



Multi-Year Program Plan FY'09-FY'15

Solid-State Lighting Research and Development

Section 4.0 Technology Research and Development Plan

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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 toward 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 2025.⁴³

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 6 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 process of updating the content of this chapter for FY09 began with a series of roundtable sessions convened in Washington, D.C. in September of 2008. The NGLIA members and other industry experts invited to these sessions presented short talks on current topics of interest for LED and OLED technologies and then discussed research tasks. The invited experts then formed technical committees for LEDs and OLEDs (the "LED Technical Committee" and the "OLED Technical Committee," respectively). During the fall of 2008, the Technical Committees further revised the research tasks and other aspects of the chapter during a series of teleconferences.

[Portions of this chapter will be discussed at the DOE SSL R&D Workshop in February of 2009 after which additional revisions to the chapter will be made.]

⁴³ 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.



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 Luminaire⁴⁴

Subsequent sections of this multiyear plan describe both LED and OLED white-light general-illumination luminaires. Understanding each component of a luminaire and its contribution to overall luminaire efficiency helps to highlight the opportunities for energy-efficiency improvements and thereby to define priorities for 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. We can identify two essential levels of product based on whether or not the product includes a driver,⁴⁵ and a number of terms can be defined for each level. Please note that these definitions have been updated from prior editions of the MYPP to reflect the agreed definitions in IES Standard RP-16, Addendum a, as updated and released in 2008.

Component level (no power source or driver)

- LED Package (also known as an LED device) refers to a package of one or more light-emitting semiconductor chips (“dies”) including the mounting substrate, encapsulant, phosphor if applicable, electrical connections, and possibly optical components along with thermal and mechanical interfaces.
- LED Array. Several LED devices may be assembled on a common substrate or wiring board (possibly with additional optical components and mechanical, thermal, or electrical interfaces) in order to increase total light output or improve the spectrum.
- LED Module. This term refers to an LED that is connected to the load side of an LED power source or driver. The module may include additional components such as optical components and thermal, mechanical, or electrical interfaces.

⁴⁴ To be consistent with terms used in the DOE Commercially Available LED Product Evaluation and Reporting (CALiPER) program and Addendum a of ANSI/IESNA RP-16-05, “luminaire” is used here to describe the entire solid state lighting product. 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

⁴⁵ 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.



Subassemblies and systems (including a driver)

- LED Lamp refers to an assembly with a standardized base designed for connection to an LED luminaire. The lamp may consist of an LED device integrated with an LED driver (“integrated”), or the LED driver may be separate from the lamp (“non-integrated”). 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 Luminaire refers to the complete lighting unit, intended to be directly connected to an electrical branch circuit. It consists of a light source and driver along with parts to distribute the light and to connect, position, and protect the light source.

Figure 4.1, below, illustrates a few of these definitions.

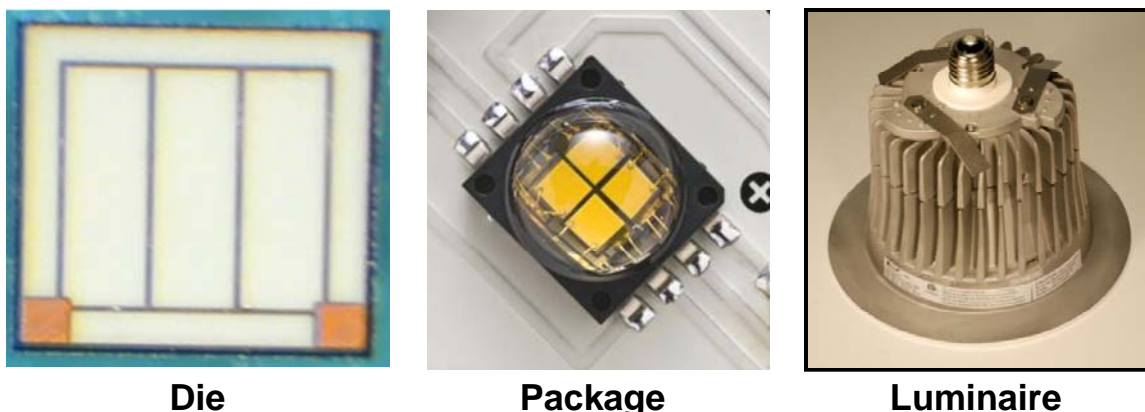


Figure 4.1: Photos of LED Components
Photo source: Cree

4.1.2. Components of OLED Luminaires

A structure parallel to LEDs can be used to define the components of an OLED luminaire.

- OLED Device roughly corresponds to the LED package. It refers to a pixel-sized (a few centimeters or less in dimension) assembly of layers of materials, including a set of charge transporting and emissive layers (made of organic materials) that correspond to those of the LED chip. The device also includes other layers for encapsulation and electrical connection to the device.
- OLED Panel refers to a collection of OLED devices that are assembled to create a unit with significant light output (at least 500 lumens). The OLED panel, approximately corresponds to an LED array or module, depending on whether thermal management components are included as well. The OLED panel may



also incorporate panel packaging, thermal management, and optical outcoupling.

- OLED Luminaire refers to the complete lighting unit, intended to be directly connected to an electrical branch circuit. It consists of an assembly of one or more interconnected OLED panels along with the OLED electrical driver and fixture. The OLED driver converts line voltage to appropriate power and current for the device. The OLED fixture provides for thermal management, if not included in the panels, as well as mounting and mechanical support, interconnection with the driver, and diffusion or direction of the light from the OLED device to the task.

Geometries that emit downward through a transparent substrate or upward from a reflective substrate are currently being considered for OLEDs. The simple planar structure shown in Figure 4.2 below displays an OLED which emits downward through a transparent substrate. These structures typically employ a reflective, metal cathode.

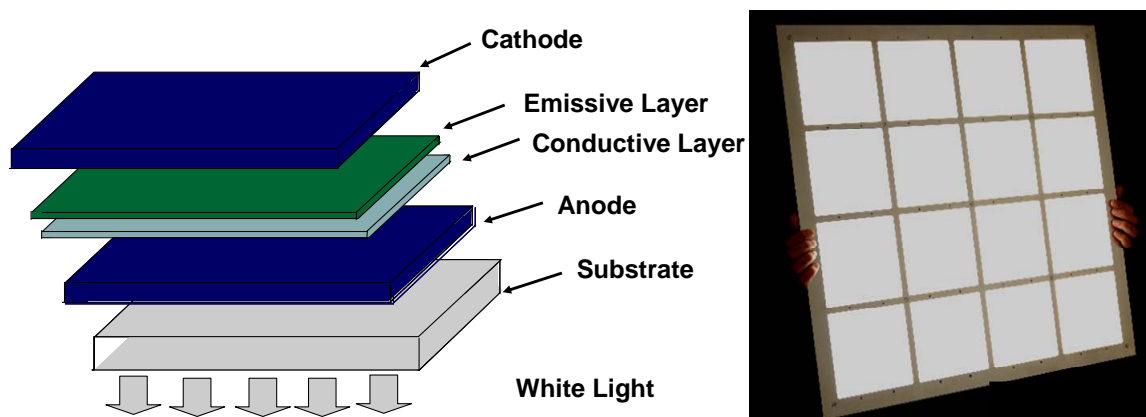


Figure 4.2: Diagram of OLED Device Structure and Photo of OLED Panel
Photo source: General Electric.

It is also possible to manufacture an OLED with a highly transparent cathode (typically with up to 80% transmission across the visible spectral region). These structures can emit upward from a reflective substrate, such as a reflective metal foil, or can be entirely transparent devices. Figure 4.3 displays an entirely transparent OLED luminaire employing a transparent substrate and cathode.

