report) include implementing technology procurements, a process used successfully by DOE in recent years to help establish new technologies in the marketplace. "We help organize large buyers and use their buying power to pull new products into the marketplace. We work collaboratively to develop technical specifications for products that would meet their needs and then we reflect those needs in the RFPs we issue to manufacturers."

In addition, the DOE Gateway Demonstration Program is developing consortia or user groups (e.g., municipalities, academia, retailers) organized around similar lighting needs to develop joint projects and specifications and communicate with manufacturers.

Another significant update involves the new competition for "Bright Tomorrow Lighting Prizes," established by the energy legislation passed in December 2007. Ledbetter explained that "DOE will issue an RFP asking manufacturers to submit proposals for products that meet very rigorous technical specifications. We want to find products that are highly likely to meet the needs of buyers."

Ledbetter highlighted key SSL standards and test procedures nearing completion, including IESNA LM-79 (photometric measurement), IESNA LM-80 (lumen depreciation), and ANSI C78-377A (chromaticity). He also mentioned a design guide, jointly developed by DOE and IESNA, that will provide lighting designers with key information on SSL technology and characteristics to be considered in designs. Publication is expected in 2008. More information on SSL standards is available at http://www.netl.doe.gov/ssl/usingLeds/measurement-series-standards.htm.

The DOE Technical Information Network for SSL holds monthly planning committee meetings. The planning committee is made up of energy efficiency organizations including the Consortium for Energy Efficiency and Northeast Energy Efficiency Partnerships. In 2008, DOE anticipates hosting 6-7 webcasts, developing 10 new technology fact sheets, and developing parallel website content for end-users.

DOE also plans to commission new market studies and technical evaluations such as a life cycle environmental analysis of SSL, studies on cost-effectiveness of SSL for specific applications, and further analysis of lessons learned from CFL market introduction. “We didn’t ask yet: ‘How would we best apply the CFL Lessons Learned to SSL?’ We will be doing that now.”

Ledbetter concluded by mentioning the DOE SSL Market Introduction Workshop, “Voices for SSL Efficiency 2008,” scheduled for July in Portland, Oregon. More details will be available soon on the DOE SSL website.

5.2 ENERGY STAR® Criteria for SSL Update

Richard Karney, DOE’s ENERGY STAR Program Manager, presented an update on the ENERGY STAR criteria for SSL. ENERGY STAR is a voluntary energy-efficiency labeling program that helps consumers identify products that save energy, relative to standard technology. It is designed to set industry-wide specifications for SSL products and to ensure the quality of all products bearing its mark, and as Karney stated, “to provide consumers with a floor of what we consider good, cost effective products.” DOE released the ENERGY STAR criteria for SSL products in September 2007, with an effective date of September 2008, contingent upon related standards and test procedure finalization.

The ENERGY STAR criteria for SSL specify a transitional two-category approach for both residential and commercial lighting applications. Category A covers near-term niche applications, where SSL can be appropriately applied today. Category B establishes a future efficacy target for all applications, which will take effect as SSL technology improves. At some point in the next three to five years, Category A will be dropped, and Category B will become the sole basis for ENERGY STAR criteria. This transitional approach recognizes the rapidly evolving pace of SSL technology developments, yet allows early participation of a limited range of SSL products for directional lighting applications in Category A.

Category A niche applications include undercabinet kitchen and shelf-mounted task lighting, portable desk/task lighting, recessed downlights, outdoor porch, step and pathway lights. These seven applications are the first that will be eligible to qualify for the ENERGY STAR label. Category B will cover innovative SSL systems of all types.

The DOE ENERGY STAR criteria for SSL focus on luminaire efficacy as the key metric, based on the soon-to-be-released IESNA LM-79 test procedure in development. Luminaire efficacy is defined as luminaire light output divided by driver input power, or as Karney noted, “Light leaving the luminaire, or what the consumer will see.” Karney also detailed the overall requirements for CCT, color spatial uniformity, color maintenance, CRI, off-state power, warranty, and thermal management.

Karney described the ENERGY STAR qualification process, which includes lumen depreciation testing based on the soon-to be released LM-80 procedure. The “Product Group Qualification

Process" allows an applicant to define grouping of similar products and provide one luminaire to represent the product family. If this representative product passes, all of the proposed grouping will receive ENERGY STAR qualification. Karney stated that luminaire fixture manufacturers must participate in the quality assurance testing process to ensure products meet or exceed customer expectations. This process is designed to label quality products that pass the quality assurance testing, and to disqualify product failures.

Karney concluded by showing the proposed timeline for program implementation.

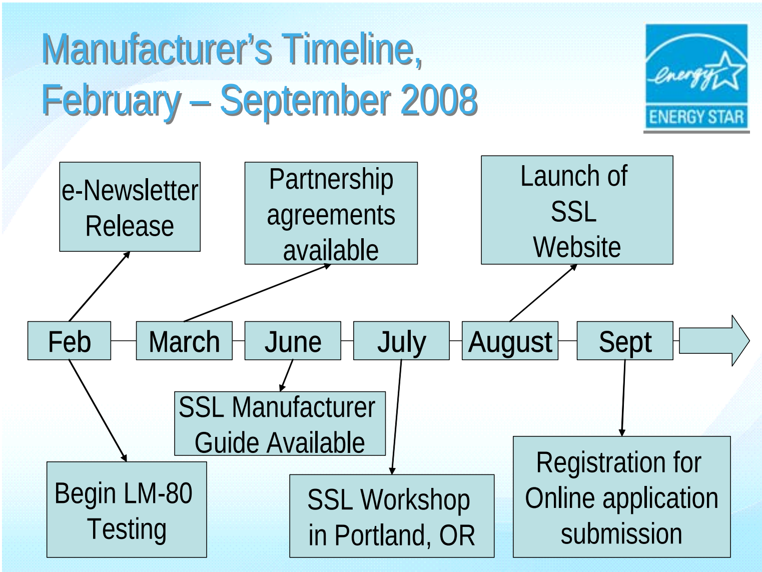


Figure 5-1: SSL Manufacturer's Timeline for ENERGY STAR Qualification

More details on program implementation and the qualification process will be posted soon at http://www.netl.doe.gov/ssl/energy_star.html.

5.3 DOE CALiPER Program – The Latest Test Reports and Analysis

Mia Paget, Pacific Northwest National Laboratory

Mia Paget of PNNL gave an update on DOE's CALiPER Program, which supports testing of commercially available SSL products for the general illumination market, including luminaires and replacement lamps (white light), indoor and outdoor, and residential and commercial products.

CALiPER test results provide unbiased product performance information, guiding DOE planning for R&D, Gateway Demonstration, and ENERGY STAR initiatives, and informing the development of industry standards and test procedures. The test results also serve to discourage low quality products, helping to reduce the risk of buyer dissatisfaction from products that do not perform as claimed.

Paget provided an overview of CALiPER test results from Rounds 1 through 4. More than 70 products have been tested to date, with a focus on overall luminaire performance. CALiPER testing measures the luminaire as a complete system, based on IESNA draft standard LM-79 for photometric testing. The testing is based on absolute photometry rather than relative photometry, and Paget observed that not all stakeholders are familiar with these new testing paradigms. "Absolute photometry is a new paradigm, a new way of thinking. One of our roles is to help people get comfortable with that concept."

Paget offered detailed analysis of SSL downlight performance and benchmarking to CFL, incandescent, and halogen downlights; T8 and MR16 replacement lamp performance; task lamp performance; and outdoor luminaire performance comparisons. In conclusion, she noted that test results vary widely; some products perform very well, while others fall short of their product claims. Manufacturer product literature is not always consistent nor reliable. Paget's recommendations:

- Be careful not to generalize
- Be informed
- Request luminaire testing results.

In Paget's appraisal, a number of positive influences have come about as a direct result of CALiPER testing, including increased industry awareness and discussion, and improvements in SSL product literature. CALiPER testing also provides input to validate and refine new standards and test procedures for SSL. At the CALiPER Roundtable in November 2007, standards setting organizations and testing laboratories provided input on the status of product testing and suggestions for additional standards needed. The Roundtable report is available at: www.netl.doe.gov/ssl/comm_testing.htm.

Paget concluded by reminding attendees that CALiPER Summary Reports and detailed test results are available via the DOE SSL website at www.netl.doe.gov/ssl/comm_testing.htm.

6. DOE Technology Demonstrations

6.1 Oakland, Atlantic City, and Others

My Ton, Pacific Northwest National Laboratory

PNNL's My Ton reported on the progress of DOE's SSL Technology Demonstration Gateway Program, focusing on lessons learned from 2007 and growth to date. Regarding the program's scope and process, Ton explained that it supports demonstrations of high-performance SSL products in order to develop empirical data and experience with in-the-field applications. The intent is to provide a source of independent, third-party data for use in decision-making by lighting users and professionals. However, Ton noted, data should be considered in combination with other information relevant to the particular site and application under examination. Each Gateway Demonstration compares one SSL product against the incumbent technology used in that location. Depending on available information and circumstances, the SSL product may also be compared to alternate lighting technologies. Ton urged audience members seeking fuller program details to visit www.netl.doe.gov/ssl/techdemos.htm.

Progress has been made in a number of areas, Ton stated, including a completed street lighting project with the City of Oakland and Pacific Gas and Electric (PG&E) and a walkway/area lighting project at the Federal Aviation Administration (FAA) office in New Jersey, as well as team and product selections for a USPS outdoor lighting project now. In addition, significant interest is coming from the federal and private sectors, including the Armed Forces and various utilities. A number of submitted products have been through testing at independent laboratories.

Ton also noted programmatic advancements, including development of consortia and a change in DOE's approach to the Gateway process to "better adapt to the rate of technology change." The consortia or user groups will organize around similar lighting needs to develop joint projects and specifications and communicate with manufacturers. Program changes are designed to streamline the proposal evaluation process and accelerate implementation of demonstrations. Changes include an open solicitation timeframe with no deadlines and compressed project schedules. In addition, non-DOE demonstrations meeting minimum requirements will be eligible for inclusion in the Gateway Demonstration Program. "We have been receiving four-to-six applications a month so far," Ton reported. Projects under development include parking garage lighting, residential downlights, undercabinet lighting, and other outdoor applications.

Ton then detailed select results from completed demonstrations that make clear that "well-designed SSL products can outperform incumbents. For example, we have better consistency of color."

	HPS Luminaires	LED Luminaires
Sample 1	1851	6284
Sample 2	1965	6212
Sample 3	2156	6269
Average	***1991***	***6255***

Figure 6-1: Color Correlated Temperature: LEDs versus HPS

“Economics are key,” Ton continued, “so product costs remain a challenge. High hours of use and the increasing price of electricity may help balance costs, but we need accurate information on maintenance costs for realistic comparisons.”

The complete report on the Oakland Gateway Demonstration project is available on the SSL website at www.netl.doe.gov/ssl/PDFs/EmergingTechReport-LEDStreetLighting.pdf.

6.2 LEDs in Outdoor Lighting

Eric Haugaard and Alan Ruud, Beta LED

Eric Haugaard and Alan Ruud from Beta LED provided a detailed look at the performance characteristics of LEDs for general outdoor illumination. Haugaard began by pointing out that Beta’s goal as a lighting manufacturer is to optimize integration in fixture design and applications, notably in the two key system attributes of thermal management and optical control. Understanding thermal effects on performance can have “dramatic effects on initial system efficacy as well as lumen depreciation and maintenance,” he stated.

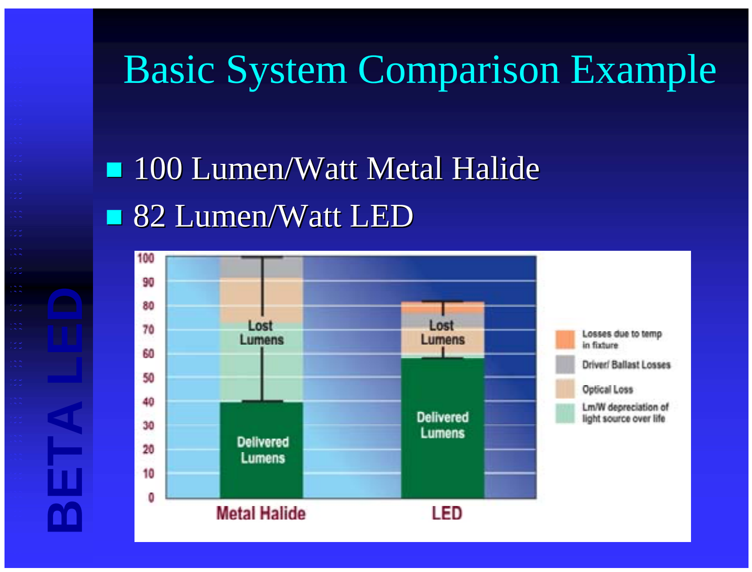


Figure 6-2: Basic System Comparison

Haugaard offered a basic system comparison example between 100 lm/W metal halide and 82 lm/W LED systems, contrasting losses due to fixture temperature, ballast, optics, and depreciation of the light source over life.

“The complete system must be tested,” Haugaard emphasized. “We are always asked ‘How do you compare this to the old stuff – it’s so different?’ Well, a fair comparison can certainly be drawn with a certified photometric test report from an independent agency. Absolute photometry offers very credible data for comparisons between LED and competing systems.”

"We look at life data – lumen depreciation value – for the LED system. This is based on the life of the application, using L70 = end of life limit. Also, any side-by-side performance evaluation must look at appropriate maintenance factors for the competing systems, and you must understand costs." Additional points of comparison include reliability, warranty, serviceability and maintenance, chromaticity selection and variation, and environmental impact factors such as disposal and recyclability.

Alan Ruud then offered a series of detailed application comparisons drawn from Beta LED demonstration projects and installations with LED systems for outdoor lighting. The metal halide/LED parking structure comparison shown in Figure 6.3 makes a compelling case for LEDs. "What we are seeing in these applications is averages of at least 2-to-1 improvements," Ruud stated.

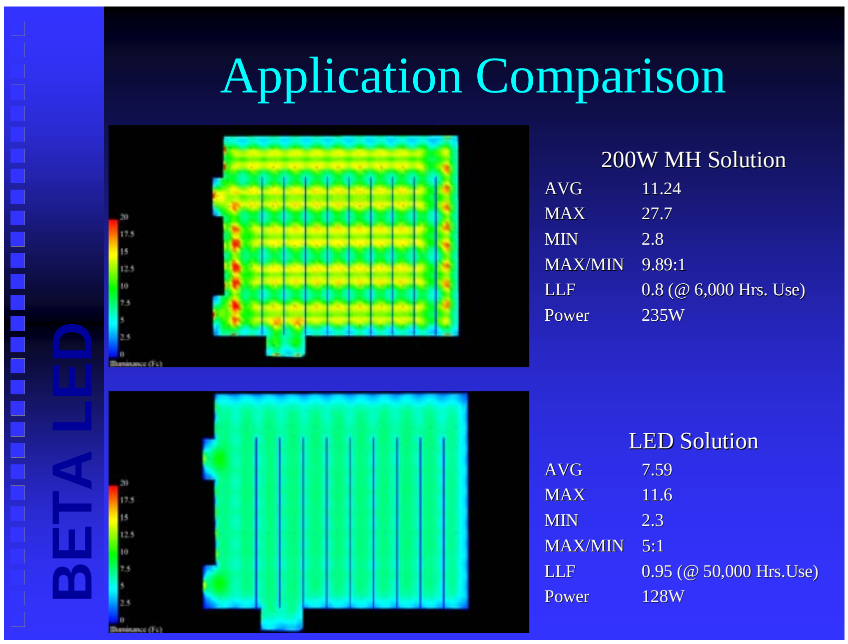


Figure 6-3: Metal Halide/LED Parking Structure Comparison

"Quality is improved [with LEDs] – not just color, but uniformity and where you can put light. This comparison is a typical parking structure with 200W pulse-start metal halides and LEDs. At the top you see where it started with the halides and below, the uniformity of LEDs, with 50% energy savings or better, and longer life."

7. Next Steps

Moving forward, the Department of Energy will continue to work closely with the SSL R&D community, manufacturers, energy efficiency organizations, utilities, and standards generating organizations to speed energy-efficient SSL technologies from lab to market.

In March 2008, DOE released the final version of the updated *Multi-Year Program Plan FY'09-FY'14; Solid-State Lighting Research and Development*. This latest version includes higher near-term efficacy targets for LEDs, new emphasis on luminaire performance, new milestones for LEDs, and some redirection of resources to reflect updated task priorities. For OLEDs, MYPP updates include additional focus on cost and reliability.

DOE anticipates issuing a competitive solicitation for SSL Core Technology Research (Round 5) in April 2008; a solicitation for Product Development (Round 5) will follow in May 2008. In September, DOE's Small Business Innovation Research (SBIR) Program (http://sbir.er.doe.gov/sbir/) will issue its annual solicitation, which includes topics related to solid-state lighting.

DOE's Basic Energy Sciences (BES) Program will also issue a solicitation in 2008, to launch a new initiative that centers around the establishment of Energy Frontier Research Centers (EFRCs). These centers will seek to accelerate the rate of scientific breakthroughs needed to create advanced energy technologies for the 21st century, and will address research needs detailed in 10 recent BES workshop reports, including "Basic Research Needs for Solid-State Lighting." To learn more about the upcoming BES solicitation, see http://www.sc.doe.gov/production/bes/EFRC.pdf .

7.1 Standards and Testing

On the standards front, ANSI released ANSI C78.377, "Specifications for Chromaticity of Solid-State Lighting Products" in March 2008. This new specification will soon be followed by IESNA LM-79, "Approved Method for the Electrical and Photometric testing of Solid-State Lighting Devices," and IESNA LM-80, "Approved Method for Measuring Lumen Depreciation of LED Light Sources." For a complete listing of SSL standards and test procedures in development, see http://www.netl.doe.gov/ssl/standards_dev.html.

Both LM-79 and LM-80 are integral to the new ENERGY STAR criteria for solid-state lighting, issued by DOE in September 2007. The first ENERGY STAR-qualified SSL products are expected on the market in late 2008. Learn more on the SSL website at http://www.netl.doe.gov/ssl/energy_star.html.

DOE's CALiPER program continues to test commercially available LED products, providing unbiased information on product performance. Test results on more than 70 products are available by request at http://www.netl.doe.gov/ssl/comm_testing.htm. DOE anticipates that Round 5 test results will be available in May 2008.

7.2 Opportunities to Partner and Participate

The DOE Gateway Demonstration Program will continue to showcase high-performance SSL products in commercial and residential applications. The program is currently establishing consortia or user groups (e.g., municipalities, academia, retailers) organized around similar lighting needs to develop joint projects and specifications and communicate with manufacturers. To learn more about the consortia, or to download applications for host sites, manufacturers, or utilities/energy efficiency organizations, see http://www.netl.doe.gov/ssl/techdemos.htm.

National design competitions also showcase energy-efficient SSL products. In May, DOE will partner with IESNA and the International Association of Lighting Designers (IALD) to launch the Next Generation Luminaires Competition, which will focus on LED-based commercial luminaires. More information will be available soon at http://www.netl.doe.gov/ssl. In mid-September, the 2008 *Lighting for Tomorrow* design competition winners will be announced at the American Lighting Association Conference in Washington, D.C. Information on the winning residential lighting fixtures will be posted at http://www.lightingfortomorrow.com/.

The new "Bright Tomorrow Lighting Prizes" competition, established by recent energy legislation, will heighten awareness of high-performance SSL products even further. The legislation specifies significant prizes for the development of high-performance products in three categories: a 60W incandescent replacement, a PAR-38 halogen replacement, and a 21st Century Lamp. More details will be announced in mid-2008.

The DOE Technical Information Network for SSL (TINSSL) remains active, with monthly planning committee meetings. In 2008, DOE anticipates hosting 6-7 webcasts, developing 10 new technology fact sheets, and developing parallel website content for end-users. Learn more at http://www.netl.doe.gov/ssl/technetwork.htm.

In March 2008, DOE hosted a Lighting Designer Roundtable on Solid-State Lighting. Co-hosted by IALD and IESNA, the Roundtable provided insights on the designer perspective regarding SSL, and what it will take to achieve viable products and market acceptance. DOE and IESNA also shared a draft design guide to provide lighting designers with key information on SSL technology and characteristics to be considered in designs. Feedback from roundtable participants will be incorporated into the final design guide, and publication is expected in 2008. A report on the Lighting Designer Roundtable will be posted on the DOE SSL website in April.

In July, DOE will host "Voices for Efficiency 2008" in Portland, Oregon. Co-hosted by the Northwest Energy Efficiency Alliance, Energy Trust of Oregon, and Puget Sound Energy, this workshop focuses on market introduction issues and provides a forum for federal, state, and private-sector organizations to work together to shape markets for high-performance SSL products. More details on the workshop will be posted at http://www.netl.doe.gov/ssl.

To stay apprised of DOE SSL program activities, progress, and events, register for ongoing updates at http://www.netl.doe.gov/ssl/index.html.

8. Appendices

APPENDIX A: Workshop Attendee List

APPENDIX B: DOE SSL Program Fact Sheets

- Guiding Technology Advances from Laboratory to Marketplace
- Coordinated Efforts Provide Enabling Knowledge to Advance SSL Technology
- Operational Plan for DOE Solid-State Lighting Research and Development
- Solid-State Lighting Patents Submitted as a Result of DOE-Funded Projects
- Guiding Market Introduction of High Efficiency, High Performance SSL Products
- CALiPER Program Supports Unbiased Testing, Promotes Consumer Confidence
- ENERGY STAR® Criteria for Solid-State Lighting Products
- Competition Recognizes Innovative, Energy-Efficient Residential Lighting Design
- Gateway Demonstrations Showcase LED Product Performance

APPENDIX C: DOE SSL R&D Multi Year Plan – Section 4.0 Draft Update

APPENDIX A: Workshop Attendee List

2008 DOE SOLID-STATE LIGHTING WORKSHOP
Transformations in Lighting
January 29 – 31, 2008
Atlanta, Georgia

Srinath Aanegola
GE Lumination

Richard Abernethy
Dialight

Tom Abt
Utility Solutions

Steven Aggas
NthDegree Technologies

Diane Allard
Akoya

Mehmet Arik
GE Research Center

Edward Bailey
Transducin Optics

Teresa Bair
Cooper Lighting

Bob Baird
Lighting Technologies

Daniel Barton
Sandia National Laboratories

Thomas Benton
Cooper Lighting

Debasis Bera
University of Florida

Rolf Bergman
Rolf Bergman Consulting

Derry Berrigan
DBLD

Joseph Berry
National Renewable Energy Laboratory

Vrinda Bhandarkar
Strategies Unlimited

Robert Biefeld
Sandia National Laboratories

Jean Black
PPL Services Corp.

George Brandes
Cree, Inc.

James Brodrick
U. S. Department of Energy

April Brown
Duke University

Christopher T. Brown
Plextronics

Chantal Brundage
greenTbiz

Anthony Burrell
Los Alamos National Laboratory

Paul Burrows
Pacific Northwest National Laboratory

Mike Burton
ThinkEquity Partners LLC

Julian Carey
LUXIM

Martha Carney
Outsourced Innovation

Megan Carroll
Lighting Sciences Group

Joel Chaddock
National Energy Technology Laboratory

Michael Chan
Digital Optics

Maddanmohan Chawla
MMC Group and Associates

Yong Che
IMRA America Inc.

Liang Y. Chen
Applied Materials, Inc.

Peter Chen
Spelman College

Wayne Chen
Pro Brand International, Inc.

Yong-Seok Choi
University of California, Santa Barbara

WengOnn Choong
ItraMAS Malaysia

Terry Clark
Finelite, Inc.

Isaac Cohen
Texas Instruments

Ilkan Cokgor
Intematix

Michael Colalillo
Cooper Lighting

Michael Coltrin
Sandia National Laboratories

Ronald Content
GO Lighting Technologies Inc.

Keith Cook
Philips Lighting

James Creighton
Sandia National Laboratories

Steven Crimi
Light Emotions Design, LLC

Jim Crockett
Architectural SSL Magazine

Brian Crone
Los Alamos National Laboratory

John Curran
LED Transformations, LLC

Dan Curry
Optimation Technology Inc.

Brian D'Andrade
Universal Display Corporation

J. Lynn Davis
RTI International

Robert Davis
Carnegie Mellon University

James Decker
Hubbell Lighting, Inc.

Daryl DeJean
PG&E

TJ Dejony
Exclara

Andrea Denver
Pacific Gas & Electric

Menko Deroos
Xicato

Gerald DiBattista
Bayer MaterialScience

Vic Diegues
Cooper Lighting

Deepak Divan
Georgia Institute of Technology

Brian Dlugosch
AIXTRON Inc.

Dhaval Doshi
Cabot

Brian Dotson
National Energy Technology Laboratory

Kevin Dowling
Color Kinetics/NGLIA

Dan Doxsee
Nichia America Corporation

Andre Duljas
Sea Gull Lighting

Chad Duty
Oak Ridge National Laboratory

David Edwards
Intertek ETL

Ryan Egidi
National Energy Technology Laboratory

Jeffrey Elam
Argonne National Laboratory

Ian Ferguson
Georgia Institute of Technology

Arthur Fischer
Sandia National Laboratories

Greg Frankiewicz
Energy Focus, Inc.

Donald Fudge
Northeast Energy Efficiency Partnerships

Tai Fukizawa
Enplas USA

James Gaines
Philips

Thomas Geier
3M Company

Leo Geng
CAO Group, Inc.

David Geohegan
Oak Ridge National Laboratory

Bruce Gnade
The University of Texas at Dallas

Michael Grather
Luminaire Testing Laboratory, Inc.

Derek Greenauer
D&R International

Zachary Griffin
Energy Efficient Equipment

Joseph Gullo
GE Lumination

Mike Hack
Universal Display Corporation

John Halliwell
Electric Power Research Institute

Jung Han
Yale University

Chris Han-Adebekun
Air Products and Chemicals

Monica Hansen
Cree SBTC

Uwe Happek
The University of Georgia

Shawn Harmon
Television Production Service

Benjamin Haskell
Inlustra Technologies, LLC

Eric Haugaard
Ruud Lighting

Todd Heller
Ad-Tech International, Inc.

Paul Hergenroeder
ALCOA

Sylvia Herman
Cooper Lighting

Jose-Luis Hernandez
Canadian Standards Association, CSA

Richard Herring
Texas Instruments

Donald Hirsh
Bright View Technologies, Inc.

Angela Hohl-AbiChedid
OSRAM SYLVANIA

Matthew Holland
Eastman Kodak Company

Bin Hu
University of Tennessee

Evelyn Hu
University of California

Andrew Huang
American Technology Research

Daniel Huang
Enplas USA

Li Huang
Carnegie Mellon University

Greg Huebner
Peak Materials

Bette Hughes
Akoya

James Ibbetson
Cree SBTC

Mel Interiano
OSRAM SYLVANIA INC.

Ilia Ivanov
Oak Ridge National Laboratory

Taylor Jantz-Sell
D&R International

Vikram Jatania
Envirosys International

Andre Javier-Barry
D&R International

Peng Jiang
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Jianzhong Jiao
Osram Opto Semiconductors

Keith Kahen
Eastman Kodak Company

Guy Kallman
3M Company

John Kania
Applied Materials

Adam Karbaf
Fulham Co., Inc.

Richard Karney
U.S. Department of Energy

Rick Kauffman
Kauffman Consulting, LLC

Philip Keebler
Electric Power Research Institute

John Kendall
Pro Brand International, Inc.

Garo Khanarian
Rohm and Haas

Alex Kinnier
Khosla Ventures

Glenn Kohnke
Corning Incorporated

Daniel Koleske
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David Konkle
City of Ann Arbor

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Arrow Electronics

Samantha LaFleur
Atelier Ten

Chad Landrum
Cooper Lighting

Susan Larson
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Brandon Leafblad
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Marc Ledbetter
Pacific Northwest National Laboratory

Leslie Levine
Les Levine

An-Ping Li
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Dr. Jian Li
Arizona State University

Nola Li
Georgia Institute of Technology

Bryan Ligman
Dynamic Building Consulting

Ir Bernard Lim
ItraMAS International

Gao Liu
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Georgia Institute of Technology

Laurie Lockliear
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Craig Lofton
LLF

Stephen Love
Oikovest

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Fernando Lynch
Permlight Products

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CAO Group, Inc.

Madhav Manjrekar
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Samuel Mao
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Karen Marchese
Akoya

Thomas Marchok
Intel Capital

Brian Marinik
Dow Corning Corporation

Jim Marquardt
SRP

James Martin
Sandia National Laboratories

Mathew Mathai, Ph.D.
Plextronics

Mary Matteson Bryan
Pacific Gas & Electric

Fred Maxik
Lighting Science Group

Lawrence Mazer
Exclara

Mark McClear
Cree, Inc.

T. Mark McCleskey
Los Alamos National Laboratory

Michael McGehee
Lighting Technologies

Noam Meir
Oree

Andrew Melton
Georgia Institute of Technology

Hisham Menkara
PhosphorTech

Alexander Mikhailovsky
University of California, Santa Barbara

Andrew Minor
Lawrence Berkeley National Laboratory

Kailash Mishra
OSRAM SYLVANIA

Martin Moeck
Osram Opto Semiconductors

Andrew Moran
Avago Technologies

Thomas Morris
PhosphorTech

G. R. Mortenson
QuNano Inc.

Donald Mulvey
ROAL Electronics

Edward Nash
Actown Sign Products

Jeff Nause
Cermet, Inc.

Aaron O'Brien
Pure Lighting

James O'Connor
Carclo Technical Plastics

Mohammad Omary
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LED Lighting Fixtures, Inc.

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Oak Ridge National Laboratory

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greenTbiz / LED City Toronto

Asanga Padmaperuma
Pacific Northwest National Laboratory

Mia Paget
Pacific Northwest National Laboratory

Steven Paolini
Telelumen LLC

Adam Partee
Energy Efficient Equipment

Ellis Patrick
Cooper Lighting

Paul Pattison
SSLS, Inc.

Jason Paulsel
Cooper Lighting

Dennis Pearson
Tempo Industries, Inc.

Michael Petagna
ROAL ELECTRONICS

Petko Petkov
Georgia Institute of Technology

Edward Petrow
Lincoln Technical Services, Inc.

Oanh Pham
3M Company

Paul Phillips
LSI Industries

Kyle Pitsor
NEMA

Dewey Pitts
Ad-Tech International, Inc.

Lisa Porter
Carnegie Mellon University

Chris Primous
ICF International

Wendy Priolo
CRS Electronics

Mark Pugh
Xicato

Jeff Quinlan
Acuity Brands Lighting

Ramachandran Radhakrishnan
Materials Modification, Inc.

David Ramer
Renaissance Lighting, Inc.

James Reginelli
GE Lumination

Michael Reznikov
Physical Optics Corporation

Scott Riesebosch
CRS Electronics

Spilios Riyopoulos
SAIC

Victor Roberts
Roberts Research & Consulting, Inc.

Lauren Rohwer
Sandia National Laboratories

Dr. Harry Ross
AVP

Gordon Routledge
Dialight

Alan Ruud
Ruud Lighting

Timothy Sands
Purdue University

Linda Sapochak
Pacific Northwest National Laboratory

John Schlueter
Argonne National Laboratory

Leo Schowalter
Crystal IS, Inc.

Mark Seitz
Molex

Anant Setlur
GE Global Research

Lin Sheng
Texas Instruments

David Shepard
LUXO

Joseph Shiang
GE Global Research

Paul Shnitser
Physical Optics Corporation

Cecilia Shou
Pro Brand International, Inc.

Philip Shou
Pro Brand International, Inc.

Frank Shum
Frank Shum Consulting

Olin Sibert
Oxford Systems, Inc.

Dr. Gary S. Silverman
Arkema Inc.

Jerry Simmons
Sandia National Laboratories

Dave Simon
ilumisys

Jasprit Singh
University of Michigan

Bob Smith, PE
Cooper Lighting

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Franky So
University of Florida

James Speck
University of California, Santa Barbara

Ron Steen
Philips

Heidi Steward
Pacific Northwest National Laboratory

Andrew Stockham
MEMS Optical

Matthew Stough
OSRAM SYLVANIA

Todd Straka
Intertek

Peter Strasser
International Dark-Sky Association

Christopher Summers
PhosphorTech

Nicolas Sunderland
Bayer

David Sypes
Philips Lighting

Ford Tamer
Khosla Ventures

Ruth Taylor
Pacific Northwest National Laboratory

Jack Thomas
Thomas Lighting

Gerry Thornton
Hadco Lighting

Paul Thurk
ARCH Venture Partners

Andrew Timmerman
Fairfield Crystal Technology

My Ton
Pacific Northwest National Laboratory

George Townsend
LumiTrak, Inc.

Bruce Trimbur
Trimbur Group

Gary Trott
LED Lighting Fixtures Inc.

Ralph Tuttle
Cree, Inc.

Howard Tweddle
Group IV Semiconductor

Yuan-Sheng Tyan
Eastman Kodak Company

Anand Upadhyay
Philips

David Veazie
Clark Atlanta University

Dr. Thomas Vogt
USC NanoCenter

Peter Wagner
Powerbox USA

Karen Waldrip
Sandia National Laboratories

George T. Wang
Sandia National Laboratories

Shaoping Wang
Fairfield Crystal Technology

Shen-Jie Wang
Georgia Tech ECE

Derral Ward
Howard Lighting Products

Charles Warren
ALCOA

Michael Webb
Permlight Products

Ronald Weber
Tyco Electronics

Warren Weeks
Permlight Products

William Weidner
Dow Corning Corporation

Frederic Welsh
Radcliffe Advisors

Christian Wetzel
Rensselaer Polytechnic Institute

George Woodbury
Republic ITS

Craig Wright
Progress Lighting

Chao Wu
University of Southern California

Jiangeng Xue
University of Florida

Steven Yang
Kohler Co.

Steffen Zahn
Air Products & Chemicals, Inc.

David Zaziski
Nanosys Inc.

Yi Zheng
OSRAM SYLVANIA

Brad Zinke
3M Company

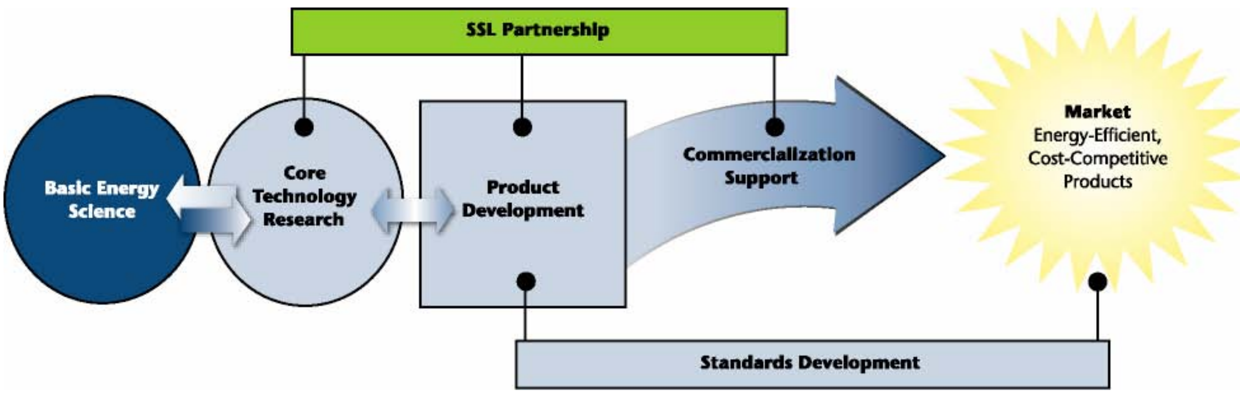
APPENDIX B: DOE SSL Program Fact Sheets

Guiding Technology Advances from Laboratory to Marketplace

The U.S. Department of Energy's solid-state lighting (SSL) portfolio draws on the Department'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, Commercialization Support, Standards Development, and an SSL Partnership.

Basic Research Advances Fundamental Understanding. Projects conducted by the Basic Energy Sciences program focus on 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.

DOE SOLID-STATE LIGHTING PORTFOLIO



- DOE's **Basic Energy Sciences** program conducts basic research to advance fundamental understanding of materials behavior. Project results often have multiple applications, including SSL.
- **Core Technology Research** projects focus on applied research for technology development, with particular emphasis on meeting efficiency, performance, and cost targets.
- **Product Development** projects focus on using the knowledge gained from basic or applied research to develop or improve commercially viable materials, devices, or systems.
- To ensure that these investments lead to SSL technology commercialization, DOE has drawn on its ongoing relationships with the SSL industry and research community to develop appropriate **Commercialization Support** strategies.
- In addition, DOE is working with the National Electrical Manufacturers Association (NEMA), the Next Generation Lighting Industry Alliance (NGLIA), and other standards setting organizations to accelerate the **Standards Development** process.
- The **SSL Partnership** provides input to enhance the manufacturing and commercialization focus of DOE's SSL portfolio.

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.

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 the success of the proposed product. Project activities range from product concept modeling through development of test models and field-ready prototypes.

Commercialization Support Activities Facilitate Market Readiness. To ensure that DOE investments in Core Technology Research and Product Development lead to SSL technology commercialization, DOE has also developed a national strategy to guide market introduction of SSL for general illumination. Working with the SSL Partnership and other industry and energy organizations, DOE is implementing a full range of activities, including:

- Testing of commercially available SSL products for general illumination
- Technology demonstrations showcasing high-performance products in commercial and residential applications and providing real-world experience and data on performance and cost effectiveness
- 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
- ENERGY STAR® designation for SSL technologies and products
- Design competitions for lighting fixtures and systems using SSL
- Technical information resources on SSL technology issues, test procedures, and standards
- 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 SSL Partnership provides input to shape DOE 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 the Illuminating Engineering Society of North America (IESNA), NEMA, NGLIA, the American National Standards Institute (ANSI), 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 are expected to be issued in early 2008.