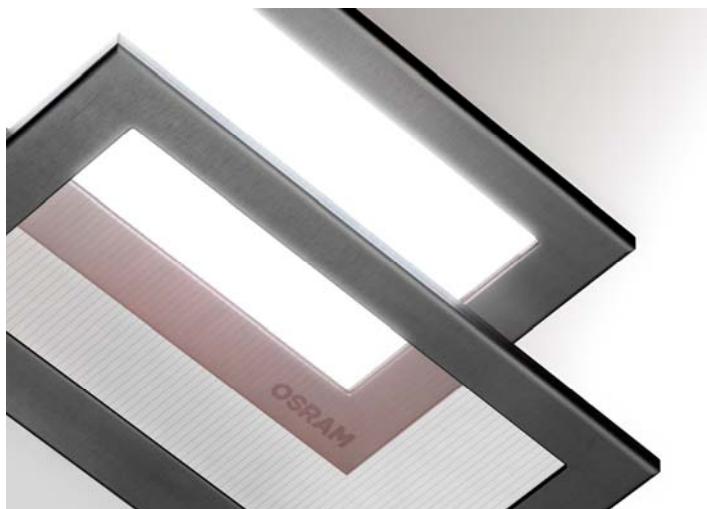


Figure 4.3: Photo of a Transparent OLED Lighting Tile
Photo source: OSRAM Opto-Semiconductor

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, LED luminaires are now routinely more efficient than incandescent sources and are at or near parity with CFLs⁴⁶. More work will be necessary to assure that luminaires and power conditioners do not excessively degrade the performance or lifetime of the devices. More work will also be necessary both to reach efficiencies that can compete with linear fluorescent lamps, and achieve high efficiency devices with a warmer light (i.e., lower correlated color temperature). OLED performance lags behind LEDs, as might be expected from that technology's later start. One niche product using OLEDs for general illumination has become available on the market at a high price and in very limited quantities. The niche product is a table lamp, shown in Figure 4.4, produced by the designer Ingo Maurer. This product appears to be more efficacious than incandescent sources, but it is not near the efficacy of a CFL. Although general market products for OLEDs have still not been introduced, the introduction of this niche product shows promise.

⁴⁶ DOE. 2007c. *DOE Solid-State Lighting CALiPER Program: Summary of Results: Round 3 of Product Testing*. http://www.netl.doe.gov/ssl/comm_testing.htm



Figure 4.4: A Commercial OLED Table Lamp by Ingo Maurer

Photo source: OSRAM Opto-Semiconductor

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 4.5, Figure 4.6, and Figure 4.7). 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 the human eye’s spectral filtering of light 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 at room temperature, so it does not include the driver, fixture, or thermal 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); maximizing the extraction of those photons from the material (extraction efficiency); and tailoring the spectrum of the radiated light to increase the eye response. Tailoring of the spectrum to the eye response is constrained by the need to provide light of appropriate color quality (correlated color temperature (CCT) and color rendering index (CRI)). Further improvements in phosphors and optimization of the spectrum of the LED are still needed to provide an appropriate color quality while increasing luminosity.

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 consensus numbers were developed in consultation with members of the LED and OLED Technical Committees as mentioned in the introduction to this chapter. It is important to realize there may be significantly different allocations of loss for any specific design, which may nevertheless result in an overall efficient luminaire. The allocation of typical current efficiency values and targets used in the sections to follow, however, serves as a guide for identifying the opportunities for improvement (*i.e.*, those components with the greatest differences between current and target values). That said, it is *not* the program's intention to impede novel developments that use a different allocation of losses that result in a better overall luminaire performance.

For consistency, OLED efficiencies throughout this chapter are reported assuming a pixel-sized device, as defined in section 4.1.2, above, at a fixed brightness (1,000 cd/m²). Targets for OLED devices have been set with the goal of enabling the development of high quality OLED panels and luminaires. LED efficiencies are reported for a fixed drive current (350 mA) and area (1 mm²). These values are simply used to compare efficiency levels and set targets to a common reference. It is not the DOE's intention to dictate the brightness, size, or current drive of devices used in practice.

4.2.1. Light Emitting Diodes

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

- a) phosphor-conversion LEDs (pc-LEDs)
- b) discrete color-mixing LEDs
- c) a hybrid consisting of phosphor (white) and monochromatic devices.

Phosphor Converting LED

Figure 4.5 presents a diagram of a phosphor converting LED luminaire. On the left side of the figure is a simplified breakdown of the elements of luminaire efficiency that includes driver efficiency, thermal losses associated with steady state operation and thermal management design, and fixture and optical considerations. On the right hand side is a breakdown of device efficiencies. These efficiencies are independent of spectrum to first order, although the spectrum *will* determine the resulting efficacy. The table shows the efficiencies (both current and target) as typically reported for devices (e.g. pulsed measurements taken at 25°C). Target efficiencies represent the ultimate target of DOE's SSL program. Depending on the difficulty of the task, target efficiencies could be reached before or after the year 2015. Note that the targets for R&D research tasks are for the year 2015. For purposes of comparing various experimental results, this diagram and the next one for color-mixing LEDs assume 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. Currently available 2008 products typically have color temperatures in the range



of 4100-6500°K and often a lower CRI than 80, although more warm white products are beginning to appear. The 2008 typical numbers reflect these less than optimal parameters, and therefore may overstate our current capability. The following definitions provide some clarification on the efficiency values presented in the figures and for the project objectives over time.

Driver efficiency represents the efficiency of the electronics in converting input power from 120V alternating current to low voltage direct current as well as any controls needed to adjust for changes in conditions (e.g. temperature or age) so as to maintain brightness and color.

Device efficiency represents the total efficiency of the LED device (excluding the driver and luminaire) and consists of several components that are shown on the right in Figure 4.6 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.

Thermal efficiency is the ratio of the lumens emitted by the device in thermal equilibrium under continuous operation in a luminaire to the lumens emitted by the device as typically measured and reported in production at 25°C.⁴⁷ The thermal efficiency can be improved by minimizing temperature rise through innovative thermal management strategies.

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

⁴⁷ Standard LED device measurements use relatively short pulses of current to eliminate thermal effects, keeping the device at 25°C (or other controlled point). In standard operation, however, the LED is driven under CW (continuous wave) conditions. Under these conditions, in thermal equilibrium the device operates at temperature higher than 25°C.



in the LED material and electrode injection barriers add to the forward voltage. This efficiency also includes the injection efficiency, which reflects any loss of charge carriers that occurs away from the active region of the 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.⁴⁸

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.⁴⁹

External quantum efficiency, EQE, is the ratio of extracted photons to injected electrons.⁵⁰ It is the product of the IQE and the extraction efficiency χ .

Color-mixing efficiency, η_{color} , 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 4.6 is assumed to occur in the device.

Phosphor efficiency, η_{phos} , refers to the efficiency with which current state of the art green-yellow phosphors create white light using a blue emitting LED. The phosphor efficiency includes quantum efficiency and the Stokes loss of the phosphor. 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. Improvement in the efficiency of phosphors that emit in the red wavelengths will enable the development of more efficacious warm white products.

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.

⁴⁸ The internal quantum efficiency is difficult to measure, although it can be measured indirectly in various ways, for example using a methodology described by S. Saito, et al., Phys. Stat. Sol. (c) 5, 2195 (2008).

⁴⁹ The extraction efficiency may be calculated by several methods; one example is described in [R. Windisch et al. IEEE J.Sel. Top. Quantum Electron. 8, 248 (2002)] and in S. Riyopoulos, T. D. Moustakas and J. S. Cabalu, J. Appl. Phys. 102, 04311 (2007).

⁵⁰ The external quantum efficiency can be measured experimentally using the expression $\eta_{ex} = (P_{opt} / hv) / (I / q)$ where P_{opt} is the absolute optical output power, hv is the photon energy, I is the injection current and q is the electron charge.