Coordinated Efforts Provide Enabling Knowledge to Advance SSL Technology

To accelerate solid-state lighting (SSL) technology developments, the U.S. Department of Energy (DOE) leverages the strengths and capabilities of the Office of Science and the Office of Energy Efficiency and Renewable Energy (EERE).

- The Basic Energy Sciences (BES) program within the Office of Science conducts basic research to advance fundamental understanding of materials behavior, with the goal of impacting future directions in applied research and technology development.
- EERE's SSL portfolio guides technology advances from laboratory to marketplace with a comprehensive approach that includes Core Technology Research, Product Development, Commercialization Support, and Standards Development. Core Technology Research focuses on applied research for technology development, with the goal of meeting performance and cost targets.

Through coordination and collaboration, these DOE research programs are working together to provide the scientific foundation for new forms of lighting. In February 2006, BES held a Contractors' Meeting in conjunction with the DOE SSL Program Planning Workshop. BES researchers shared project updates on BES-supported fundamental research related to SSL. The workshop also included presentations on all DOE-funded SSL projects, providing a snapshot of DOE's SSL R&D portfolio and opportunities for further discussion and potential partnerships. In May 2006, BES hosted a workshop to focus specifically on identifying basic research needs and challenges that impact on energy-efficient SSL. The complete BES workshop report is available for download at www.science.doe.gov/bes/reports/files/SSL_rpt.pdf. The research directions identified in this report provide additional guidance for DOE planning.

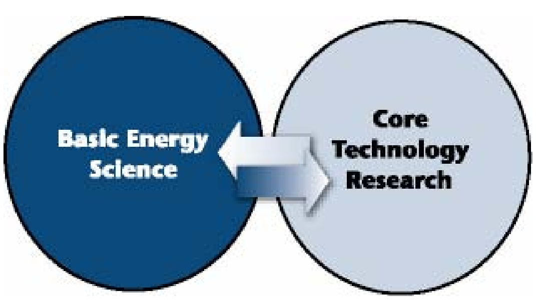
DOE SSL RESEARCH

Basic Research to Advance Fundamental Understanding

Focus
Basic scientific questions underlying materials behavior

Deliverables
Knowledge of physical, chemical, and materials sciences that enables development of new synthesis techniques and novel materials

Characterization capabilities to support these investigations



Applied Research for Technology Development

Focus
Technical targets for performance and cost

Deliverables
Materials and components for SSL technologies that meet efficiency, performance, and cost targets

Basic Research Advances Fundamental Understanding

BES projects focus on 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. BES encourages the development of results from its experimental and theoretical research programs and user facilities that will impact future directions in applied research and technology development. Project results often have multiple applications, including SSL.

Core Technology Research Focuses on Technical Targets

EERE's SSL portfolio draws on its long-term relationships with the SSL industry and research community, using a series of ongoing, interactive workshops to refine an extensive R&D agenda. This approach ensures that DOE funds the appropriate research topics that will improve efficiency and move SSL into the market. Input from these workshops helps to shape research priorities and the development of solicitations. Core Technology Research projects focus on applied research for technology development, with particular emphasis on improving the performance and durability of materials and components, as well as cost reduction.

DOE Drives Emphasis on Energy Efficiency

DOE's support of SSL is essential to ensure the development of *energy-efficient* SSL technology—an emphasis that, without DOE leadership, might be lost on the path to commercialization. The Department's involvement in SSL technology development pushes industry to higher levels of efficiency than they might otherwise achieve.

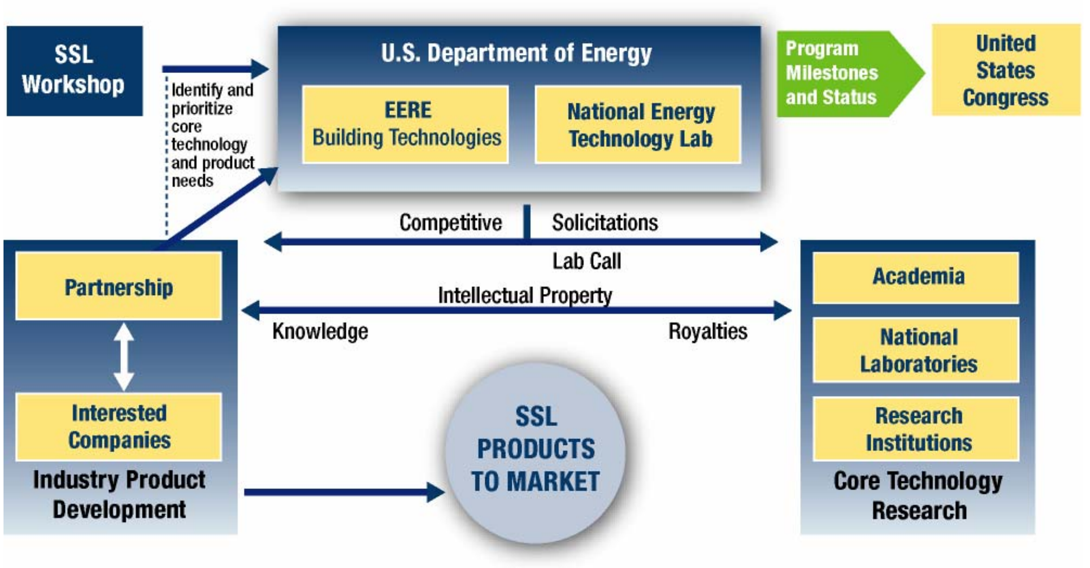
The Department's support also maintains our nation's technology leadership. While projected energy savings are significant, high efficiency white-light sources represent a somewhat risky investment that industry is unlikely to fund exclusively. If our nation is to maintain its leadership position in SSL technology development, the U.S. must meet or exceed other countries' commitment to SSL initiatives. The results from DOE's collaborative projects will ultimately deliver substantial energy savings and position U.S. companies as global leaders in new lighting products, systems, and service markets.

Operational Plan for DOE Solid-State Lighting Research and Development

The U.S. Department of Energy (DOE) supports domestic research, development, demonstration, and commercial application of advanced solid-state lighting (SSL) technologies that are significantly more energy efficient than current lighting technologies. 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. DOE has set aggressive targets for SSL research and development (R&D): By 2025, to develop advanced SSL technologies that, compared to conventional lighting technologies, are much more energy efficient, longer lasting, and cost-competitive. DOE is targeting a product system efficiency of 50 percent with lighting that accurately reproduces sunlight spectrum.

DOE has structured an operational plan for SSL R&D (see Figure 1) that features two concurrent, interactive pathways. **Core Technology Research** is conducted primarily by academia, national laboratories, and research institutions. **Product Development** is conducted primarily by industry. Although the pathways and participants described here are typical, some crossover does occur. For example, a product development project conducted by industry may include focused, short-term applied research, as long as its relevance to a specific product is clearly identified and the industry organization abides by the solicitation provisions. For more detailed definition of the SSL R&D pathways, see DOE's SSL website at *www.netl.doe.gov/ssl/definition.html*. The operational structure also includes innovative intellectual property provisions and an **SSL Partnership** that provides significant input to shape Core Technology Research and Product Development priorities.

OPERATIONAL PLAN FOR SSL R&D (Figure 1)



SSL Partnership. In 2004, DOE competitively selected an SSL Partnership composed of manufacturers and allies that are individually or collaboratively capable of manufacturing and marketing the desired SSL products. Partnership members must comply with pertinent DOE guidelines on U.S.-based research and product development. A key function of the SSL Partnership related to R&D is to provide input to shape Core Technology Research and Product Development priorities. As SSL technologies mature, identified research gaps are filled through Core Technology Research—allowing the SSL industry to continue the product development process, while much-needed breakthrough technologies are created in parallel. The Partnership members confer among themselves and communicate technical guidance to DOE program managers, who in turn use this feedback and input from DOE workshop participants to shape DOE SSL R&D solicitations.

Core Technology Research. Core Technology Research provides the focused research needed to advance SSL technology—research that is typically longer-term in nature and not the focus of sustained industry investment. DOE funds these research efforts primarily at universities, national laboratories, and other research institutions through one or more competitive solicitations. Core Technology Research supports the SSL program by providing problem-solving research to overcome technical barriers. Participants in the Core Technology Research 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. Core Technology Research projects are subject to peer review by DOE.

Product Development. DOE solicits proposals from interested companies (or teams of companies) for product development, demonstrations, and market conditioning. 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 offerors must not only have all the technical requirements to develop the desired SSL technology, but also must have reasonable access to manufacturing capabilities (substantially in the U.S.) and targeted markets identified to quickly move their SSL product from the industry laboratory to the marketplace. Product Development projects are subject to peer review by DOE.

High-Level Timeline. Figure 2 details the high-level timeline for the SSL R&D operational plan. Each year, DOE expects to issue at least three competitive solicitations: the Core Technology Research Solicitation, Core Technology to National Labs (Lab Call), and the SSL Product Development 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 DOE SSL R&D projects
- Provide individual project reviews by DOE

R&D OPERATIONAL PLAN PROCESS (Figure 2)

This document provides an overview of the high-level structure of the DOE SSL R&D program. More detailed program documents, such as annual solicitations and cooperative agreements, take precedence over information in this document.

Solid-State Lighting Patents Submitted as a Result of DOE-Funded Projects

As of January 2008, a total of eighteen solid-state lighting (SSL) patents have been granted as a result of Department of Energy-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 71 patent applications have been applied for or awarded as follows: large businesses – 40; small businesses – 15; universities – 13; and national laboratories – 3.

Organization	Title of Patent Application (Bold title indicates granted patent)
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
	Two other patent applications filed.
Eastman Kodak	Five 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.

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**
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	One patent application filed.
University of California, Santa Barbara	**Plasmon Assisted Enhancement of Organic Optoelectronic Devices**
	Silicone Resin Encapsulants for Light Emitting Diodes
	Four other patent applications filed.
University of Southern California	Fluorescent Filtered Electrophosphorescence

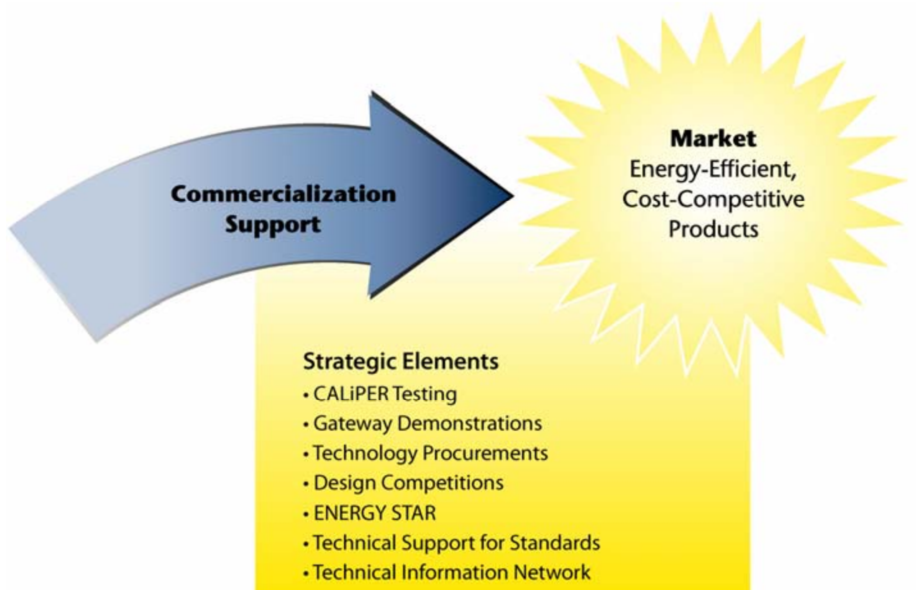
Guiding Market Introduction of High Efficiency, High Performance SSL Products

The U.S. Department of Energy (DOE) has developed a comprehensive national strategy to guide solid-state lighting (SSL) technology from lab to market. To leverage DOE's $100 million investment in SSL technology research and development (R&D), 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

DOE SSL PATHWAYS TO MARKET



DOE Commercialization Support Plan

DOE's plan focuses federal resources on strategic areas that foster the market for high-performance solid-state lighting products.

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. www.netl.doe.gov/ssl/comm_testing.htm

Technology Demonstration Gateway. 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. www.netl.doe.gov/ssl/techdemos.htm

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 undercabinet fixture, and an outdoor wall lantern. 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, with an effective date of September 2008, contingent on related standards and test procedure finalization. www.netl.doe.gov/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 are expected to be issued in early 2008. www.netl.doe.gov/ssl/standards_dev.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. www.netl.doe.gov/ssl/technetwork.htm

CALiPER Program Supports Unbiased Testing, Promotes Consumer Confidence

Solid-state lighting (SSL) technologies are changing and improving rapidly as a growing stream of new products is introduced to market. Industry groups, standards setting organizations, and the U.S. Department of Energy (DOE) are moving quickly to develop and implement needed standards and test procedures for SSL products. At the same time, there is a need for reliable, unbiased product performance information in the dynamic early years of a developing market.

DOE's Commercially Available LED Product Evaluation and Reporting (CALiPER) Program (formerly the Commercial Product Testing Program) addresses that need. CALiPER test results guide DOE planning for R&D, technology demonstration, procurement, and ENERGY STAR® initiatives; convey objective product performance information to the public; and inform the development and refinement of standards and test procedures for SSL products.

Launched in October 2006, CALiPER supports testing of a widely representative array of SSL products available for general illumination, using test procedures currently under development by standards organizations. Guidelines for selecting products for testing ensure that the overall set of tests delivers insights across a range of lighting applications, product categories, and performance characteristics, a mix of manufacturers and devices, and variations in geometric configurations that may affect testing and performance. In addition, CALiPER testing measures variability across units and establishes benchmarking data with respect to other light source technologies and LED thermal management.

Testing Procedures and Methods

Products selected for the CALiPER Program are purchased and sent to qualified independent lighting testing laboratories. All luminaires are tested with both spectroradiometry and goniophotometry, along with temperature measurements (taken at the hottest accessible spots on the luminaire) and off-state power consumption. Standardized procedures are used for the tests, including the new LM-79 draft standard for electrical and photometric measurement of SSL products. The Illuminating Engineering Society of North America (IESNA) expects to finalize and issue LM-79 by early 2008.

Why CALiPER?

- Solid-state lighting is different from traditional sources.
- Existing standards and test procedures are not appropriate for evaluating SSL products.
- New standards and test procedures for evaluating LED-based luminaires (light source and fixture) are in development.
- CALiPER results help industry develop, understand, and implement a new way of testing.
- CALiPER results support DOE planning.
- Credible performance information is needed to avoid early buyer dissatisfaction and delay of market development.

Manufacturers of tested products are given the opportunity to comment on test results prior to report completion. Testing results, summaries, and analysis are then distributed via the DOE SSL website. The Department allows its test results to be distributed in the public interest for noncommercial, educational purposes only. Detailed test reports can be requested by users who provide their name, affiliation, and confirmation of agreement to abide by DOE's "No Commercial Use" Policy.

Performance Characteristics Studied Under CALiPER

- **Light Output and Distribution**
  - Luminaire output (lumens)
  - Luminaire efficacy (lumens/watt)
  - Intensity distribution curves
- **Color Qualities**
  - Spectral power distribution
  - Correlated color temperature
  - Color rendering index
  - Spatial distribution of color
- **Reliability**
  - Thermal management
  - Lumen depreciation
  - *In situ* performance
- **Electrical Characteristics**
  - Power factor
  - Off-state power use

Early Results

CALiPER testing to date has revealed a wide range of performance, from poor to excellent. Some SSL products tested deliver light output and efficacies that equal or exceed comparable incandescent and CFL products. Others perform poorly and do not produce enough light output for their intended application to be considered a suitable replacement for any similar product in use today.

The great divergence in applications and performance characteristics highlights the need for buyers to consider the performance of each product separately and to require clear and accurate luminaire performance information from manufacturers. While some manufacturers are publishing credible values for luminaire output and efficacy, there is often wide disparity between performance claims in marketing literature and actual tested luminaire performance. The need for reliable standards, credible testing, and accurate information—both for manufacturers and the public—is clear.

Next Steps

Ongoing CALiPER testing shows notable improvement in each round of testing, underscoring the significant potential of SSL and the rapid pace of technology advances. Luminaire manufacturers continue to integrate improvements in component efficiencies and new LED chips, which lead to improvements in overall luminaire efficacy and color quality. Underlying product characteristics will be strengthened by developing best practices for thermal management, good power quality profiles, and elimination of off-state power consumption. And as manufacturers become aware of the importance of assessing SSL luminaires on overall luminaire performance (i.e., testing of the entire luminaire, including LEDs, drivers, heat sinks, optical lenses, and housing), more reliable product performance information will emerge.

DOE and industry leaders will apply lessons learned to address concerns raised by the subset of products that are underperforming and/or featuring misleading performance claims. DOE anticipates this targeted effort will help pinpoint why some products are underperforming, enabling an industrywide focus on effective improvements in design and associated product literature.

ENERGY STAR® Criteria for Solid-State Lighting Products

ENERGY STAR is a voluntary energy efficiency labeling program that establishes criteria manufacturers can use to promote qualifying products, guiding consumers in making informed decisions about products that save energy, relative to standard technology. Designed to set industry-wide specifications for solid-state lighting (SSL) products and to ensure the quality of all products bearing its mark, final ENERGY STAR criteria for SSL luminaires were released in September 2007, with an effective date of September 2008, contingent on related standards and test procedure finalization.

The ENERGY STAR label is a highly valued and widely recognized mark of energy efficiency, used by the American public to select cost-effective, energy-efficient products. As part of the Department of Energy's national strategy to accelerate market introduction of high-efficiency SSL products, DOE is leading ENERGY STAR management, specification development, and partner relations for SSL luminaires used for general illumination.

The ENERGY STAR criteria for solid-state lighting specify a transitional two-category approach.

- **Category A** addresses near-term applications, where SSL technology can be appropriately applied
- **Category B** establishes a future efficacy target for all applications, which will take effect once SSL technology improves

ENERGY STAR CRITERIA TIME LINE

Category A covers residential, commercial, industrial, and outdoor lighting SSL applications of all types. This category includes near-term products such as undercabinet kitchen, undercabinet shelf-mounted task, portable desk/task, and recessed downlights for residential and commercial applications, outdoor wall-mounted porch, outdoor step, and outdoor pathway lighting. These lighting applications were chosen on the basis of their suitability for solid-state lighting, given the current state of the technology.

Category B covers innovative SSL systems applications of all types, including "free-form" SSL systems, and those incorporated into furniture, buildings, and equipment. This category encompasses a much wider range of future applications that will emerge as the technology matures further, and serves as a target for lighting manufacturers as they develop products over the next several years. SSL products will be able to qualify under Category B approximately three years after the effective date of the criteria.