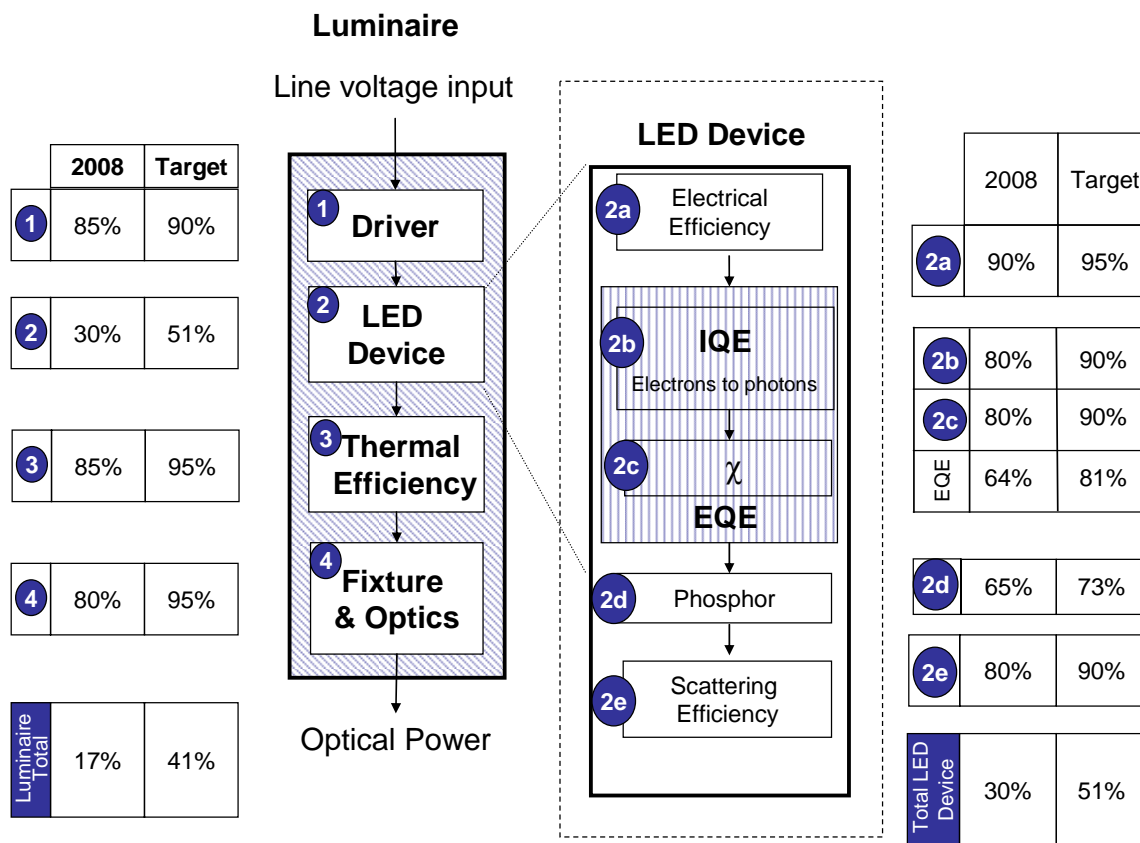
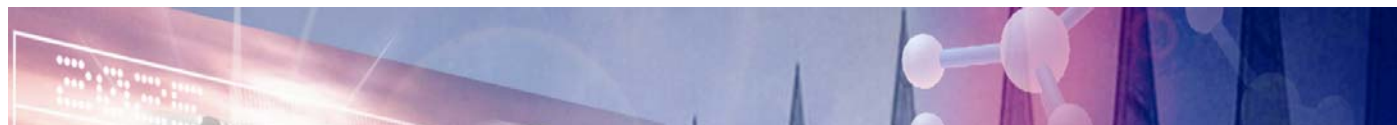


Figure 4.5: Phosphor Converting LED - Current and Target Luminaire Efficiencies for Steady State Operation

Source: LED Technical Committee, Fall 2008

Note: The target assumes a CCT of 4100K and CRI of 90; Current CCT: 4100-6500K, CRI: 75

Note: The target for 2d includes the loss due to the Stokes shift (90% quantum yield times the ratio of the the average pumped wavelength and the average wavelength emitted); the value here is typical of a blue diode/yellow phosphor system.

In Figure 4.5, Component 2a (the LED device electrical efficiency) is estimated to have an efficiency of 90% for 2008 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 of DOE's SSL program is to raise the extraction efficiency of the mounted, encapsulated chip to 90%.

Members of the LED Technical Committee estimated that today's driver efficiency is 85%, excluding possible additional losses for special control circuitry. The program target for the driver is to improve the efficiency to 90%. There is considerable room for improvement of the fixture and optics. Assuming a simple functional luminaire like a recessed downlight, fixture efficiencies for LEDs are currently around 80%. DOE expects the efficiency of the fixture can be ultimately increased to 95%. However, efficiencies for more decorative luminaires may not be able to reach this target because of



losses due to color-altering diffusers or shades added for aesthetic purposes.

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 51%, and the luminaire an efficiency of 41%. The device power efficiency (W_o/W_e), indicated in Figure 4.5 as the “Total White LED Device” efficiency, measures the power of light emitted by the device divided by the electrical power put into the device. This metric is independent of the spectrum of light emitted by the device. Electrical luminous efficacy (in lm/W_e),⁵¹ on the other hand, measures the amount of useful visible light out of a device per unit of electrical energy. The electrical luminous efficacy of the phosphor converting 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 $360 \text{ lm}/W_o$ (exact value varies with the CRI and CCT for the particular design and the available wavelengths⁵²). Using this conversion, the target for a phosphor converting LED device would be close to $184 \text{ lm}/W_e$ (51% power efficiency, above, multiplied by $360 \text{ lm}/W_o$). This would result in an overall luminaire efficacy, absent significant breakthroughs, of approximately $147 \text{ lm}/W_e$ ($360 \text{ lm}/W_o \times 41\%$ luminaire efficiency). These additional luminaire losses are the reason that the 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 $400 \text{ lm}/W_o$ for a CRI of 80, if optimal wavelengths (or more colors) are available. This would yield a higher overall figure for lumens per watt.

Color-Mixing LED

Figure 4.6 presents a diagram of a color-mixing LED luminaire. For simplicity, three colors are used, although a fourth color, e.g. amber, or even more could be used to improve the spectrum. The definitions for the various efficiencies are the same as listed for Figure 4.5. The percentage efficiencies in the table next to each component indicate the typical performance in 2008 and targets that will satisfy the goals of the program. From this diagram one can infer the headroom for improvement for the various luminaire and device elements.

⁵¹ 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.

⁵²NIST has simulated an LER of $361 \text{ lm}/W_o$ at a CRI of 97 and CCT of 3300K. (Ohno, Y. "Color Rendering and Luminous Efficacy of White LED Spectra." Proc. SPIE 49th Annual Mtg., Conf. 5530 (2004).)