At some point in the next three to five years, Category A will be dropped, and Category B will become the sole basis for ENERGY STAR criteria. This transitional approach recognizes the rapid pace of SSL technology developments, yet allows early participation of a limited range of products for directional lighting applications in Category A.

DOE intends to periodically review and amend the criteria to parallel technology advances and ensure that criteria remain up-to-date. For more information on DOE ENERGY STAR criteria for solid-state lighting, or to view the complete criteria, see: www.netl.doe.gov/ssl/energy_star.html.

Key Partners in Criteria Development

DOE worked closely with key partners in developing the new ENERGY STAR criteria and the testing procedures upon which the criteria are based, including the Next Generation Lighting Industry Alliance (NGLIA), Illuminating Engineering Society of North America (IESNA), and American National Standards Institute (ANSI). DOE also received extensive advice and useful comments from individual lighting companies, electric utilities, energy efficiency organizations, and others.

NGLIA is an organization of U.S. lighting manufacturers, administered by the National Electrical Manufacturers Association (NEMA), which works with DOE to enhance the manufacturing and commercialization focus of the SSL portfolio. The Alliance provides input to shape research priorities, develop needed standards and test procedures, and support DOE voluntary market-oriented programs such as ENERGY STAR. More information about the Alliance is available at: www.nglia.org.

General Requirements

The principal energy efficiency metric used in the criteria is luminaire efficacy (net light output from the fixture divided by the input power). Additional standards and test procedures necessary to address the nuances of SSL technology are currently being developed by IESNA, ANSI, and other organizations. DOE anticipates the key standards and test procedures will be completed by their respective organizations in early 2008.

More details on the ENERGY STAR requirements and qualification process, along with application forms, will be available on the ENERGY STAR website in early 2008. DOE will also issue periodic updates to stakeholders discussing implementation procedures, submittal dates, and marketing opportunities.

Competition Recognizes Innovative, Energy-Efficient Residential Lighting Design

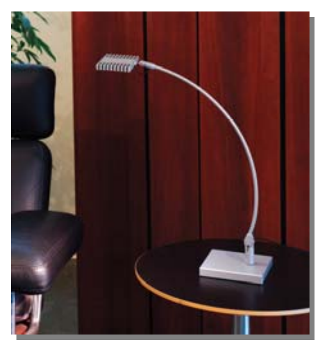
Lighting for Tomorrow encourages technical innovation and recognizes and promotes excellence in the design of energy-efficient residential lighting fixtures. Organized by the American Lighting Association, the U.S. Department of Energy, and the Consortium for Energy Efficiency, the design competition stimulates the market for attractive, energy-efficient residential lighting fixtures that use a fraction of the electricity of standard incandescent fixtures.

By encouraging manufacturers to develop the next generation of innovative, attractive – and energy-efficient – residential lighting fixtures, Lighting for Tomorrow increases market acceptance and awareness of the growing opportunities in energy-efficient lighting. The competition focus extends to marketing, promotion, and sales through primary distribution channels for both new construction and renovation markets. More than two dozen energy efficiency organizations in the U.S. and Canada pledge their support to the competition each year.

The LR6 downlight by LED Lighting Fixtures received the 2007 grand prize.

2007 Solid-State Lighting Winners

Lighting for Tomorrow was launched in 2002, with an initial focus on CFL fixtures. In 2006, a category for solid-state lighting was added, attracting 30 entrants. In 2007, two dozen companies submitted 45 solid-state lighting entries. Grand Prize Winner LED Lighting Fixtures Inc. (LLF) from North Carolina utilized LEDs in an innovative downlight that scored high marks for light output and color quality, with luminaire efficacy exceeding even the most efficient fluorescent downlights available today. California-based Finelite, Inc. won in the portable desk/task and undercabinet lighting categories. Progress Lighting, from South Carolina, won in the outdoor category with its Strata outdoor wall lantern. For more details or purchasing information on the winning products, visit www.lightingfortomorrow.com.



Lighting for Tomorrow 2008

The 2008 Lighting for Tomorrow competition was launched at the Dallas Lighting Market in January 2008. Included this year is a new “Future LED” category that calls for use of the world’s most energy-efficient white LED devices. The 2008 competition categories include:

- **Near-term applications:** Undercabinet, portable desk/task, downlights, and outdoor porch/path/step lighting capable of meeting ENERGY STAR® criteria for solid-state lighting, Category A
- **Other applications:** Additional fixture types including wall sconces, table/floor lamps, pendants, and chandeliers, among others
- **Future LED showcase:** Fixtures that use the most energy-efficient, pre-production LED devices

Judging Criteria

Designs are evaluated on the basis of potential market impact, innovation, and functionality. Specifically in the LED category, judging criteria include lighting quality (color appearance, color rendering, illuminance levels, and distribution), application efficiency, thermal management, and aesthetic appearance.

Bonus points will be given for innovative designs that take advantage of unique LED attributes, fixtures eliminating off-state power consumption, indoor entries capable of dimming, and outdoor entries that are dark-sky friendly. Lighting for Tomorrow judges are drawn from across the lighting industry, creating a diverse panel of experts who sell, design, evaluate, and write about residential lighting design.

Timeline

The deadline for entries in the 2008 competition is April 30. Winners will be announced in September at the ALA Annual Conference in Washington, D.C. Winners gain further visibility and recognition as they are showcased at DOE and industry events, and in various publications. They also become eligible for promotion by energy efficiency programs across the U.S. and Canada.

For complete guidelines and rules for the 2008 competition, see www.lightingfortomorrow.com.

2008 Timeline

- January 2008: **Competition Announced**
- February 29, 2008: **Intent to Submit Forms Due**
- April 30, 2008: **Entries Due**
- May 2008: **Judging**
- September 14-16, 2008: **Winners Announced at ALA Annual Conference**

Gateway Demonstrations Showcase LED Product Performance

The U.S. Department of Energy (DOE) Solid-State Lighting (SSL) Technology Demonstration Gateway Program features high performance SSL products for general illumination in a variety of commercial and residential applications. Results provide real-world experience and data on product performance and cost effectiveness, and connect DOE technology procurement efforts with large-volume purchasers. Performance measures include energy consumption, light output, color consistency, and installation/interface/ control issues.

Demonstration in Oakland, California, with Beta LED streetlights (foreground) and HPS streetlights (background). Photo: Beta LED.

How to Participate

The first "Invitation to Participate" was issued in March 2007. A second invitation followed in November 2007, and remains open through May 2008. 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. Demonstration teams typically include a product manufacturer, a host site, and an energy efficiency organization or local utility where applicable.

- **Manufacturers** provide products for demonstration and may assist in site selection and installation.
- **Host sites** provide locations for demonstrations, assistance with installation and evaluation/measurement, and a willingness to participate in demonstration-related activities such as tours and webcasts.
- **Energy efficiency organizations and utilities** provide contacts with potential host site organizations and assist with related outreach and promotional activities.

Potential participants are encouraged to submit expressions of interest using the application forms available at: www.netl.doe.gov/ssl/techdemos.htm. Team members are not restricted to a single team or a particular project. A large hosting organization might demonstrate products from more than one manufacturer or a single manufacturer might participate with multiple products designed for different applications and locations.

Sharing Results

Results from DOE Gateway demonstrations enable participants to evaluate and refine their lighting requirements before making large-scale purchasing decisions. Demonstration project results are shared through the DOE SSL website, workshops, webcasts, and other demonstration-related activities.

DOE is also interested in working with team members, host site organizations, and other entities to form "user groups" to share information among users with similar needs. Participants in these user groups can join or initiate procurement efforts for high efficiency applications using information gained from demonstration projects, which can result in large scale purchases and/or promotion of featured products. More information on the formation of user groups will be posted on the DOE SSL website in early 2008.

Other Ways to Participate

For parties conducting their own demonstrations and interested in widely sharing results, or for demonstrations already under way and wanting to access available resources, DOE is developing a Demonstration Checklist. Demonstrations meeting the Checklist requirements and/or developed using the Checklist may be able to access DOE support on a case-by-case basis. Successful demonstrations developed through this approach will be promoted via the DOE SSL website, events, and other appropriate venues and means. The Demonstration Checklist will be posted on the DOE SSL website in early 2008.

DOE TECHNOLOGY DEMONSTRATION PROCESS

- **Initial Screening:** Applications received are screened; prospective products and host sites deemed eligible are informed of their eligibility or requested to provide additional information.
- **Participant Team Identification:** Host sites and other team members are identified to carry out the actual demonstration of products.
- **Laboratory Testing:** Concurrent with team identification, testing of sample products is conducted to establish or verify important measures of performance.
- **Installation:** Products are installed with appropriate pre- and post-measurements; demonstration steps are carried out, including any publicity and education events.
- **Evaluation:** DOE's Pacific Northwest National Laboratory evaluates the results, including energy and cost savings and related economic analyses, as well as qualitative occupant and user responses to the installed LED light source.
- **Results Reporting:** Results of successful demonstrations are widely publicized; results from long-term testing are released as they become available. While no sales of demonstrated products are assured, DOE expects large-scale product purchases or promotions by demonstration team members will also occur at this stage for products that have performed to buyers' satisfaction.

APPENDIX C: DOE SSL R&D Multi Year Plan – Section 4.0 Draft Update

(Final version available in PDF format on the SSL website at
http://www.netl.doe.gov/ssl/PDFs/SSLMYPP2008_web.pdf)

Multi-Year Program Plan

Solid-State Lighting Research and Development Portfolio

Draft Section 4.0: Technology Research and Development Plan

FY'08-FY'12

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

Prepared by:
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January 2008

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COMMENTS

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4.0 Technology Research and Development Plan

The U.S. Department of Energy supports domestic research, development, demonstration, and commercialization activities related to SSL to fulfill its objective of advancing energy-efficient technologies. The Department'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.

Improving the efficiency and decreasing the cost of SSL will have a large contribution towards DOE's goal of a net-zero energy building (ZEB). Lighting constitutes approximately 12 percent of residential building energy consumption and 25 percent of commercial building energy consumption. 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. Further technology and cost improvements and market acceptance of SSL technologies will dramatically reduce lighting energy consumption, and thereby the total energy consumption, of residential and commercial buildings by 2025.[1]

A part of the Department'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. Over the next few years, SSL sources will expand their presence in the general illumination market, replacing some of today's lighting technologies. The Department'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 R&D activities under the SSL program for the next 7 years, with some general observations to 2025. Actual accomplishments will result in changes to the plan over this time period which will be reflected in future revisions.

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

4.1. Components of the SSL Luminaire[2]

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

---

[1] 2006 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., September 2006. Hereafter, BED.

[2] To be consistent with terms used in the SSL Testing and Energy Star Programs, "luminaire" is used here to describe the entire solid state lighting product

energy-efficiency improvements and thereby to define priorities for the Department's SSL R&D Portfolio.

4.1.1. Components of LED Luminaires

As solid state lighting has evolved, a number of product configurations have appeared in the market. While definitions are still in flux, they are beginning to solidify so that we can identify two essential levels of product based on whether or not they include a driver and a number of terms in each level:

Component level (no power source or driver)

- LED Device refers to the packaged light-emitting semiconductor chip or die including the mounting substrate, encapsulant, phosphor if applicable, and electrical connections.

- LED Array. Several LED chips may be packaged together on a common substrate or wiring board in order to increase total light output or improve the spectrum.

- LED Module. This term is new and refers to an LED packaged with additional components such as thermal, mechanical, or electrical interfaces

Subassemblies and Systems (including a driver)

- LED Lamp refers to an assembly with a standardized base consisting of an LED device integrated with an LED Driver. Such assemblies are generally intended as replacement products for conventional light bulbs, although this situation may evolve over time should standardized bases specific to LEDs come into being.

- LED Light Engine is a term in fairly wide use now, and refers to a subsystem of a luminaire that includes one or more LED Devices, arrays or modules, an LED Driver, an integral heat sink, and appropriate mechanical interfaces. It is intended to be a building block for an LED Luminaire, below.

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

In the above definitions, the term LED Driver means a power source with integral control circuitry designed to meet the specific needs of an LED Device, Array, or Module. The driver converts line voltage to appropriate power and current for the device and may also provide sensing of and corrections for shifts in color or intensity that occur over the life of the product or due to temperature variations. Other special features, such as dimming controls, may also be included.

Figure 4-1, below, illustrates a few of these definitions.

Driver Chip Device Luminaire

Figure 4-1: Photos of LED Luminaire Components
Sources: Lumileds, Color Kinetics.

4.1.2. Components of OLED Luminaires

Because of the nature of the OLEDs, the number of product configurations can be described below in simpler terms. At the component level, there is the OLED device and at the system level, there is the OLED luminaire.

- <u>OLED Device</u> refers to the layers of materials, including a set of charge transporting and emissive layers (made of organic materials) that correspond to those of the basic LED chip. Other layers provide encapsulation, electrical connection and packaging. Because OLEDs are a diffuse light sources, large areas are needed for general illumination applications. Therefore the electrodes of an OLED must be relatively complex in order to spread current out over a large area efficiently. A number of specific OLED device structures are possible, and a few are mentioned below.

- <u>OLED Luminaire</u> refers to the complete lighting unit, intended to be directly connected to an electrical branch circuit. It consists of the OLED device, driver, and fixture. The OLED driver converts line voltage to appropriate power and current for the device. The OLED fixture provides for mounting and mechanical support for the device, interconnection with the driver, and diffusion or direction of the light from the OLED device to the task. Because OLEDs are more diffuse light sources, less complicated fixtures may be possible relative to LEDs or conventional light sources.

Geometries that emit downwards through a transparent substrate or upward from a reflective substrate are currently being considered for OLEDs. The simple planar structure shown in Figure 4-2 below displays an OLED which emits downward through a transparent substrate. These structures typically employ a reflective, metal cathode.

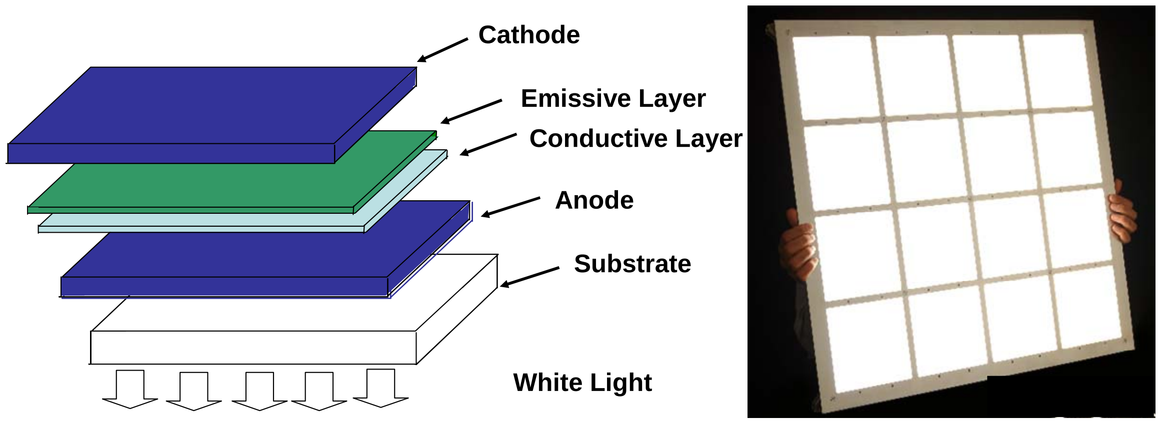

Figure 4-2: Diagram/Photo of OLED Panel
Photo source: General Electric.

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 4-3 displays an entirely transparent OLED employing a transparent substrate and cathode.

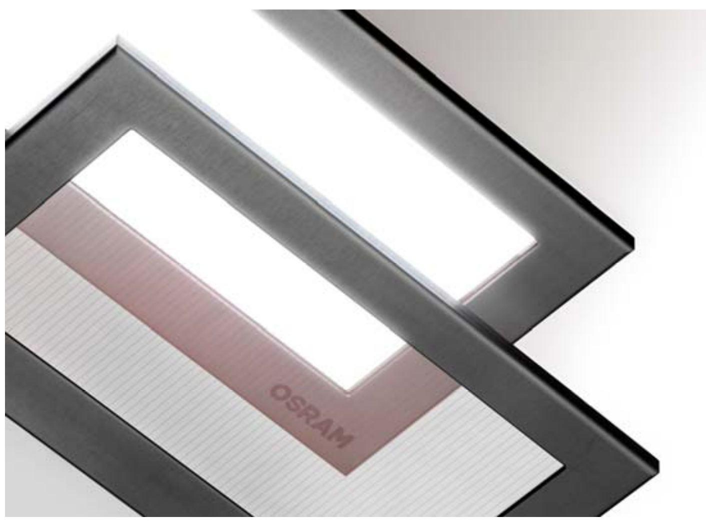

Figure 4-3: Photo of a Transparent OLED Lighting Tile
Photo source: OSRAM Opto

4.2. 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. More are expected in the coming year. LED device 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, some LEDs are now more efficient than incandescent sources and are approaching parity with CFLs. More work will be necessary to assure that luminaires and power conditioners do not excessively degrade the performance of the devices. More work will also be necessary to reach efficiencies that can compete with linear fluorescent lamps. OLED performance lags behind LEDs, as might be expected from that technology's later start. There are essentially no viable OLED products for general illumination available today; however, there is reason to believe that they are not too far off.

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 SSL device and for the luminaire as a whole. These losses and consequent opportunities for LED and OLED luminaires are apparent in the several figures that follow (Figure 4-4, Figure 4-5, and Figure 4-6). Generally, the losses identified result from the conversion of energy, either electrical or optical depending on the stage, into heat. However, 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 essentially spectral filtering of light by the eye that has already been radiated by the SSL luminaire.

The electrical *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 electrical *device* efficacy refers to the ratio of lumens out of the *device* to the power applied to the device; so it does not include the driver or fixture efficiencies. This technology plan forecasts both 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 device include: reducing electrical and optical losses in the device; improving the efficiency of conversion of electrons into photons (IQE); 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 (CCT) and color rendering index (CRI)).

The following sections compare the current typical efficiency values for the individual luminaire elements to a set of suggested program goals for LED and OLED technologies. These are consensus numbers, developed over a series of weekly consultations with members of the NGLIA. It is important to realize there may be significantly different allocations of loss for any specific design, which may also result in an efficient luminaire. This allocation of typical current efficiency values and targets serves as a useful guide for identifying the opportunities for improvement (*i.e.*, those components with the greatest differences between current and target values). It is *not,* however, the program's intention to impede novel developments which use a different allocation of losses that result in a better overall luminaire performance.

For consistency, OLED efficiencies throughout this chapter are reported at a fixed brightness (1,000 cd/m^2) and output (>500 lm). LEDs are reported for a fixed drive current (350 mA) and area (1mm^2). These values are simply used to compare efficiency levels and set targets. Using these reference values is not intended to imply that they are ideal or even the most desirable drive current densities or brightness levels.