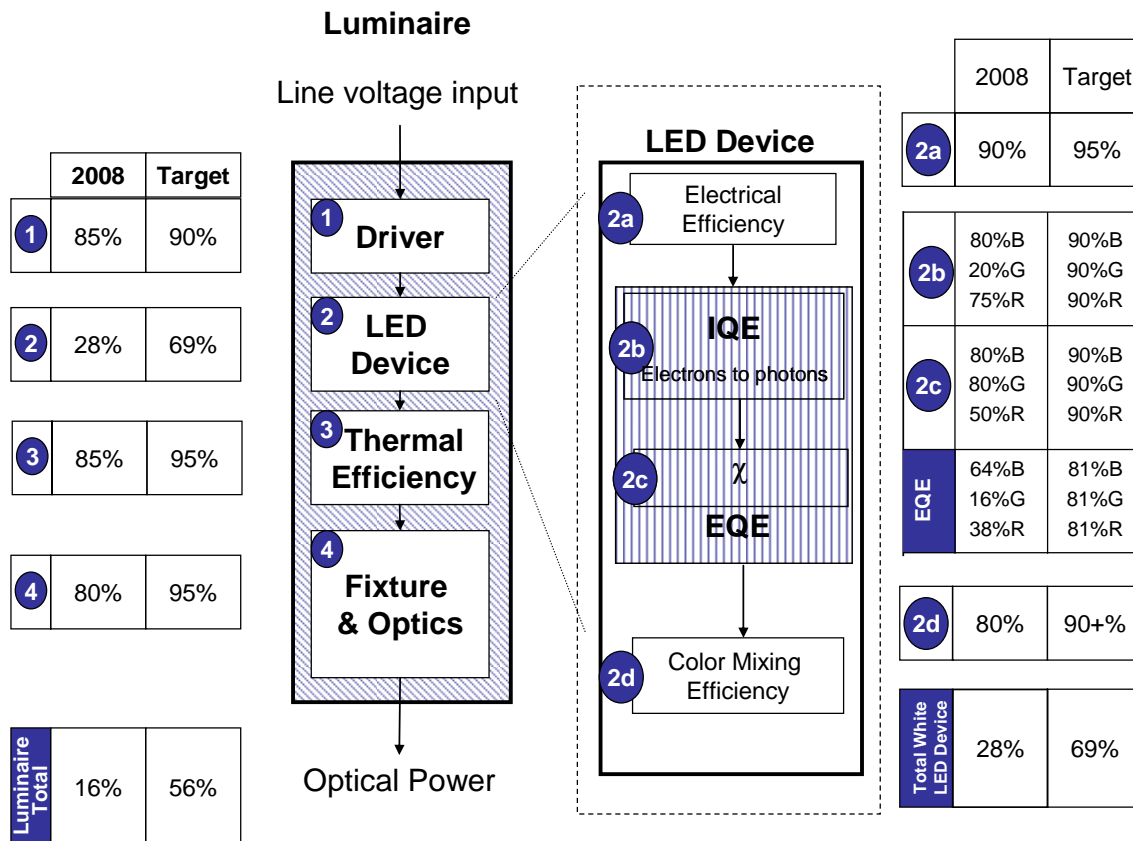


Figure 4.6: Color-Mixing LED - Current and Target Luminaire Efficiencies for Steady State Operation

Source: LED Technical Committee, Fall 2008

Note:

1. The target assumes a CCT of 4100K and CRI of 80; Current CCT: 4100-6500K, CRI: 75.
2. IQE statuses and targets assume wavelengths of 610 nm for red, 540 nm for green, and 450 nm for blue.

Because there is no Stoke's loss, the color-mixing LED is, in principle, capable of higher efficacies than the pc-LED. However, there are trade-offs in the design of color mixing devices (such as additional driver complexity and cost and the lower efficiency of green LEDs.). Other options are possible for obtaining different color temperatures or color rendition indices using a hybrid approach. For example, a warm white color can be achieved by mixing phosphor converted white LEDs with monochromatic red or amber LEDs. In fact, several very successful high efficacy warm white luminaires employing this hybrid approach have recently appeared on the market.

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 4.6 will require more efficient emitters (particularly in the green area of the spectrum) and other improvements elsewhere in the luminaire.



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 69%. As the LEDs become more efficient, there will necessarily be more emphasis on the other luminaire losses in order to maximize overall efficiency.

Currently, the simple, functional, color-mixing LED luminaire is approximately 16% efficient at converting electrical energy into visible white light. If all targets are achieved, the LED device would have an efficiency of 69%, with an overall luminaire efficiency of 56%. Similarly to the phosphor-converting device, the electrical luminous efficacy (in lm/W_e) of the color-mixing 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. A practical target for a color-mixing LED luminaire is about $202 \text{ lm}/W_e$. Improving the color mixing efficiency and temperature performance could improve the efficacy even more.

4.2.2. Organic Light Emitting Diodes

Figure 4.7 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. The definitions for the various efficiencies are the same as listed for Figure 4.5, with additional definitions for electrode efficiency and substrate optical losses. Additional clarification is also given for internal quantum efficiency.

Electrode efficiency accounts for the losses that occur between the external electrical contacts of the device and the charge-injecting interfaces of the device.

Internal quantum efficiency, IQE, is the ratio of the photons generated within the active region of the OLED to the number of electrons *injected into* the active region. IQE is the product of the fraction of all electrons and holes that eventually combine, the efficiency with which electrons and holes form an emissive state, and the quantum yield of the emissive state.

Electrical efficiency is the ratio of photon electron volts to the electrical voltage input to the OLED. The electrical efficiency accounts for the internal device resistance and the barrier to charge injection at the electrode-organic interface.

Substrate optical losses are losses incurred as photons exiting the device encounter the substrate and electrode materials. While such losses are small for glass and very thin electrodes such as those made from indium tin oxide, substrate optical losses may be substantial for different substrates (such as flexible substrates made from plastics) and non-ITO electrodes.

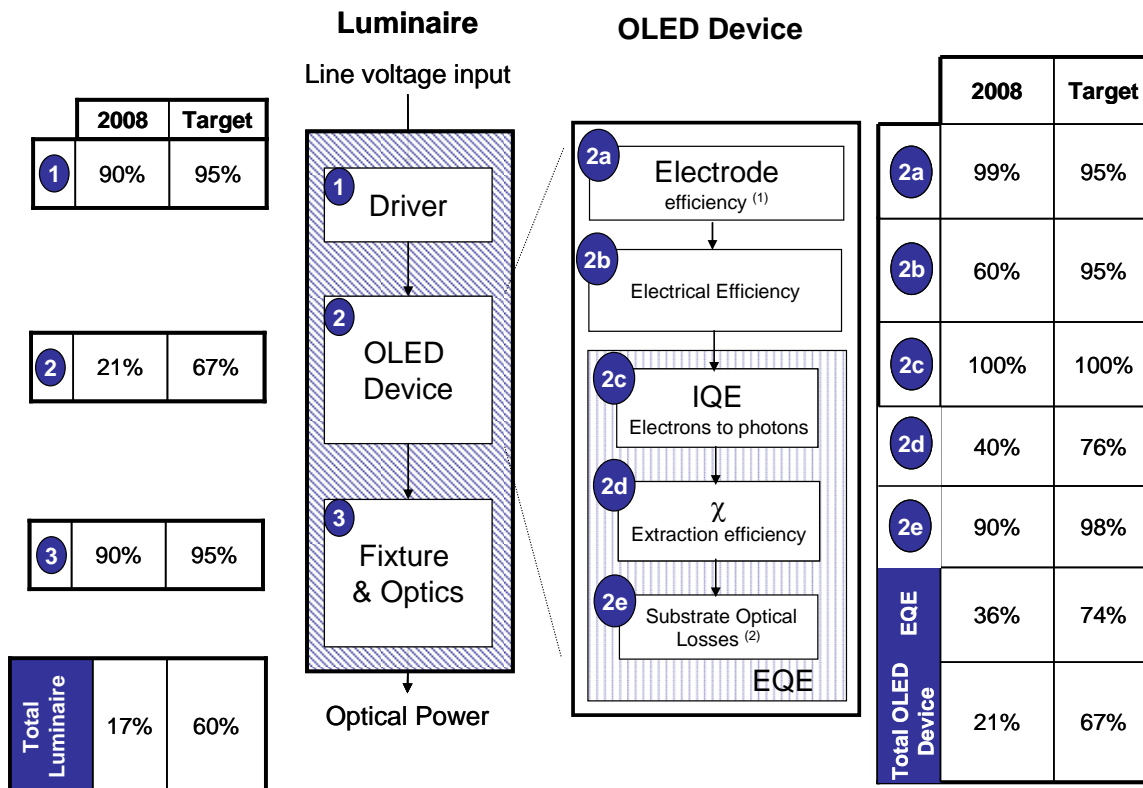


Figure 4.7: OLED Luminaire Efficiencies & Opportunities

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

Source: OLED Technical Committee, Fall 2008

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. Current 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 95% 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 in 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. Due to waveguiding, EQE in planar OLED designs is limited to around 20% if one does not include any outcoupling enhancement. Innovation is needed to enhance EQE, as the goal is to achieve EQE values in the 70% range (with outcoupling enhancement). The same discussion with regard 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, although this has yet to be shown. 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. Although fixture efficiencies could increase, prices of these fixtures could rise as the area of the OLED increases. Also, it is important to note that because there are no commercial products on the market, estimates of luminaire efficiencies are based on laboratory prototypes.

Keys to efficiency improvements in OLEDs continue to revolve around finding suitable stable materials with which to realize white light, with blue colors being the most difficult. Progress on efficiencies for OLEDs has been relatively rapid, as discussed in the next section. However, achieving efficiency gains alone will not be sufficient to reach viable commercial lighting products. The films must also be producible in large areas at low cost, which highlights the importance of minimizing substrate and electrode losses, as noted above and in the figure, and may also limit materials choices.

4.3. SSL Performance Targets

The projections of the performance of SSL devices created in consultation with the Technical Committees assume adequate funding by both government and private industry for the duration of the program. Although the authorization level for the SSL program is \$50M for 7 years, actual appropriations have never reached this level. Appropriated funding steadily increased until 2007 (see Figure 3.1) but declined in 2008. Meeting these goals, however, assumes that there are no unforeseen resource availability problems.



In order to capture the ultimate objectives of the SSL program that relate to *luminaire* efficacy or cost, objectives for luminaire performance are also included along with device performance objectives. Although the graphs show large improvements in device performance, reaching the luminaire objectives will take longer, as shown by the luminaire efficacy values in Table 4-3 and Table 4-5. 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. Despite this degradation, SSL will still help DOE meet its Zero Energy Building (ZEB) goals by providing a luminaire that is more efficient than luminaires of 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 light 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.

Actual results through 2008 show that efficacy improvement continues to be faster than was expected in earlier forecasts. We are beginning to approach what are perceived to be the practical limits of efficacy as shown in Table 4-1, however, so we may expect progress to begin to slow down. 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: LED Technical Committee, Fall 2008

Figure 4.8 shows device efficacy improvement forecasts over time. This year's forecast does not differ greatly from the 2008 MYPP, except that a somewhat slower rate of improvement is now projected for warm white light. The asymptotes on the graph show the extremes of the above table: warm white with high CRI at 162 lm/W and cool white with a low CRI at 228 lm/W. The earlier diagrams (Figure 4.5 and Figure 4.6) showed efficiencies for targets in between, giving values for a neutral white (4100K) and a moderate-to-high CRI. By 2013 the efficacy for high power cool white laboratory prototypes should reach 184 lm/W, near the limit in the table above. 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 "reasonable" device life.

A number of actual reported results for high power diodes are plotted, although these specific examples may not meet all of the criteria specified in the footnotes. Low power LEDs also exist, but examples are not plotted. 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.

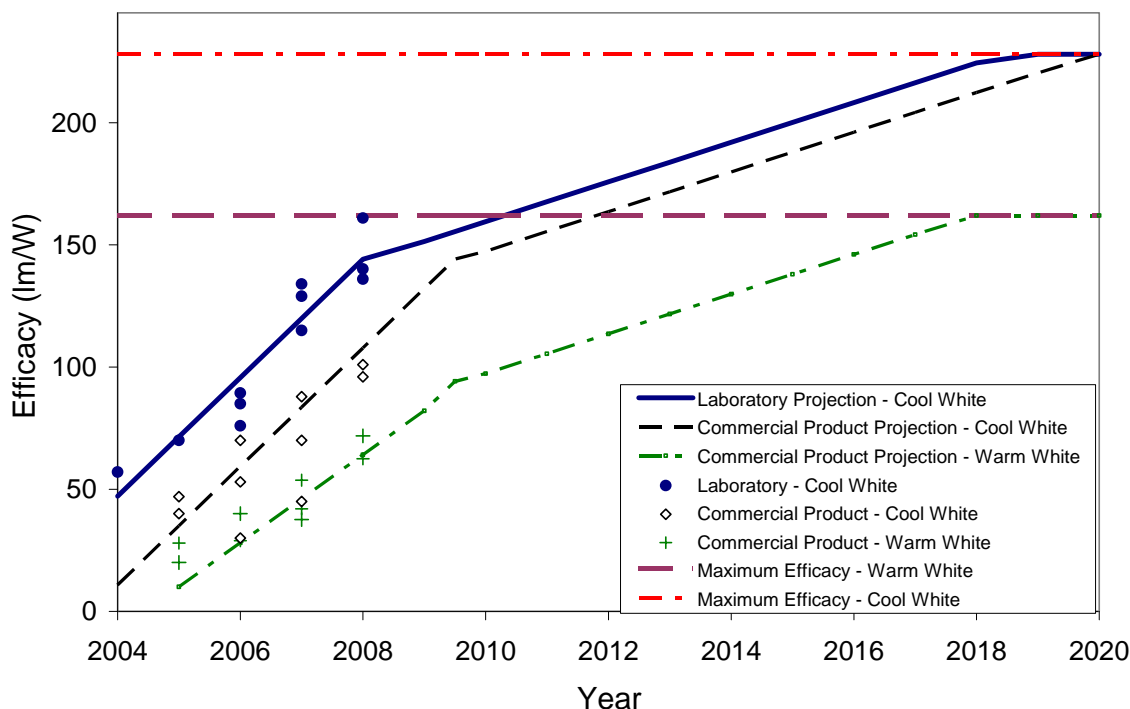


Figure 4.8: White Light LED Device Efficacy Targets, Laboratory and Commercial

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, 1mm² chip size, device-level specification only (driver/luminaire not included), and reasonable device life.
4. The maximum efficacy values displayed in Table 4-1 for warm white (3000K and 90 CRI) and cool white (6500K and 75 CRI) are shown above as asymptotes. The target efficiency in Figure 4.5 assumes a CRI of 90 and a CCT of 4100K and would lie in between these two extremes.

Source: LED Technical Committee and the Department of Energy, Fall 2008; Press Releases

The cost estimates represent the average purchase cost of a white light LED replacement lamp with an integrated driver. The projected original equipment manufacturer (OEM) lamp price, assuming the purchase of “reasonable volumes” (i.e. several thousands) and good market acceptance, is shown in Figure 4.9. The price decreases exponentially from approximately \$200/klm in 2007 to \$2/klm in 2025. By way of rough comparison prices for conventional technologies are shown on the same chart. It is important to keep in mind that energy savings, replacement cost, and labor costs factor into a lamp’s overall cost of ownership. LEDs are already cost competitive on that basis with certain incandescent products.⁵³

⁵³ Typical 2008 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; self-ballasted compact fluorescent lamps (13W), \$1.90 per klm; 2-lamp fluorescent lamp-and-ballast system (F32T8), \$3.97 per klm