4.2.1. Light Emitting Diodes

As described in Section 2.3.4, white-light LED luminaires are typically based on one of two common approaches:

(a) discrete color-mixing and
(b) phosphor-conversion LEDs (pc-LEDs).

Color-mixing LED

Figure 4-4 presents a diagram of a color-mixing LED luminaire. The percentage efficiencies in the diagram next to each component indicate the typical performance in 2007 and targets that will satisfy the goals of the program. Therefore, this diagram depicts the present inefficiencies of the various luminaire components and the headroom for improvement. For purposes of comparing various experimental results, this diagram, as well as the next one, assumes a target correlated color temperature of 4100°K (the equivalent CCT of a cool white fluorescent lamp), and a CRI of at least 80. Other combinations may provide acceptable light for particular market needs, but may then be inappropriate for the targets indicated. Currently available 2007 products typically have color temperatures in the range of 4100-6500°K, and usually a lower CRI.[3] The 2007 typical numbers reflect these less than optimal parameters, and therefore may overstate our current capability. For simplicity, Figure 4-4 depicts RGB color-mixing using LEDs that are not phosphor converted. However, other options are possible. Some manufacturers mix phosphor converted white LEDs with monochromatic red or amber LEDs to achieve a warm white color.

Over the course of the program, performance improvements will make possible the manufacturing of devices with lower color temperature and better CRIs without seriously degrading the efficiency. Achieving the efficiency targets identified in Figure 4-4 will require more efficient emitters (particularly in the green area of the spectrum) and other improvements elsewhere in the luminaire.

[3] The DOE Commercially Available LED Product Evaluation and Reporting (CALiPER) supports the testing of a wide, representative array of SSL products available for general illumination, using test procedures currently under development by standards organizations. More information is available at: http://www.netl.doe.gov/ssl/comm_testing.htm

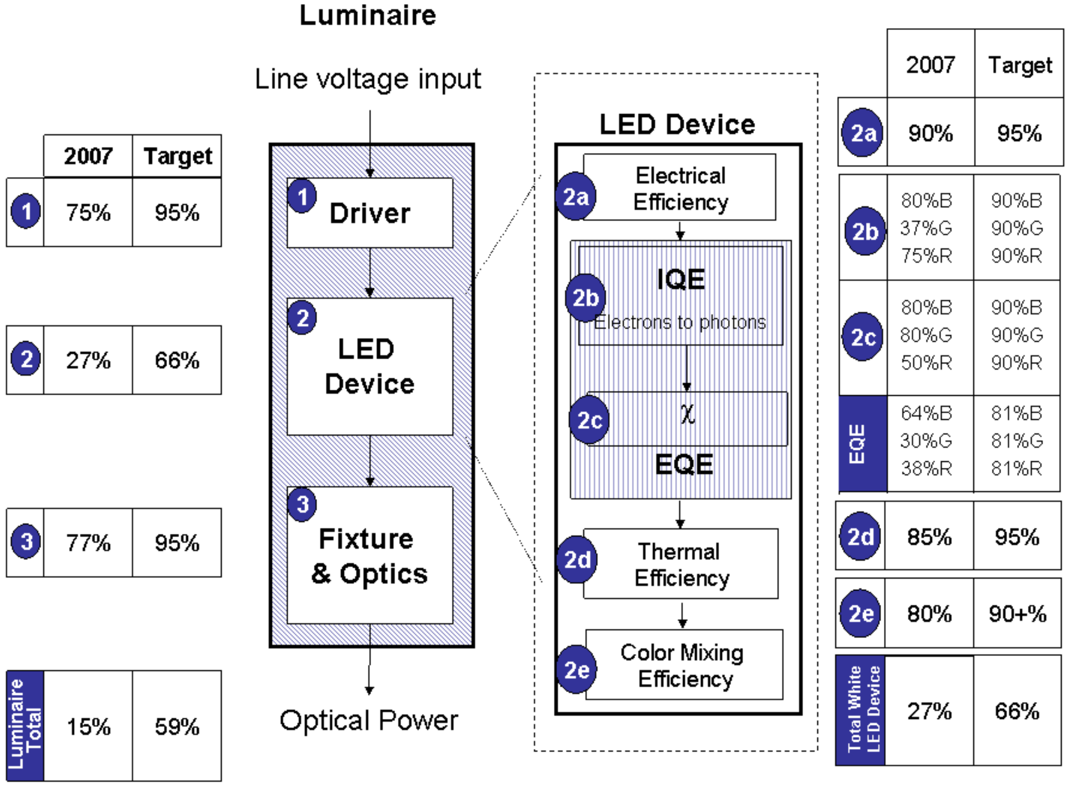

Figure 4-4:Color-Mixing LED- Current and Target Luminaire Efficiencies for Steady State Operation

Source: NGLIA LED Technical Committee, Fall 2007
Note: The target assumes a CCT of 4100K and CRI of 80; Current CCT: 4100-6500K, CRI: 75

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

> <u>Driver efficiency</u> 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.
>
> <u>Device efficiency,</u> There are several components of the device electrical efficacy that are shown on the right in Figure 4-4 and also defined below. The output of the “LED device” in this figure is useful lumens; that is, the spectral effects are not included within the “device” box.

Fixture and optics efficiency, η_{fo}, is the ratio of the lumens emitted by the luminaire to the lumens emitted by the LED device in thermal equilibrium. Losses in this component of the luminaire include optical losses. (For purposes of this illustration, spectral effects in the fixture and optics are ignored, although this may not always be appropriate.)

Considering the device portion of the luminaire, the power efficiency is the ratio of electrical input from the driver (i.e., applied to the device) to the optical power out (irrespective of the spectrum of that output). As such, device power efficiency excludes driver losses. The device *efficacy* is the product of the power efficiency of the device and the spectral or optical efficacy due to the human eye response. Elements of the device power efficiency are:

Electrical efficiency, η_V, accounts for the ohmic losses within the device and the loss of any charge carriers that do not arrive at the active region of the device. The forward voltage should be as low as possible in order to achieve the maximum number of charge carriers into the device active region. 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 any loss of charge carriers that occurs away from the active region of the device.

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.

Extraction efficiency, χ, 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. It is the product of the internal quantum efficiency, IQE, and the extraction efficiency χ.[4]

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[4] In practice, it is very difficult to separate the relative contributions of internal quantum efficiency and extraction efficiency to the overall external quantum efficiency. At the same time, it is useful to make the distinction when discussing the objectives of different research projects. At present, it is common for individual laboratories to compare measurements of different device configurations in order to estimate relative improvements. This makes it difficult to compare and use results from different labs, and so it would be worthwhile to try to develop some measurement standards for these parameters.

Thermal Efficiency is the ratio of the lumens emitted by the device in thermal equilibrium under continuous operation to the lumens emitted by the device at 25°C.[5]

Color-mixing efficiency, η_{color} , here refers to losses incurred while mixing the discrete colors in order to create white light (not the spectral efficacy, but just optical losses). Color-mixing could also occur in the fixture and optics, but for the purposes of Figure 4-4 is assumed to occur in the device.

The device-related parameters of the luminaire have the greatest headroom for improvement in the short term. For example, the internal quantum efficiencies (2b) of the chips range from 20% to 80%, depending on color. The ultimate goal is to raise the IQE to 90% across the visible spectrum, bringing the total device efficiency to 66%. As the LEDs become more efficient, there will necessarily be more emphasis on the other luminaire losses in order to maximize overall efficiency.

In this figure, the driver (1) has an efficiency of 75% in today's products. This driver efficiency is somewhat lower than that for a phosphor converting LED (see Figure 4-5) because the driver needs to produce different colors at different drive voltages with controllable intensities. The ultimate target for this component is to improve the efficiency to be greater than 95%. Likewise, there is considerable room for improvement of the fixture and optics. Currently, the color-mixing LED luminaire is approximately 15% efficient at converting electrical energy into visible white-light. If all targets are achieved, the LED device would have an efficiency of 66%, with an overall luminaire efficiency of 59%.

The device power efficiency (W_o/W_e) measures the energy of light emitted by the device divided by the electrical energy put into the device. This metric is independent of the spectrum of light emitted by the device. Electrical luminous efficacy (in lm/W_e)[6], on the other hand, measures of the amount of useful visible light out of a device per unit of electrical energy. The electrical luminous efficacy of the color-mixing LED device can be calculated by multiplying the device power efficiency by the *optical* or *spectral* luminous efficacy of radiation (LER). For blended LEDs, the LER is approximately 360 lm/W_o (exact value varies with the CRI and CCT for the particular design and the available wavelengths[7]). Using this conversion, the target for a color mixing LED device would be close to 237 lm/W_e (66% efficiency, above, multiplied by 360 lm/W_o). This would result in an overall luminaire efficacy, absent significant breakthroughs, of approximately 213 lm/W_e. These additional luminaire losses are the reason that the

[5] Standard LED device measurements use single pulses of current to eliminate thermal affects, keeping the device at 25°C. In standard operation, however, the LED is driven under CW (continuous wave) conditions. Under these conditions, in thermal equilibrium the device operates a temperature higher than 25°C.

[6] The subscript "e" denotes electrical power into the device and "o" denotes optical power within the device. Unless otherwise stated, "efficacy" means electrical luminous efficacy.

[7] NIST has simulated an LER of 361 lm/W_o at a CRI of 97 and CCT of 3300K. (Ono, Y. "Color Rendering and Luminous Efficacy of White LED Spectra." Proc. SPIE 49th Annual Mtg., Conf. 5530 (2004).)

program includes tasks directed at fixture and driver efficiency as well as those emphasizing the basic LED device, and also why the most energy-efficient installations of the future will have purpose-designed luminaires as opposed to simply retrofit lamps. These are "practical" figures based on the sources and technology that can be envisioned now. The electrical to optical power conversion efficiency could improve and the spectral luminous efficacy could also be higher, as much as 400 lm/W_o for a CRI of 80, if optimal wavelengths are available. This would yield a higher overall figure for lumens per watt.

Phosphor Converting LED

Figure 4-5 below, presents a diagram of a phosphor converting LED luminaire. The definitions for the various efficiencies are the same as listed for Figure 4-4, with additional definitions for phosphor efficiency and scattering efficiency:

> Phosphor efficiency, η_{phos} , the value given in 2e is given for current state of the art green-yellow phosphors necessary to create a simple white emitting device using a blue emitting LED. In order to improve the color quality of phosphor converted white devices while maintaining high efficiency it will be necessary to improve the phosphor efficiency of phosphors that emit in the red wavelengths and, possibly, the efficiency of phosphors that emit in the green to blue-green region of the spectrum. The phosphor efficiency includes the Stokes loss of the phosphor.
>
> Scattering efficiency is the ratio of the photons emitted from the LED device 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 device.

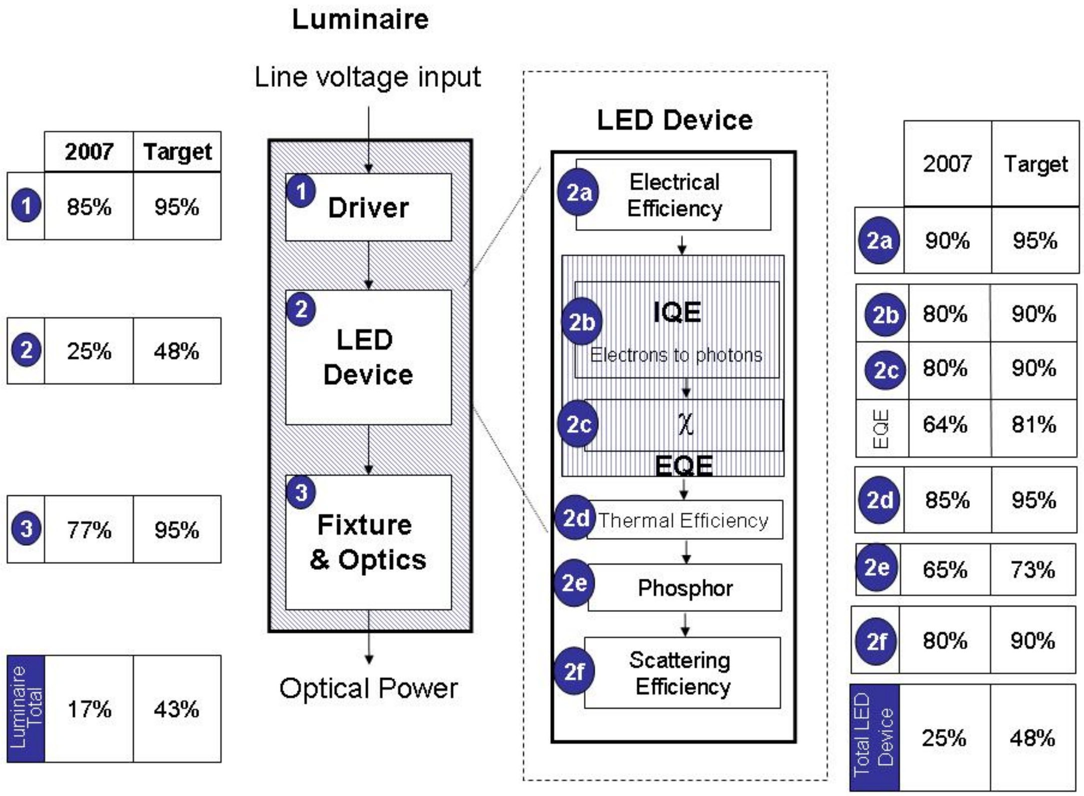

Figure 4-5: Phosphor Converting LED- Current and Target Luminaire Efficiencies for Steady State Operation

Source: NGLIA LED Technical Committee, Fall 2007
Note: The target assumes a CCT of 4100K and CRI of 80; Current CCT: 4100-6500K, CRI: 75
Note: The target for 2e includes the loss due to the Stokes shift (90% quantum yield times wavelength ratio); the value here is typical of a blue diode/yellow phosphor system.

In the above figure, Component 2a, the LED device electrical efficiency, has an efficiency of 90% for 2007 products (with available switching techniques). The ultimate target for this component is to improve the efficiency to greater than 95%. In comparison, other components of the luminaire have more room for efficiency improvements. For example, the extraction efficiency of the LED chip is currently 80%. The ultimate goal is to raise the extraction efficiency of the mounted, encapsulated chip to 90%.

The areas with the greatest headroom for improvement are the internal quantum efficiency (2b) and extraction efficiency (2c) of the LED chip, and the fixture and optics (3). Currently, the phosphor-converting LED luminaire is approximately 17% efficient at converting electrical energy into visible white-light. If all targets are reached, the LED device would have an efficiency of 48%, with a luminaire efficiency of 43%. Similarly to the color-mixing device, the electrical luminous efficacy (in lm/W_e) of the phosphor converting LED device can be calculated by multiplying the device power efficiency (W_o/W_e) by the *optical* luminous efficacy (useful light out (lm) divided by the optical power in (W_o)) of a phosphor. Similar to color-mixing LEDs, a practical target for a phosphor-converting LED luminaire is about 171 lm/W_e. Improving the phosphor efficiency and temperature performance could improve the efficacy even more.

4.2.2. Organic Light Emitting Diodes

Similarly, Figure 4-6 presents a diagram for an OLED luminaire and compares the current typical efficiency values for the individual system elements to a set of suggested program targets.

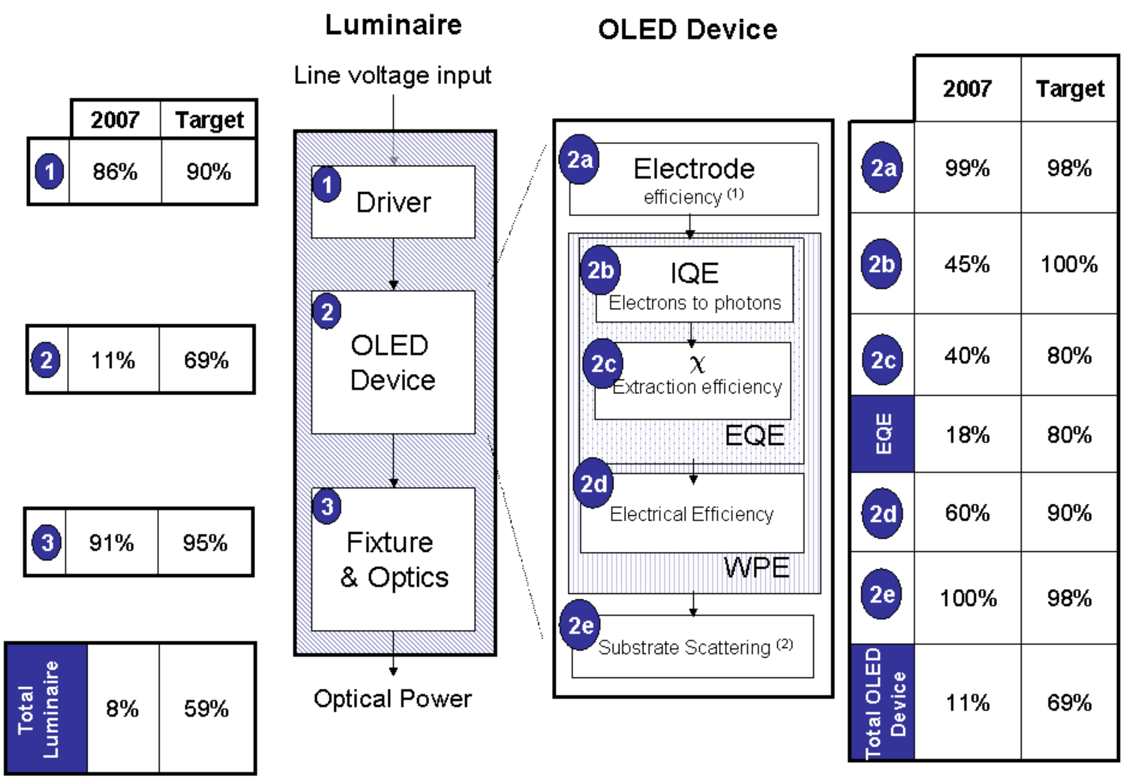

Figure 4-6: OLED Luminaire Efficiencies & Opportunities

(Assumptions for "Target" figures: CCT: 2700-4100K, CRI: 80, 1,000 cd/m2, total output ≥ 500 lm)

Note 1: Electrode loss is negligible for devices currently used for small displays but will be an issue for large area devices necessary for general illumination applications in the future.

Note 2: Includes substrate and electrode optical loss – negligible for glass and very thin electrodes but may be important for plastic or thicker electrodes

Source: NGLIA OLED Technical Committee, Fall 2007

While there is significant room for improvement in the active layers which comprise the device, considerable attention will have to be paid to the practicalities of OLED manufacturing. Early assembly technologies for OLEDs, which are focused on display applications, usually employ glass substrates with virtually no scattering loss. Transitioning to a flexible polymer substrate may be necessary to realize low cost manufacturing, but that may also reduce the device efficiency. The figure above estimates a target of 98% electrode efficiency, but this may be optimistic. Similarly, electrode design techniques may reduce losses in the conductors, but could also obstruct or impair portions of device emission, thus reducing overall device efficiency. Today, this is sometimes evidenced by dim regions on even a relatively small panel. There are electrode design techniques that can improve but not entirely eliminate electrode resistance, but it could become a significant issue as panel sizes increase. Thus, while this diagram shows very small source losses from these effects, as they can be in lab devices, a commercialized product with that level of loss may be difficult to achieve.