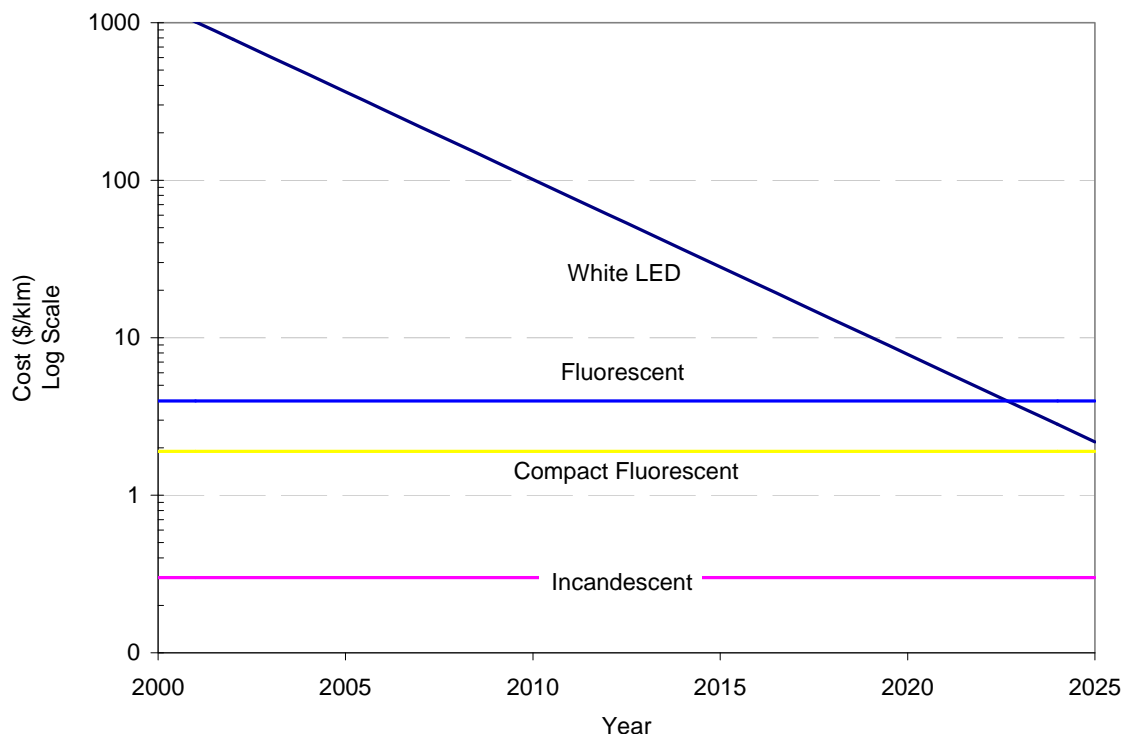


Figure 4.9: White Light LED Replacement Lamp Cost Projection (logarithmic scale)

Note: Price targets assume “reasonable volumes” (several 1000s), CRI=70 → 80,

CCT = 4100-6500K

Assumes LED replacement lamp with integrated driver, 13 W self-ballasted compact fluorescent lamp, 2-lamp 32 W T8 linear fluorescent lamp-and-ballast system, and 60 W A19 incandescent lamp with 2008 prices

Source: LED Technical Committee, Fall 2008

The device life, measured to 70% lumen maintenance,⁵⁴ 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

⁵⁴ The device life stated above accounts for the lumen maintenance of the LED but does not account for other failure mechanisms.



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.

Table 4-2: Summary of LED Device Performance Projections

Metric	2008	2010	2012	2015
Efficacy- Lab (lm/W)	144	160	176	200
Efficacy- Commercial Cool White (lm/W)	108	147	164	188
Efficacy- Commercial Warm White (lm/W)	64	97	114	138
OEM Lamp (\$/klm)	85	50	30	14

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, 1mm² chip size, device-level specification only (driver/fixture not included), and lifetime as stated in table.
3. Price targets assumes an integrated LED lamp, “reasonable volumes” (several 1000s), CRI=70 → 80, color temperature = 4100-6500K
4. Device life is approximately 50,000 hrs assuming 70% lumen maintenance, “1 Watt device,” and 350 mA drive current.

Source: LED Technical Committee, Fall 2008

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 are luminaire performance projections to complement the device and lamp performance projections given in Table 4-2. Table 4-3 assumes a linear progression over time from the current 2008 fixture and driver efficiency values to eventual fixture and driver efficiency 2015 program targets as given in section 4.1.1. Estimating the



factors that affect the performance of an LED luminaire, it appears that a cool white luminaire in 2008 was capable of achieving 63 lm/W (although not all did so). By 2015 cool white luminaire efficacies should reach a capability of 152 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	2008	2010	2012	2015
Device Efficacy- Commercial Cool White (lm/W, 25 degrees C)	108	147	164	188
Thermal Efficiency	85%	89%	91%	95%
Efficiency of Driver	85%	89%	90%	90%
Efficiency of Fixture	80%	84%	88%	95%
Resultant luminaire efficiency	58%	66%	72%	81%
Luminaire Efficacy- Commercial Cool White (lm/W)	63	97	118	152

Notes:

1. Efficacy projections for cool white luminaires assume CRI=70 → 80 and a CCT = 4100-6500°K.
2. All projections assume a 350mA drive current, 1mm² chip size, reasonable device life and operating temperature.
3. Luminaire efficacies are obtained by multiplying the resultant luminaire efficiency by the device efficacy values.

Source: LED Technical Committee, Fall 2008

4.3.3. Organic Light Emitting Diodes

In consultation with the Technical Committee, 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 4.10 (plotted on a logarithmic scale) predicts that the efficacy of laboratory prototypes will grow exponentially to reach 150 lm/W by 2012. As noted earlier, only one commercial OLED luminaire appears to have been produced for sale as of this writing, and in very limited quantities. Given such limited availability for commercial



OLED lighting products, the estimated efficacies for commercial products are not very meaningful but have been assumed to lag approximately three years behind the laboratory products. Although the overall SSL program may be expected to continue until 2025 in order to achieve technologies capable of full market penetration, the commercial OLED efficacy forecast in this section only projects performance to 2015 due to a lack of knowledge about the ultimate limit of this technology. These projections assume the CRI and CCT mentioned above and a luminance of 1,000 cd/m² for a pixel-sized OLED device. These projections apply to a white light OLED device with a color point “near” the blackbody curve ($\Delta c_{xy} < 0.005$)⁵⁵, which may be a necessary criterion to market the products for various general illumination applications. The figure indicates CRI and CCT values for devices with available CRI and CCT information. 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.

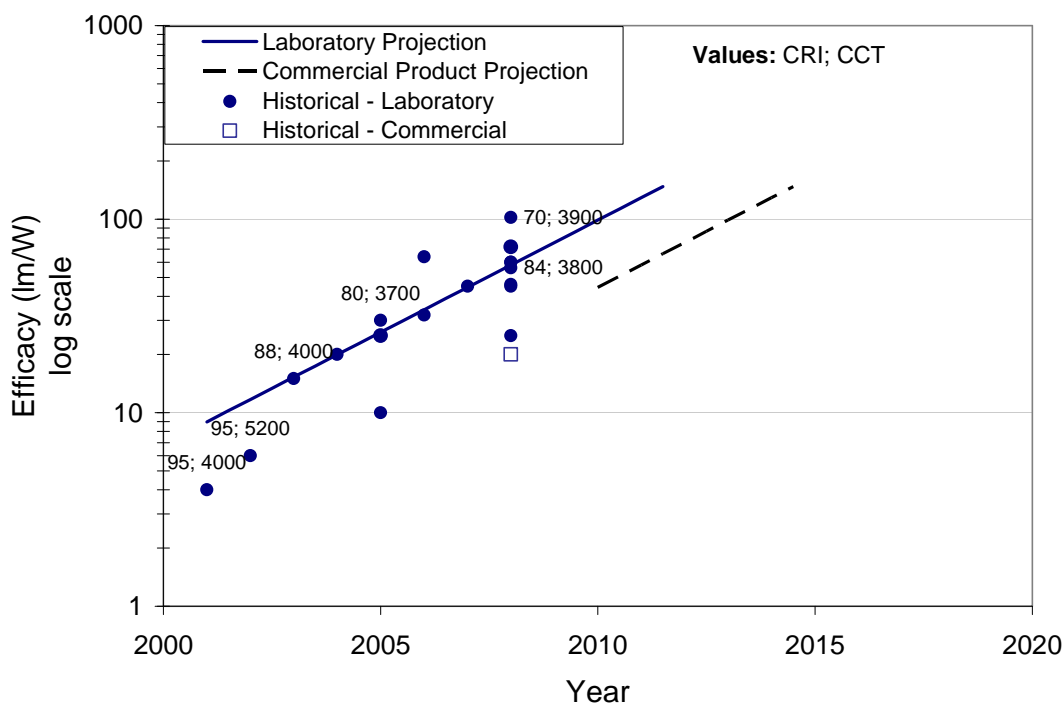


Figure 4.10: White Light OLED Device Efficacy Targets, Laboratory and Commercial (On a logarithmic scale)

Note: Efficacy projections assume CRI > 80, CCT = 2700-4100°K (“near” blackbody curve ($\Delta c_{xy} < 0.005$), lifetime > 1000 hrs, luminance of 1,000 cd/m², and device level specification only (driver/luminaire not included). CRI and CCT shown for those devices for which it is known.