The external quantum efficiencies OLED layers can be relatively good for green (in contrast to the situation for LEDs) but are lower for blue and red, thus depressing the overall performance of white light. The goal is to achieve EQE values in the 80% range within the time period of this forecast. The same discussion with regards to the overall efficacy as outlined in the LED section applies here as well; lumens per optical watt depends on available wavelengths and efficiencies while the power efficiency depends on the other loss mechanisms.

Fixture efficiencies for OLEDs may also be relatively high when compared to conventional fixtures. Because OLEDs can be large area emitters, fixtures, to the extent that they are used to reduce glare, could almost be eliminated if the total lumen output of the OLED is distributed over a large enough area.

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 is nonetheless expected to be 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.

4.3. SSL Performance Targets

With these improvement goals in mind, a projection of the performance of SSL devices was created in consultation with the NGLIA Technical Committee, a team of solid-state lighting experts, assuming adequate funding by both government and private industry. The authorization level for the SSL program is $25M for 20 years, which has not been achieved so far, but is still a reasonable estimate of the need. Appropriated funding has steadily increased over the life of the program (see Figure 3-1). Meeting these goals assumes that there are no unforeseen resource availability problems. Although the overall SSL program may be expected to continue until 2025 in order to achieve technologies capable of full market penetration, the OLED efficacy forecast in this section only projects performance to 2012 due to a lack of knowledge about the ultimate limit of this technology. However, a discussion of the performance of LEDs as well as the expected price of OLEDs up to the year 2025 is presented.

In order to capture the ultimate objectives of the SSL program which relate to *luminaire* efficacy or cost, objectives for luminaire performance are also included along with device performance objectives. It is important to note that the graphs are of device performance. Reaching the luminaire objectives will take longer, as shown by the luminaire efficacy values in Table 4-2. Innovative fixtures for LEDs can have a significant impact on overall efficacy. For example, device efficiencies (and operating lifetime) can be degraded by 30% or more when operating at full temperature at steady state in a luminaire. Although device efficiencies can be degraded in luminaires, SSL will still help DOE meet its Zero Energy Building (ZEB) goals by providing a luminaire that is more efficient than other lighting technologies. Accommodating both aesthetic and marketing considerations, while preserving the energy-saving advantages of solid state lighting is a challenge in commercializing this technology. Section 5.6 of the SSL MYPP discusses DOE's commercialization support plan.

4.3.1. Light Emitting Diodes

The performance of white LED devices depends on both the correlated color temperature (CCT) of the device and, to a lesser extent, on the color rendering index (CRI). While we cannot examine every case, we have shown efficacy projections for two choices: one for cooler CCT (4100K to 6500K), and the other for warmer CCT (2700K to 3500K). Because the majority of commercial products sold today are cool white products, forecasts for these products are more predictable. Therefore for the cool white case, projections are shown both for laboratory prototype LEDs, and for commercially available packaged LEDs. Experience suggests that a one and a half year lag between laboratory results and commercial product is fairly typical. Efficacy projections for warm white commercial LEDs are also given.

Figure 4-7 shows device efficacy improvement over time. Actual results through 2008 show that progress has been faster than was expected in the March 2007 projection. However, progress is not expected to continue at this rate over the next few years.

We are beginning to approach what are perceived to be the practical limits of efficacy as shown in Table 4-1. These limits depend on the choice of CCT and color quality demanded by the application. Apart from these more or less predictable limits, manufacturing and cost considerations may further reduce efficacies below their maxima. Based on our expected rates of improvements going forward, these maximum efficacies should be achieved in products between the years 2016 and 2020.

Table 4-1: Practical Maximum Device Efficacy for LEDs

Maximum Efficacy (lm/W)		
CCT	**75 CRI**	**90 CRI**
3000K	182	162
4100K	220	193
6500K	228	186

Source: NGLIA LED Technical Committee, Fall 2007

By 2013 the efficacy for high power cool white laboratory prototypes should reach 184 lm/W. Cool white commercial products should reach a level of approximately 172 lm/W by that time. By 2025, the projections approach the practical maximum efficacies for LEDs of 228 lm/W for cool white LEDs and 162 lm/W of warm white LEDs (with a CRI of 90). All projections assume a prototype with a "reasonable" device life.

A number of actual reported results for both high power and low power diodes are plotted, although these specific examples may not meet all of the criteria specified. Because many more low power diodes are required to make a useful light source, reported results between low and high power LEDs are not directly comparable. For example, although one can achieve a high efficacy light source using these low-power devices, there may be issues of higher assembly cost that need attention. While higher efficacy claims have been made, they cannot be compared unless all parameters are known.

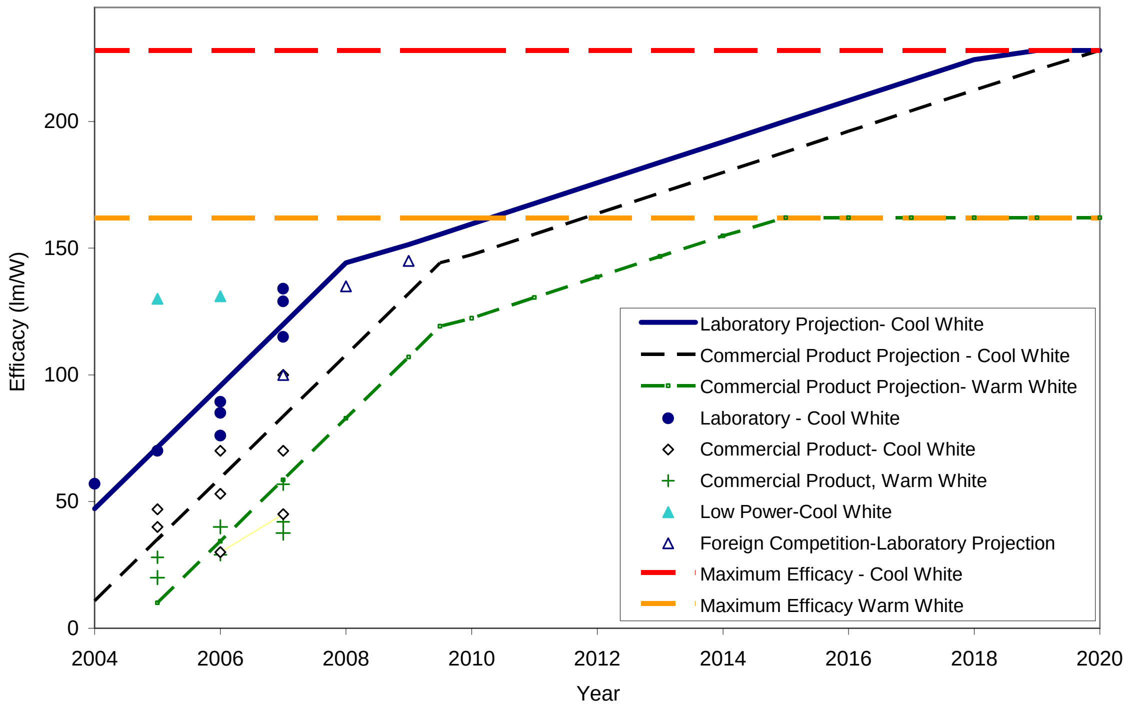

Figure 4-7: White Light LED Device Efficacy Targets, Laboratory and Commercial

Note:

1. Cool white efficacy projections assume CRI=70 → 80, CCT = 4100-6500°K,
2. Warm white efficacy projections assume CRI>85, CCT =2800-3500°K
3. All projections are for high-power diodes with a 350 ma drive current at 25°C, 1mm^2 chip size, device-level specification only (driver/luminaire not included), and reasonable device life.
4. Low power diodes shown have a 20 mA drive current.
5. The maximum efficacy values displayed in Table 4-1 for warm white and cool white are shown above as asymptotes.

Source: NGLIA LED Technical Committee and the Department of Energy, Fall 2007 and Press Releases

The cost estimates were also developed in consultation with the NGLIA Technical Committee, and represent the average purchase cost of a 3 watt white-light LED device driven at 350 mA (excluding driver or fixture costs). The projected original equipment manufacturer (OEM) device price, assuming the purchase of "reasonable volumes" (i.e. several thousands) and good market acceptance, is shown in Figure 4-8. By way of rough comparison, *lamp* prices for conventional technologies are shown on the same chart. The price decreases exponentially from approximately $35/klm in 2006 to $2/klm in 2015. Recent price reduction announcements seem to confirm the trend, at least in the near term.[8] Beyond 2015, price projections for LEDs will remain at or near $2/klm.

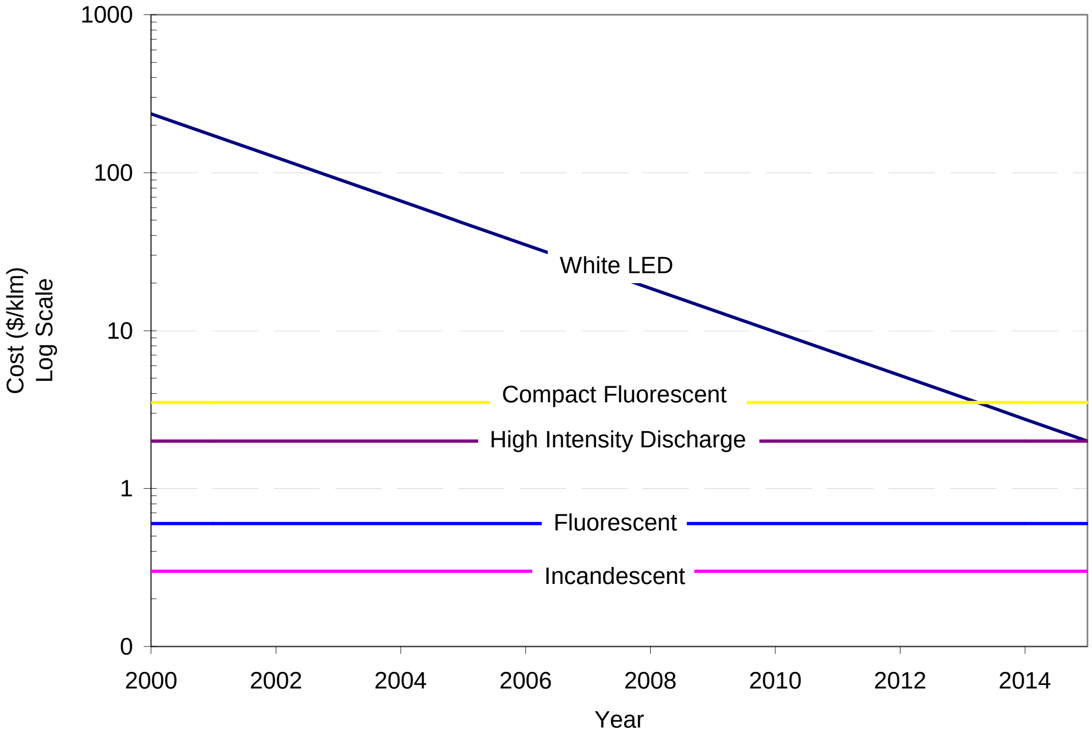

Figure 4-8: White Light LED Device Cost Projection (logarithmic scale)

Note: Price targets assume "reasonable volumes" (several 1000s), CRI=70 → 80,
CCT = 4100-6500K, and device-level specification only (i.e., driver/fixture not included)
Assumes 1-3 W white LED device, 13 W compact fluorescent lamp, 250 W metal halide lamp, 32 W T-8 linear fluorescent lamp, and 60 W A19 incandescent lamp with 2008 prices.
Source: NGLIA LED Technical Committee, Fall 2007

[8] Typical lamp costs for conventional light sources listed in section 2.3.2 are also listed here for comparison: Incandescent Lamps (A19 60W), $0.30 per klm; Compact fluorescent lamp (13W), $3.50 per klm; Fluorescent Lamps (F32T8), $0.60 per klm; High-Intensity Discharge (250W MH), $2.00 per klm. It is important to note that to operate an LED device, a heat sink, fixture, and driver are required. Therefore the full price of an LED luminaire (~$100/klm in2008) is greater than that of the device ($25/klm in 2008). Furthermore, costs among light sources shown in Figure 4-8 are not directly comparable as these light sources may not need a driver, or heat sink to operate. It is also 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.

The device life, measured to 70% lumen maintenance[9], has increased steadily over the past few years and appears to be currently at its target of 50,000 hours. Although it appears that the majority of LEDs have reached the target of 50,000 hours, this has not been substantiated as yet by actual long term operating data. 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).

An average device life of 50,000 hours allows LED devices 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 makes LEDs very competitive with conventional technologies on a "Cost of Light" basis (See Section 2.3.3). However, the total cost of ownership is not substantially affected by lifetimes greater than approximately 50,000 hours. LED products for niche/specialty applications could be developed with longer device life, upwards of 100,000 hours, by trading off with other performance parameters.

It is important to note that although the device lifetime may be 50,000 hours, the luminaire lifetime may be shorter. Bad luminaire design can shorten the life of an LED dramatically through overheating. Drivers may also limit the lifetime of an LED luminaire. Therefore improving the lifetime of the driver to equal or exceed that of the LED device and improving heat management within an LED luminaire are goals of the SSL program.

Table 4-2 presents a summary of the LED performance projections in tabular form.

[9] The device life stated above accounts for the lumen maintenance of the LED but does not account for other failure mechanisms.

Table 4-2: Summary of LED Device Performance Projections

Metric	2007	2010	2012	2015
Efficacy- Lab (lm/W)	120	160	176	200
Efficacy- Commercial Cool White (lm/W)	84	147	164	188
Efficacy- Commercial Warm White (lm/W)	59	122	139	163
OEM Device Price- Product ($/klm)	25	10	5	2

Note: 1. Efficacy projections for cool white devices assume CRI=70 → 80 and a CCT = 4100-6500°K, while efficacy projections for warm white devices assume CRI= >85 and a CCT of 2800-3500°K. All efficacy projections assume that devices are measured at 25°C.
2. All devices are assumed to have a 350 mA drive current, 1mm^2 chip size, device-level specification only (driver/fixture not included), and lifetime as stated in table.
3. Price targets assume "reasonable volumes" (several 1000s), CRI=70 → 80, Color temperature = 4100-6500K, and device-level specification only (driver/luminaire not included)
4. Device life is approximately 50,000 hrs, assuming 70% lumen maintenance, "1 Watt device," 350 mA drive current.
Source: NGLIA LED Technical Committee, Fall 2007

4.3.2. LEDs in Luminaires

As stated in section 4.2.1, the LED device is only one component of an LED luminaire. To understand the true performance metrics of a solid state lighting source, one must also take into account the efficiency of the driver, and the efficiency of the fixture. Provided below in Table 4-3 is luminaire performance projections to complement the device performance projections given in Table 4-2.

Table 4-3 assumes a linear progression over time from the current 2007 fixture and driver efficiency values to eventual fixture and driver efficiency 2015 program targets as given in section 4.1.1. Estimating the factors that affect the performance of an LED luminaire, it appears that a cool white luminaire in 2007 was capable of achieving 50 lm/W (although not all did so). By 2015 cool white luminaire efficacies should reach a capability of 161 lm/W. A projected efficacy for a warm white luminaire is not given here as it depends on the details of the light source design.

Table 4-3: Summary of LED Luminaire Performance Projections (at operating temperatures)

Metric	2007	2010	2012	2015
Device Efficacy-Commercial Cool White (lm/W, 25 degrees C)	84	147	164	188
Thermal Efficiency	85%	89%	91%	95%
Efficiency of Driver	85%	89%	91%	95%
Efficiency of Fixture	77%	84%	88%	95%
Resultant luminaire efficiency	59%	68%	75%	86%
Luminaire Efficacy-Commercial Cool White (lm/W)	47	97	121	161

Notes:
1. Efficacy projections for cool white luminaires assume CRI=70 → 80 and a CCT = 4100-6500°K. All projections assume a 350mA drive current, 1mm^2 chip size, reasonable device life and operating temperature.
2. Luminaire efficacies are obtained by multiplying the resultant luminaire efficiency by the device efficacy values.
Source: NGLIA LED Technical Committee, Fall 2007

4.3.3. Organic Light Emitting Diodes

In consultation with the NGLIA Technical Committee for general illumination, DOE developed price and performance projections for white light OLED devices operating in a CCT range from 2700-4100°K and a CRI of 80 or higher. Two projection estimates are shown: one for laboratory prototype OLEDs, and one for (future) commercially available OLEDs. Because it is difficult to obtain a highly efficient blue OLED emitter, similar projections for cooler CCT values will have lower efficiencies than their warmer CCT counterparts shown below. This is unlike LEDs where cooler CCT values are more efficient than their warmer CCT counterparts. Efficacy projections for OLEDs with a CRI of 90 or higher will also be slightly lower than projections shown.

Figure 4-9 (plotted on a logarithmic scale) predicts that the efficacy of laboratory prototypes will grow exponentially to exceed 150 lm/W by 2012. Based on new data, the NGLIA OLED technical committee has changed the efficacy projection to be more aggressive than in the 2007 Multi-Year Program Plan. As there are not yet any commercial OLED lighting products, the estimated efficacies for commercial products are not meaningful until 2009 and lag approximately three years behind the laboratory products. Projections above 150 lm/W would be speculative given our current understanding of the technology. Therefore, these projections are not shown.

These projections assume the CRI and CCT mentioned above and a luminance of 1,000 cd/m^2 and total output of at least 500 lumens. These projections apply to a white-light

OLED device "near" the blackbody curve (Δc_{xy}<0.01)[10], which may be a necessary criterion to market the products for various general illumination applications. A number of actual reported results are plotted next to the performance projections, although these specific examples may not meet all of the specified criteria.

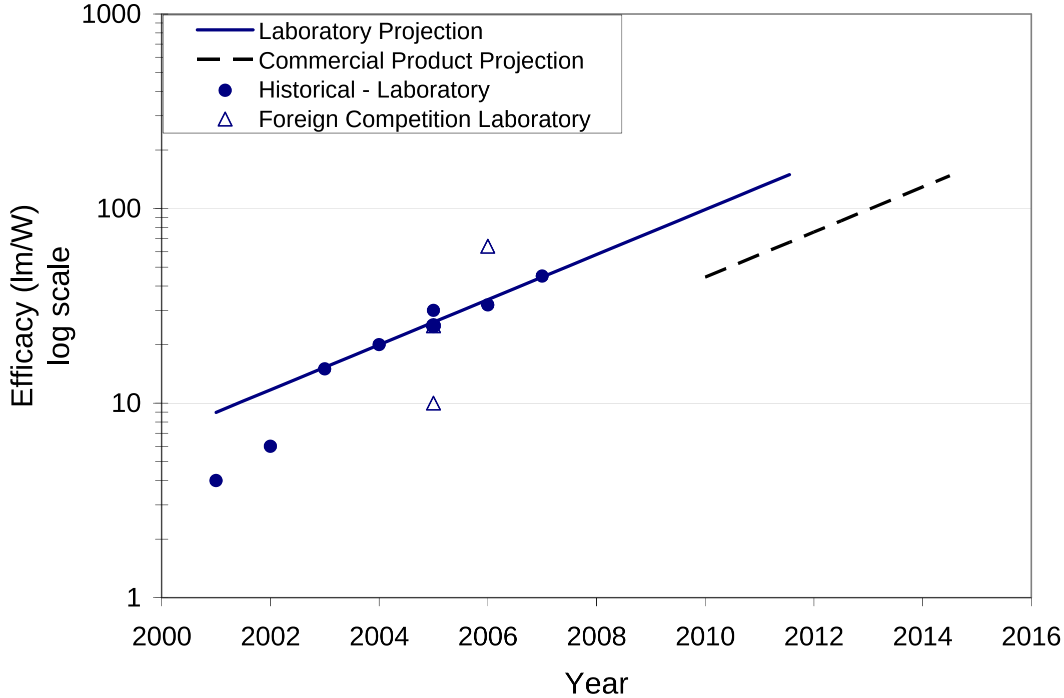

Figure 4-9: White Light OLED Device Efficacy Targets, Laboratory and Commercial

(On a logarithmic scale)

Note: Efficacy projections assume CRI > 80, CCT = 2700-4100°K ("near" blackbody curve (Δc_{xy} <0.01), lifetime > 1000 hrs, luminance of 1,000 cd/m^2, total output ≥ 500 lm, and device level specification only (driver/luminaire not included).
Source: Projections: NGLIA OLED Technical Committee, Fall 2007, Laboratory Points: Press Releases

Today, the efficacy of OLED devices lags behind LED devices, and there are no products on the market. However, researchers are optimistic and when the projections of commercial LEDs and OLEDs are compared (see Figure 4-10), the efficacy of OLED products approaches that of the LED products in the latter part of the current forecast.

[10] Δc_{xy} is the distance from the blackbody curve in C.I.E. color space.

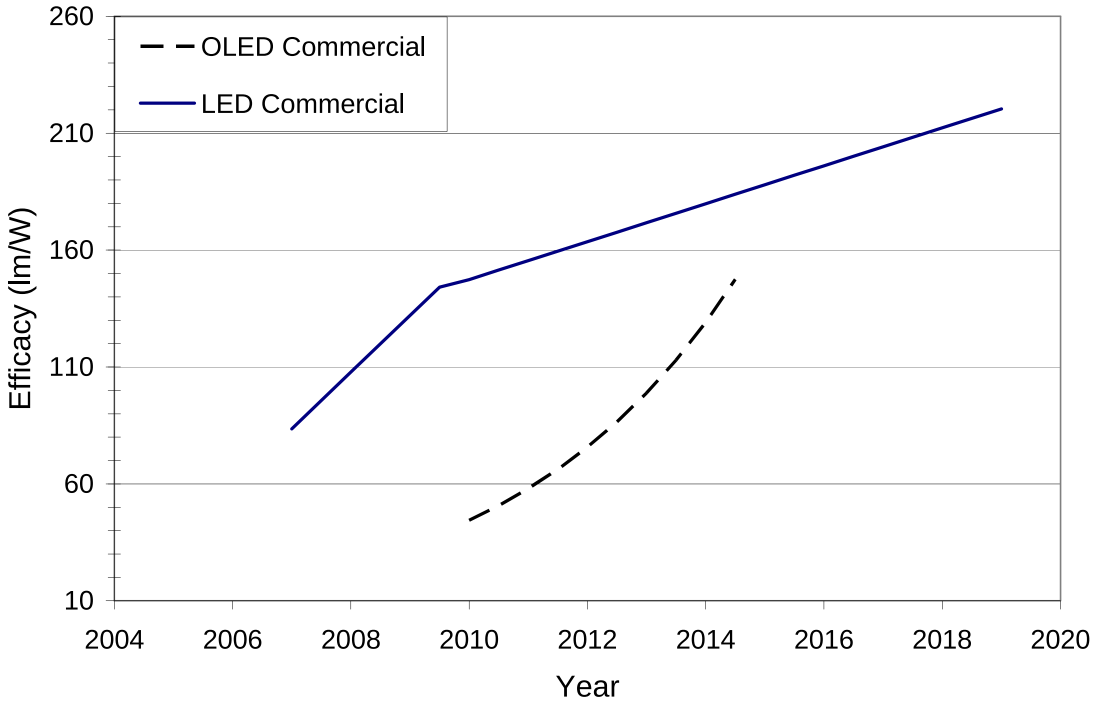

Figure 4-10: LED and OLED Device Efficacy Projections, Commercial

Source: NGLIA OLED Technical Committee and the Department of Energy, Fall 2007

Figure 4-10 presents the anticipated OEM price of commercially available white-light OLED devices (driver and fixture not included) for a luminance of 1,000 cd/m^2 and a total output of at least 500 lumens. Based on current costs of fabrication, we estimate that the 2009 OEM device price would be about $72/klm. The price is expected to fall to $10/klm by 2015, assuming reasonable volumes of tens of thousands. Prices of OLEDs may remain around $10/klm after 2015, although future price reductions are possible. The OEM device price, measured in \$/m^2 is approximately a factor of three greater than OLED device price when measured in $/klm for the assumed luminance. It is important to note that the price projections below are for OLED devices and not luminaires. Because an OLED driver and fixture may be less costly than that of a conventional lighting source, an OLED luminaire with a more expensive "device" may still be cost competitive with a conventional luminaire.

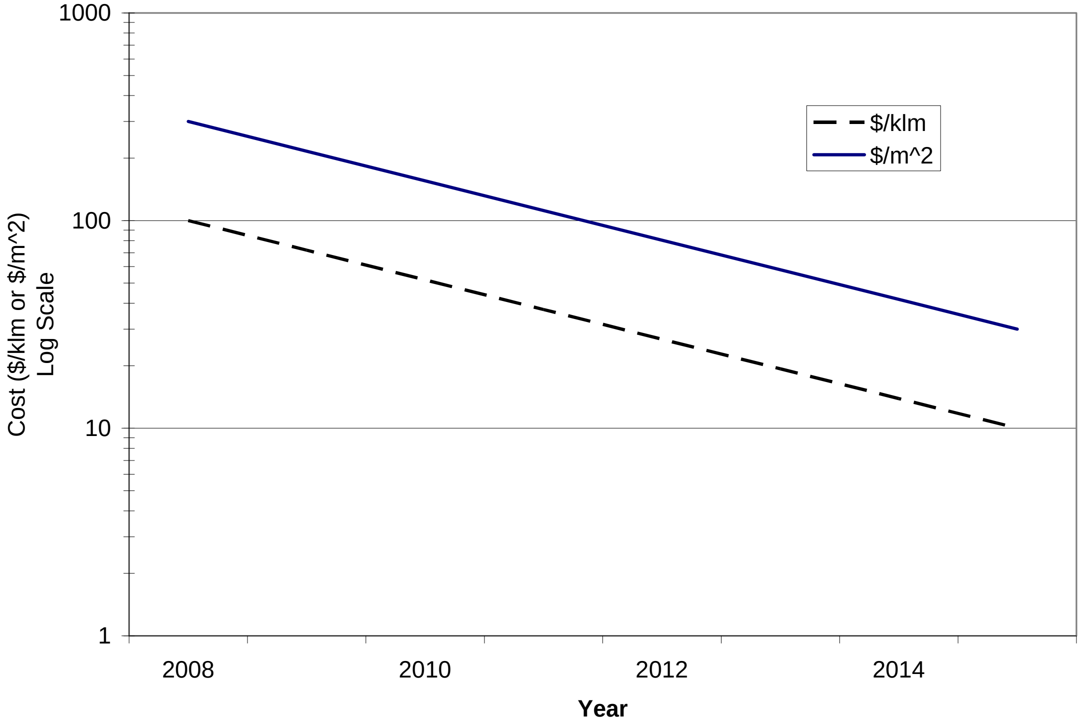

Figure 4-11: White Light OLED Device Price Targets, $/klm and $/m2
Note: Price targets are displayed on a logarithmic scale
Source: NGLIA OLED Technical Committee, Fall 2007

The device life for commercial products, defined as 70% lumen maintenance, is expected to increase linearly to a value of approximately 40,000 hours in 2015. Although 50% lumen maintenance is industry practice for evaluation of OLED displays, we use 70% lumen maintenance[11] in order to compare lifetimes with other lighting products.

Table 4-4 presents a summary of the OLED performance projections in tabular form. Lifetime projections below represent the lifetime of the device, not the entire luminaire. Because the driver may limit the lifetime of the OLED luminaire, improving the lifetime of the driver to at least equal that of the OLED device is a goal of the SSL program.

[11] Like LEDs, device lifetimes account for the lumen maintenance of the OLED but do not account for other failure mechanisms.

Table 4-4: Summary of OLED Device Performance Projections

Metric	2007	2009	2012	2015
Efficacy- Lab (lm/W)	44	76	150	150
Efficacy- Commercial (lm/W)	N/A	34	76	150
OEM Device Price- ($/klm)	N/A	72	27	10
OEM Device Price- ($/m^2)	N/A	216	80	30
Device Life- Commercial Product (1000 hours)	N/A	11	25	40

Notes:

1. Efficacy projections assume CRI = 80, CCT = 2700-4100°K ("near" blackbody curve (Δc_{xy}<0.01), luminance of 1,000 cd/m^2, total output ≥ 500 lm, and device level specification only (driver/luminaire not included)
2. OEM Price projections assume CRI = 80, luminance of 1,000 cd/m^2, total output ≥ 500 lm, and device level specification only (driver/luminaire not included)
3. Device life projections assume CRI = 80, 70% lumen maintenance, luminance of 1,000 cd/m^2, and total output ≥ 500 lm.

Source: NGLIA OLED Technical Committee, Fall 2007

4.3.4. OLEDs in Luminaires

The table below details a summary of the efficiency losses that occur when considering the entire OLED luminaire. Losses in the driver account for the majority of the efficiency degradation while losses in the fixture are assumed to be lower. In addition, OLEDs do not show significant thermal degradation loss, an effect that required the thermal efficiency component for LEDs shown in Table 4-3. Again, a linear improvement over time is assumed from current 2007 driver and fixture efficiency values to 2015 program targets as given in Figure 4-6. After taking into account all of the factors that affect the performance of an OLED luminaire and multiplying them by our original device efficacy projections, the 2009 OLED commercial luminaire efficacy status becomes 16 lm/W while the 2015 OLED commercial luminaire efficacy projection becomes 129 lm/W.

Table 4-5: Summary of OLED Luminaire Performance Projections

Metric	2009	2012	2015
Commercial Device Efficacy (lm/W) (Table 4-4)	34	76	150
Efficiency of Fixture	92%	93%	95%
Efficiency of Driver	87%	88%	90%
Total Efficiency from Device to Luminaire	80%	82%	86%
Resulting Luminaire Efficacy-Commercial Product (lm/W)	27	62	129

Notes:
1. Efficacy projections assume CRI = 80, CCT = 2700-4100°K ("near" blackbody curve (Δc<0.01xy), luminance of 1,000 cd/m^2, total output ≥ 500 lm, and device level specification only
Source: NGLIA OLED Technical Committee, Fall 2007.

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 section 2.3.2 – 2.3.3). Since the lighting market has been strongly focused on low first costs, lifetime benefits notwithstanding, lower cost LED 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 (lumens/watt) of LED and 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. 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 luminaire maintains 70% of its initial lumen output. The lifetime target for the LED device has apparently been achieved. However, it is unclear whether this same lifetime target has been achieved by the LED luminaire. Potential premature failure due to high temperature operation remains a barrier to general deployment. OLED lifetimes for both devices and luminaires still require improvement.
4. Testing: The reported lumen output and efficacies of LED 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.
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. 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, 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.

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

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 the March 2006 and March 2007 editions of the Multi-year program plan and, because of continuing progress in the technology and better understanding of critical issues, are again revised in this edition of the plan.

With respect to the March 2007 MYPP the following changes in the highest priority tasks have been made for 2008:

For LED Core Technology:

1. Subtask 1.1.3, "Reliability and defect physics for improved emitter lifetime and efficiency," was removed from the priority list. Significant progress has been reported on chip lifetime, so this is no longer a high priority for investment.

2. Subtask 1.1.1, "Large-area substrates, buffer layers, and wafer research," was moved to a lower priority. Again, this area of research is at a sufficient state of development that it no longer needs to be among the top core priorities although there is some development work to be done.

3. Subtask 1.2.2 "Strategies for improved light extraction and manipulation" was moved to a lower priority. This task is now largely covered by product development.

4. Subtask 1.3.2 "Encapsulants and Packaging Materials" was moved to the priority list. This task has been somewhat modified to emphasize lower loss and more stable encapsulants and to improve long term reliability of LEDs.

5. Subtask 1.4.x "Inorganic growth, fabrication processes, and manufacturing research" was moved to the priority list. Novel ideas to improve the consistency and uniformity of epitaxial growth and other processes, including improved measurement methods, could reduce the need for binning product and significantly reduce cost. This goes beyond refining existing methods.

For LED Product Development:

1. Subtask 2.3.3, "Power Electronics Development" was moved to the high priority list, but with a more focused scope of work. The lack of small, efficient, high power electronics suitable for converting A.C. line voltage to a suitable current for LED operation limits penetration of LED based products into the direct lamp replacement market and may limit the luminaire lifetime because of the premature failure of some electronic components.

For OLED Core Technology:

1. Subtask 3.1.3, "Improved contact materials and surface modification techniques to improve charge injection" was removed from the priority list. This task is currently at a sufficient state of development to be moved to a lower priority task.

2. Subtask 3.3.2, "Low-cost encapsulation and packaging technology", was moved to a high priority. An important aspect to improving the performance of an OLED over time is to reduce the sensitivity of organic materials to ambient conditions.

The following tables list the priority tasks for LEDs and for OLEDs for each of Core Technology and Product Development. As in the last edition of the MYPP, there are additional tables listing "later priority" tasks which may ultimately need attention to achieve the overall goals of the program as well as some "long term" research tasks that do not appear to need funding at this time, either because they have reached sufficient advancement, or because they are not immediately necessary to enable progress in the next few years towards SSL goals.

Table 4-6 LED Core Technology Research Tasks and Descriptors (2008-Priority Tasks)

Subtask		Short Descriptor	Metric	2007	2015 Target
Core Technology					
1.1.2	High-efficiency semiconductor materials	Improve IQE across the visible spectrum and in the near UV (down to 360 nm) at high current densities	IQE[12]	20% green (540 nm),75% red, 80% blue	90%
1.3.1	Phosphors and conversion materials	High-efficiency wavelength conversion materials for improved quantum yield, optical efficiency, and color stability	Quantum Yield	95%[13]	90% across the visible spectrum
			Scattering losses	10%	
			Color stability		
1.3.2	Encapsulants and packaging materials	Develop a thermal/photo resistant encapsulant that exhibits long life and has a high refractive index.	Retention of original transmittance[14]		>97%
			Lifetime[15]	50 khrs	
			Refractive Index	1.4-1.57	1.7
1.4.x[16]	Inorganic growth and fabrication processes and manufacturing research.	Novel approaches to improving uniformity and yield for epitaxial growth and other manufacturing processes. Research on diagnostic tools and efficient reactor designs and methods.	Wavelength spread across the wafer	20 nm	5 nm

[12] IQE and EQE status and projections assume pulsed measurements at 350 mA drive currents with a 1x1mm^2 chip and Tj = 25^{o}C.
[13] Quantum Yield is measured at a pumped wavelength of 450 nm.
[14] Retention should be measured at wavelengths of 450 nm, a flux of 300mW/mm^2, and Temperature of 185^{o}C.
[15] Lifetime status and projections are for an encapsulant measured at 185^{o}C.

Table 4-7: LED Core Technology Research Tasks and Descriptors (Later Priority Tasks)

Subtask		Short Descriptor	Metric	2007	2015 Target
Core Technology					
1.2.1	Device approaches, structures and systems	Alternative emitter geometries and emission mechanisms, i.e. lasing, surface plasmon enhanced emission	EQE	50%	80%
1.2.2	Strategies for improved light extraction and manipulation	Improved chip level extraction efficiency and LED system optical efficiency, including phosphor scattering and encapsulation.	Chip extraction efficiency (χ)	80%[17]	90%
			Phosphor conversion efficiency	80%	90%
1.3.4	Measurement metrics and color perception	Standardizing metrics to measure electrical and photometric characteristics of LED devices.			

Table 4-8: LED Core Technology Research Tasks and Descriptors (Long Term Tasks)

Subtask		Short Descriptor
Core Technology		
1.1.1	Large-area substrates, buffer layers, and wafer research	Develop low cost, high quality substrates that enable epitaxial growth of high quality emitting material
1.1.3	Reliability and defect physics for improved emitter lifetime and efficiency	- Dopant and defect physics - Device characterization and modeling
1.3.3	Electrodes and interconnects	Low resistance electrodes

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[16] There are several subtasks to 1.4, designated "x"; all need attention.

[17] M. R. Krames, O. B. Shchekin, R. Mueller-Mach, G. O. Mueller, L. Zhou, G. Harbers, and M. G. Craford, " Status and Future of High-Power Light-Emitting Diodes for Solid-State Lighting," J. Display Technol. 3, 160-175 (2007)

Table 4-9: LED Product Development Tasks and Descriptors (2008-Priority Tasks)

Subtask		Short Descriptor	Metric	2007	2015 Target
Product Development					
2.2.1	Manufactured materials	**[Phosphor or Encapsulant product]** Develop high efficiency phosphors, luminescent materials, encapsulants, or materials suitable for high-volume, low-cost manufacture, and improved lifetime. Demonstrate improvements in a high-quality packaged prototype chip.	% of original transmission per mm	85-90% (@150C and 10-15kHrs)	95% (@150C Junction Temp. and 50 kHrs)[18]
2.2.2	LED packages and packaging materials	**[Packaged chip or material]** Design and demonstrate a high-quality packaged chip product employing practical, low-cost, designs, materials, or methods for improving light out-coupling and removing heat from the chip to produce a product with high total lumen output efficiently.	Thermal resistance (junction to case)		5ºC per Watt
2.3.1	Optical coupling and modeling	**[Luminaire]** Develop and demonstrate an application-specific luminaire product that solves the problem of extracting useful task-oriented photons from an LED. This task includes addressing issues such as coupling to multiple sources and the multi-shadowing problem.	Optical/Fixture Efficiency	90%	95%
2.3.4	Thermal design	**[Luminaire]** Demonstrate a luminaire or array of LEDs that solves the problem of removing heat from the chip so as to improve luminaire and chip lifetime and reliability.			
2.3.6	Evaluate luminaire lifetime and performance characteristics	**[Luminaire]** Develop and demonstrate a luminaire with significant improvements in lifetime associated with the design methods or materials. Provide extensive characterization to prove the effectiveness of the approach.	Mean time to failure	May be limited by driver lifetime	As good as source lifetimes – >40K hours

[18] This target may change to 185°C as efficiency goals are met and cost becomes a higher priority.