Source: Projections: OLED Technical Committee, Fall 2008; Laboratory Points: Press Releases

Today, the efficacy of OLED devices lags behind LED devices. However, researchers are optimistic and when the projections of commercial LEDs and OLEDs are compared (see Figure 4.11) the efficacy of OLED products appears to approach that of the LED

⁵⁵ Δc_{xy} is the distance from the blackbody curve in C.I.E. color space.



products in the latter part of the current forecast.

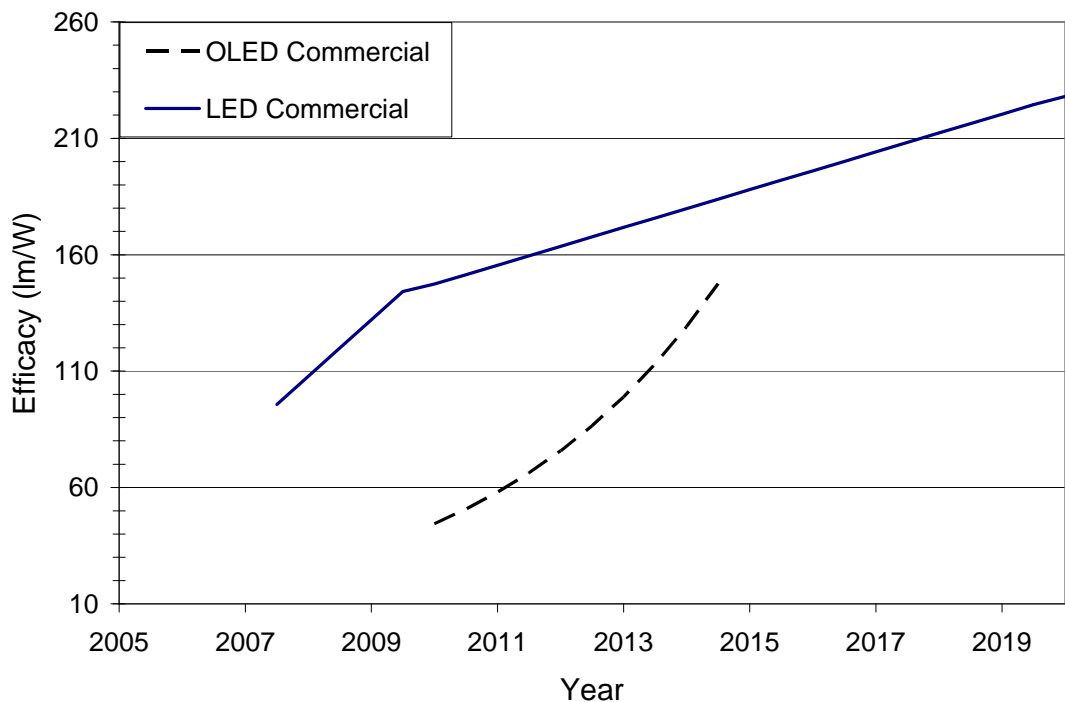


Figure 4.11: LED and OLED Device Efficacy Projections, Commercial

Source: LED and OLED Technical Committees and the Department of Energy, Fall 2008

Figure 4.12 presents the forecast targets for the OEM price of commercially available white light pixel-sized OLED devices (driver and fixture not included) with a luminance of $1,000 \text{ cd/m}^2$. The price is expected to fall to $\$10/\text{klm}$ by 2015, assuming reasonable volumes of OLED panels (approximately one square meter in size) are sold. Prices of OLEDs may remain around $\$10/\text{klm}$ after 2015, although future price reductions are possible. The OEM device price, measured in $\$/\text{m}^2$, is approximately a factor of three greater than OLED device price when measured in $\$/\text{klm}$ for the assumed luminance of $1,000 \text{ cd/m}^2$. 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, however, an OLED luminaire with a more expensive “device” may still be cost competitive with a conventional luminaire.

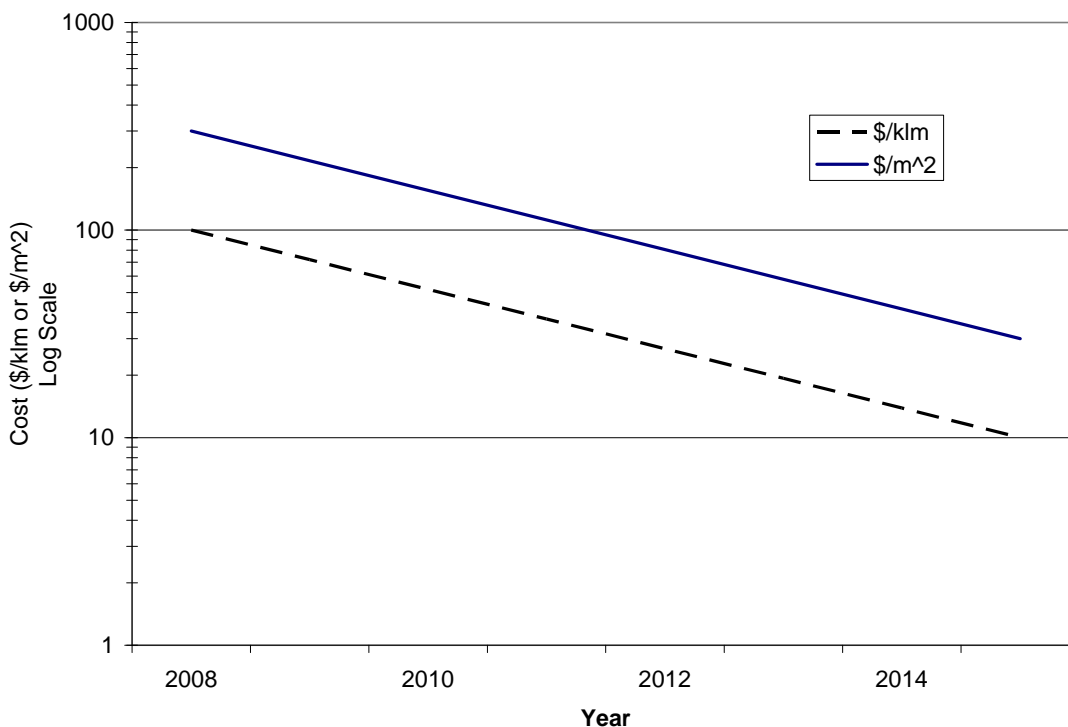


Figure 4.12: White Light OLED Device Price Targets, \$/klm and \$/m²

Note: Price targets are displayed on a logarithmic scale

Source: OLED Technical Committee, Fall 2008

The device life for commercial products, defined as 70% lumen maintenance, is expected to increase linearly to a value of approximately 50,000 hours in 2015. Although 50% lumen maintenance is industry practice for evaluation of OLED displays, we use 70% lumen maintenance⁵⁶ in order to compare lifetimes with other lighting products.