Table 4-9: LED Product Development Tasks and Descriptors (2008-Priority Tasks)(continued)

Subtask		Short Descriptor	Metric	2007	2015 Target
Product Development					
2.3.3	Power Electronics Development	**[Modular driver]** Develop a high power modular LED driver capable of converting A.C. line voltage to suitable LED operating currents with low cost, compact size, good power factor, efficient operation, and long lifetime at high operating temperatures.	%Energy Conversion	85%	90+%
			$/Watt	$0.20 /Watt	$0.03 /Watt
			Power factor		0.9
			Lifetime at high operating temperature (125C)	20-50 kHrs[19]	50 kHrs

[19] Some 50 kHr devices exist today, but these are presently for military specifications and are too costly for general illumination applications.

Table 4-10 LED Product Development Tasks and Descriptors (Later Priority Tasks)

Subtask		Short Descriptor	Metric	2007	2015 Target
Product Development					
2.1.2	High-efficiency semiconductor materials	**[Unpackaged Chip or epitaxial material]** Demonstrate a chip using materials that promote high efficiency across the visible spectrum.	IQE	20% green, 80% red, 60% blue	90%
2.1.3	Implementing strategies for improved light extraction and manipulation	**[Unpackaged Chip, or material]** Apply manufacturable techniques or material products to state-of-the art LEDs to improve light extraction under lighting conditions at low cost.			
2.2.3	Modeling, distribution, and coupling issues	**[Software tool or Luminaire]** Develop models to understand the coupling of the light between the chip and phosphor to optimize the efficiency of the interaction between chip light extraction, phosphor absorption and re-emission, and phosphor scattering. Develop practical techniques to optimize the chip-phosphor coupling and control the resulting optical distribution for various lighting applications			
2.4.1	Incorporate proven in-situ diagnostic tools into existing equipment.	**[Integrated manufacturing measurement tool]** Develop and demonstrate in-situ diagnostic tools into existing equipment to improve manufacturability of LEDs used for lighting.			
2.4.2	Develop low-cost, high-efficiency reactor designs	**[Reactor for low cost manufacture]** Develop and demonstrate growth reactors capable of growing state of the art LED materials at low-cost and high reproducibility with improved materials use efficiency.			
2.4.3	Develop techniques for die separation, chip shaping, and wafer bonding	**[Manufacturing tools]** Develop and demonstrate improved tools and methods for die separation, chip shaping, and wafer bonding for manufacturability.			

Table 4-11 LED Product Development Tasks and Descriptors (Long Term Priority Tasks)

Subtask		Short Descriptor
Product Development		
2.1.1	Substrate, buffer layer and wafer engineering and development	**[Substrate product for chip manufacture]** Develop and demonstrate high quality substrates suitable for improved device efficiency, manufacturing uniformity, and yield.
2.1.4	Device architectures with high power-conversion efficiencies	**[Array of chips]** Demonstrate an array employing large chips, multi-color chips on a single submount suitable for use in a luminaire design.
2.2.4	Evaluate component lifetime and performance characteristics	
2.3.2	Mechanical design	**[Luminaire]** Develop a luminaire mechanical design that contributes to improving energy efficiency through improved optics, thermal management, or any other efficiency factor.
2.3.5	Evaluate human factors and metrics	

Table 4-12 OLED Core Technology Research Tasks and Descriptors (2008-Priority Tasks)

Subtask		Short Descriptor	Metric	2007	2015 Target
Core Technology					
3.1.2, 3.2.2	Novel materials and device architectures.	Single and multi-layered device structures, materials, and contact materials to increase IQE, reduce voltage, and improve device lifetime.	IQE[20]	B>20%, G 100%, R 60%	100% IQE over the visible spectrum
			Voltage	4-5 V	2.8 V
			L_{70}		40,000 hrs
3.2.1	Novel strategies for improved light extraction	Optical and device design for improving light extraction.	Extraction Efficiency	40%	80%
3.2.3	Research on low-cost transparent electrodes	Better transparent electrode technology that offers an improvement over ITO materials cost and deposition rate and shows the potential for low-cost manufacturing.	Ohms/□	40 Ohms/□	<10 Ohms/□
			Transparency over the visible spectrum	75-80%	92%
3.4.2	Investigation of low-cost fabrication and patterning techniques and tools	Development of potentially low cost deposition techniques	Deposition Speed		
			Material utilization		
			Cost/area		
3.3.2	Encapsulation and packaging technology	Demonstrate a high-efficiency OLED luminaire with intrinsically stable OLED materials resilient to the ambient environment or encapsulated or packaged so as to reduce water permeability, improve lifetime, and exhibit the potential for low-cost.	Operating lifetime		40,000 hrs

[20] As noted in Section 4.5.2, these metrics should be measured at a reference brightness of 1000 cd/m^2 and total output ≥ 500 lm.

Table 4-13: OLED Core Technology Research Tasks and Descriptors (Later Priority Tasks)

Subtask		Short Descriptor
Core Technology		
3.1.1	Substrate materials for electro-active organic devices	
3.1.3	Improved contact materials and surface modification techniques to improve charge injection	n- and p- doped polymers and molecular dopants with emphasis on new systems and approaches for balanced charge injection, low voltage, and long lifetime.
3.1.4	Applied Research in OLED devices	Understand the underlying issues limiting performance in organic light emitting devices.
3.3.1	Down conversion materials	
3.3.3	Electrodes and interconnects	
3.3.4	Measurement metrics and human factors	Productivity, preference, and demonstrations; Standards for electrical and photometric measurement
3.4.1	Physical, chemical and optical modeling for fabrication of OLED devices	

Table 4-14: OLED Product Development Research Tasks (2008- Priority Tasks)

Subtask		Short Descriptor	Metric	2007	2015 Target
Product Development					
4.1.1	Low-cost substrates	**[Substrate Material]** Demonstrate a substrate material that is low cost, shows reduced water permeability, and enables robust device operation.	Cost	~$100/m	< $3/m^2
			Water permeability	10^{-6} g/m^2-day	10^{-6} g/m^2-day
4.1.2, 4.2.2	Practical implementation of materials and device architectures.	**[Device]** Demonstrate an OLED device employing architectures and materials that provide concurrently improve robustness, lifetime, efficiency, and color quality. The device should show potential for mass production.	Efficacy[21]	64 lm/W	>100 lm/W
			CRI	78	90
			Lumen Output	500	5,000
			L_{70}	L_{50}>10 khrs[22]	L_{70}=40 khrs
4.2.1	Practical application of light extraction technology.	**[Device]** Demonstrate an OLED device employing a light extraction technology that features high total extraction efficiency and the potential for large scale manufacturing at low added cost.	Extraction Efficiency	40%	80%
			Cost		
			Lumen Output[23]	500	5,000
4.4.1	Module and process optimization and manufacturing	**[Luminaire]** Produce an OLED luminaire using integrated manufacturing technologies that have a short TAC time and the ability to scale to large areas.	Total Actual Cycle (TAC) time	5 min/m^2	1 min/m^2
4.3.1	OLED encapsulation packaging for lighting applications	**[Luminaire]** Demonstrate a high-efficiency OLED luminaire packaged or encapsulated so as to reduce water permeability and improve lifetime.	$/m^2	$4/m^2	< $3/m^2
			%dark spot area adder		<10% dark spot area adder at 5 year shelf life
			Loss penalty (as compared to glass)		0%
			L_{70}	L_{50}>10 khrs[22]	L_{70}=40 khrs

[21] As noted in Section 4.5.2, efficacy and lumen output should be measured at a reference brightness of 1000cd/m^2 and total output of ≥ 500 lm.
[22] The metric L_{50} is used here because data on L_{70} lifetimes is unavailable.
[23] As noted in Section 4.5.2, lumen output should be measured at a reference brightness of 1000cd/m^2

Table 4-15 OLED Product Development Research Tasks (Later Priority Tasks)

Subtask		Short Descriptor	Metric	2007	2015 Target
Product Development					
4.1.3	Improved contact materials and surface modification techniques to improve charge injection	**[Device]** Develop and demonstrate an OLED device with improved contact materials and surface modification techniques involving n- and p- doped polymers and molecular dopants with emphasis on new systems and approaches for balanced charge injection, low voltage, and long lifetime.			
4.2.3	Demonstrate device architectures: e.g., white-light engines (multi-color versus single emission)	**[Luminaire]** Demonstrate an OLED luminaire employing multi-color chips on a single substrate for use in a luminaire design.			

Table 4-16: OLED Product Development Research Tasks (Long Term Tasks)

Subtask		Short Descriptor
Product Development		
4.3.2	Simulation tools for modeling OLED devices	**[Software Tool]** Develop software simulation tools for modeling performance characteristics of OLED devices.
4.3.3	Voltage conversion, current density and power distribution and driver electronics	**[Driver]** Demonstrate improved drivers for OLED devices with optimized voltage conversion, current density, power distribution, and electronics.
4.3.4	Luminaire design, engineered applications, field tests and demonstrations	**[Luminaire]** Demonstrate in the lab and field-test an OLED luminaire design engineered for a specific application.
4.4.2	Synthesis manufacturing scale-up of active OLED materials	**[Device]** Develop and demonstrate an OLED device using improved materials capable of being scaled-up while maintaining material purity.
4.4.3	Tools for manufacturing the lighting module	**[Manufacturing Tool or Machine]** Demonstrate an improved OLED manufacturing tool or machine.

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 FY08 LED milestone goal is to produce an LED device product with an efficacy of 80 lm/W, an OEM price of $25/klm (device only), and a life of 50,000 hrs with a CRI greater than 80 and a CCT less than 5000K. These performance characteristics represent a "good" general illumination product that can achieve significant market penetration. These goals have been met individually. In fact, some commercial products have achieved device efficacies greater than 100 lm/W. However, all of the milestone targets have not been met concurrently in a single product. For example, a commercial LED, which has an efficacy of 80 lm/W, is currently priced much higher than $25/klm.

FY10 and FY15 milestones represent efficacy or price targets of LEDs devices with a lifetime of 70,000 hrs. Although all milestones in FY08 were not met concurrently, it is expected that the FY10, interim goal of 140 lm/W for a commercial device will be exceeded. Other parameters will also progress, but the task priorities are set by the goal of reaching this particular mark. A new luminaire milestone has also been included in this update: By FY12, DOE expects to see a high efficiency luminaire on the market that has the equivalent lumen output of a 75W incandescent bulb and an efficiency of 126 lm/W. Finally, by FY15, costs should be below $2/klm for LED devices while also meeting other performance goals.

Table 4-17: LED Product Milestones

Milestone	Year	Milestone Target
Milestone 1	FY08	80 lm/W, < $25/klm, 50,000 hrs device
Milestone 2	FY10	> 140 lm/W cool white device; >90 lm/W warm white device
Milestone 3	FY12	126 lm/W luminaire that emits ~1000 lumens
Milestone 4	FY15	< $2/klm device

Assumption: CRI > 80, CCT < 5000°K, $T_j = 125^oC$

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 device, sufficient to enter the lighting market. Phase 2 is to further improve that efficiency 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.

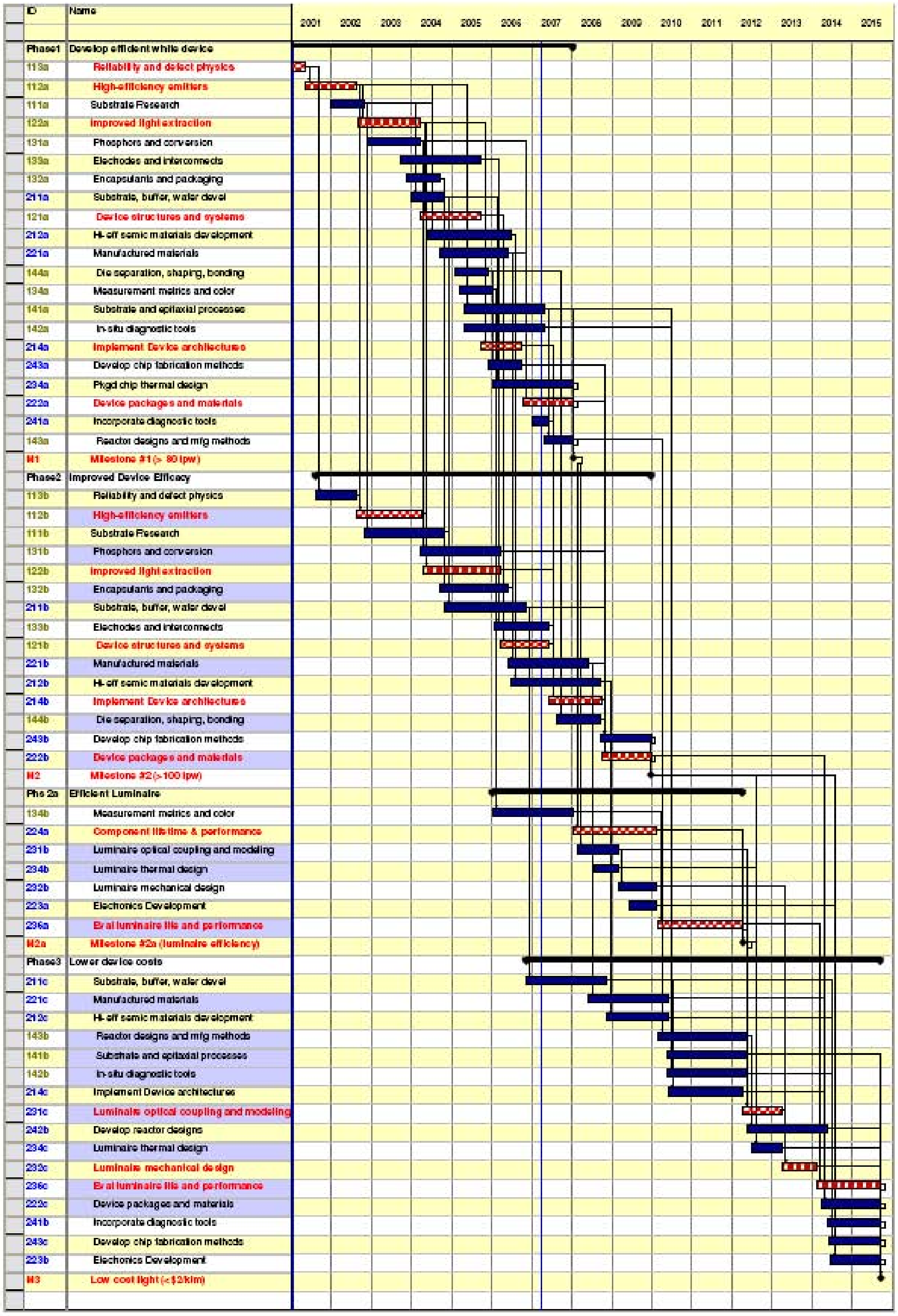
The bars on the Gantt chart indicate an estimated time period for execution of the task in question, while the connecting lines show the interdependence of tasks. The duration of the task depends to some extent on the amount of resources applied. As a deeper understanding of each task is developed, duration estimates can be refined and varied according to the applied resources. Currently, these estimates, based on past experience with funded projects in the DOE program, are approximate. The letters next to the task numbers (a,b,c) identify phases of the tasks. These phases are not to be confused with the overall program phases (1,2,3). Further task phases and program phases will be identified as the program moves past 2015 so that the full potential of solid state lighting can be realized.

Using these estimates of duration and task dependencies, one can identify critical paths to success. Those tasks on the critical path are shown with hashed bars. Tasks identified by the NGLIA/DOE team as high priority have shaded task names. For reasons noted above, the two do not necessarily coincide.

Figure 4-12: White LED Program Gantt Chart

(on page following)

LED Task Phases - Gantt Chart



4.6.2. Organic Light Emitting Diodes

The FY08 OLED milestone is 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. CRI should be greater than 80 and the CCT should be between 3,000-4,000K. 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.

Although current laboratory devices have reached efficacies between 25 and 64 lm/W (at reasonable life, luminance, and CCT), there are currently no niche OLED products available in the marketplace for general illumination applications. According to industry experts, major manufacturers will wait for OLED laboratory prototypes to achieve higher efficacies before investing in the manufacturing infrastructure to produce OLEDs for general illumination purposes. Therefore, unless a smaller manufacturer, less averse to risk, develops a niche product, the FY08 milestone will not be met. Milestone 2 targets a commercial device efficacy of 50 lm/W by FY10. At this point the lifetime should be around 5,000 hours. 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 their large area, so although the FY08 milestone may be late in coming, cost reduction remains the focus. By FY15 the target is to get a high efficacy, 100 lm/W OLED. Cost and lifetime should show continuous improvement as well.

Table 4-18: OLED Product Milestones

Milestone	Year	Milestone Target
Milestone 1	FY08	25 lm/W, < $100/klm, 5,000 hrs
Milestone 2	FY10	<$70/klm
Milestone 3	FY15	>100 lm/W

Assumptions: CRI > 80, CCT < 2700-4100K, luminance = 1,000 cd/m^2, and total output ≥ 500 lumens. All milestones assume continuing progress in the other overarching parameters - lifetime, and cost.

[The Gantt chart for OLED tasks is still under development but will appear in the final 2008 MYPP.]

4.7 Unaddressed Opportunities

Funding for the research tasks for LEDs and OLEDs is allocated, to the extent possible, according to the priorities agreed upon by the NGLIA and DOE and the annual SSL workshops. These priorities are updated annually, based on actual progress, as described in this document. The task priorities represent estimates at the time of publication as to how best to achieve the program goals, recognizing that there are limits to how much can addressed in any year. This process may leave some critical tasks unfunded at any given time. These obviously represent unaddressed opportunities to accelerate the program or improve performance. This is simply one aspect of managing technology risk, which DOE believes is currently under control.

One area of potential development is to more strongly support improved manufacturing of the products. Though outside the scope of the current program, a development in this area would represent a substantial opportunity for the industry and the country. Several potential benefits of such support are:

- Improved uniformity of processes would improve yields and lower costs.
- Improved control over manufacture would reduce color variation, an impediment to deployment.
- Advanced automation methods could reduce labor content and potentially make domestic production-“made in the USA”- a more attractive option than it is today. Currently most LED chip production has moved to the Far East.
- For OLEDs, the manufacturing issue is particularly acute since the needs for displays, the apparent synergistic technology, are actually quite different from what is needed for lighting. This makes the issue of cost reduction very problematical.

While some manufacturing subtasks are prioritized for core R&D, there is not sufficient funding at this time to support advanced manufacturing development to the extent contemplated above.