Table 4-4 presents a summary of the OLED performance projections in tabular form. Projections below represent the lifetime of the device, not an entire OLED luminaire. Although the OLED device may reach long lifetimes, other components of the OLED luminaire like the driver may limit the luminaires lifetime. Therefore improving the lifetime of these additional components to at least equal that of the OLED device is a goal of the SSL program.

⁵⁶ 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	2008	2010	2012	2015
Efficacy- Lab (lm/W)	58	99	150	150
Efficacy- Commercial (lm/W)	N/A	44	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	50

Notes:

1. Efficacy projections assume CRI = 80, CCT = 2700-4100°K (“near” blackbody curve ($\Delta c_{xy} < 0.005$), luminance of 1,000 cd/m², and device level specification only (driver/luminaire not included)
 2. OEM price projections assume CRI = 80, luminance of 1,000 cd/m², and device level specification only (driver/luminaire not included)
 3. Device life projections assume CRI = 80, 70% lumen maintenance, and luminance of 1,000 cd/m².
- Source: OLED Technical Committee, Fall 2008

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 2008 driver and fixture efficiency values to 2015 program targets as given in Figure 4.7. 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 2010 OLED commercial luminaire efficacy projection becomes 36 lm/W while the 2015 OLED commercial luminaire efficacy projection becomes 122 lm/W.



Table 4-5: Summary of OLED Luminaire Performance Projections beginning 2010

Metric	2008	2010	2012	2015
Commercial Device Efficacy (lm/W) (Table 4-4)	N/A	44	76	150
Efficiency of Fixture	90%	90%	92%	95%
Efficiency of Driver	90%	90%	92%	95%
Total Efficiency from Device to Luminaire	81%	81%	85%	90%
Resulting Luminaire Efficacy-Commercial Product (lm/W)	N/A	36	65	122

Notes:

Efficacy projections assume CRI = 80, CCT = 2700-4100°K (“near” blackbody curve ($\Delta c_{xy} < 0.005$), luminance of 1,000 cd/m², and device level specification only (driver/luminaire not included).

Source: OLED Technical Committee, Fall 2008

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. For OLEDs, the cost and future availability of indium, often used in OLED electrodes, is of particular concern.
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. For example, the industry must find ways to minimize the amount of “droop” in efficiency that occurs at high drive currents for LEDs. Improving red light emission in wavelengths specifically for color quality in efficacious lighting would also



benefit LED lighting products. While laboratory experiments demonstrate that OLED devices can be competitively efficacious as compared to conventional technologies, no products are yet available.

3. **Lifetime:** The lifetime of LEDs and OLEDs is defined as the number of hours for which the device maintains 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. Furthermore, this definition of life is inadequate for luminaires. Lumen maintenance is only one component of the lifetime of a complex system such as a luminaire which may be subject to other failure mechanisms. For example, potential premature failure due to high temperature operation remains a barrier to general deployment. OLED lifetimes for both devices and luminaires still require improvement. The development of a long-lasting blue emitter for OLEDs is critical.
4. **Testing:** The reported lumen output and efficacies of LED and OLED products in the market do not always match laboratory tests of performance. Improved and standardized testing protocols for performance metrics need to be developed. An important barrier appears to be a lack of understanding of the meaning of device specifications versus continuous operation in a luminaire on the part of designers. Furthermore, accelerated reliability testing methods for systems and materials are absolutely necessary for market penetration. Uncertainty in both device and luminaire lifetimes creates risk for manufacturers and consumers, potentially reducing adoption rates.
5. **Lumen Output:** LED luminaires are reaching reasonable total lumen output levels although many still perceive LEDs as offering only “dim” light, a significant market barrier. OLED packages with useful levels of output remain yet to be developed.
6. **Manufacturing:** While OLEDs have been built off of display manufacturing capabilities, there has been little investment by manufacturers in the infrastructure needed to develop commercial OLED lighting products. A breakthrough is necessary to produce low-cost OLEDs for general illumination. Lack of process uniformity is an important issue for LEDs and is a barrier to reduced costs as well as a problem for uniform quality of light.
7. **Codes and Standards:** New guidelines for installation, product safety certifications such as the UL provided by the Underwriters Laboratory must be developed. Common standards for fixture (or socket) sizes, electrical supplies and control interfaces may eventually be needed to allow for lamp interchangeability. Standard test methods are still lacking in some areas. In general, the development of appropriate codes and standards will enable consistency from brand to brand and year to year, reducing uncertainty for consumers.



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

4.5. Critical R&D Priorities

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, March 2007, and March 2008 editions of the Multi-Year Program Plan. Because of continuing progress in the technology and better understanding of critical issues, the task structure for the 2009 MYPP was revisited and substantially revised during DOE solid-state lighting roundtable sessions held in Washington, D.C. in September of 2008. Further refinement occurred through a series of conference calls with members of DOE SSL technical committees in the fall of 2008.

[After receiving input from participants at the 2009 DOE SSL R&D workshop, DOE will define new R&D priorities based on a new task structure. Tables with this new structure will appear at the workshop; tables with the prioritized task structure will appear in the final version of the 2009 MYPP.]

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 was 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 that 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 goals of 140 lm/W and a cost <\$10/klm for a commercial device will be exceeded. Also, DOE expects to see a high efficiency luminaire on the market by 2012 that has the equivalent lumen output of a 75W incandescent bulb and an efficacy of 126 lm/W. Finally, by FY15, costs should be below \$2/klm for LED devices while also meeting other performance goals.



Table 4-6: LED Device 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; < \$10/klm
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°C

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 while further decreasing price in order to realize the best possible energy savings. This phase should be completed in about two years. Developing a more efficient luminaire is the thrust of Phase 3, expected to last until about 2012. Finally, the fourth phase is to significantly reduce the cost of LED lighting to the point where it is competitive across the board. This phase, currently underway, is expected to continue past 2015.

[The Gantt charts referred to below are not complete for the 2009 MYPP. These charts will be added following feedback from the 2009 DOE SSL R&D workshop breakout sessions.]

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 DOE team as high priority have shaded task names. For reasons noted above, the two do not necessarily coincide.

Figure 4.13: White LED Program Gantt Chart *[to be added following the 2009 DOE SSL R&D workshop]*



4.6.2. Organic Light Emitting Diodes

The FY08 OLED milestone was to produce an OLED niche product with an efficacy of 25 lm/W, an OEM price of \$100/klm (device only), and a life of 5,000 hrs, with a CRI greater than 80 and a CCT between 3,000-4,000K. A luminance of 1000 cd/m² 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 102 lm/W (at reasonable life, luminance, and CCT), there appears to be just one niche OLED product available in the marketplace for general illumination applications. This is a table lamp produced by the designer Ingo Maurer and sold in limited quantities. The lamp is shown in Figure 4.4 at the beginning of this chapter. With an efficacy of 20 lm/W, it does not appear to meet the milestone precisely. The other parameters for this product are unknown at this time but the price point has undoubtedly also not been met.

According to industry experts, major manufacturers are likely to wait for OLED laboratory prototypes to achieve higher efficacies before investing in the manufacturing infrastructure to produce high efficacy, competitively priced OLED products for general illumination purposes. Milestone 2 targets an efficacy of greater than 45 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 the large area of OLED panels, so although the FY08 milestone may be late in coming, cost reduction remains the focus of the milestone for FY12.⁵⁷ By FY15 the target is to get a 100 lm/W OLED panel. Cost and lifetime should show continuous improvement as well.

⁵⁷ Initially, cost reductions were targeted for FY10, however this was moved to FY12 for the 2009 report as products have just begun to enter the market.



Table 4-7: OLED Panel Milestones

Milestone	Year	Milestone Target
Milestone 1	FY08	25 lm/W, < \$100/klm, 5,000 hrs
Milestone 2	FY10	> 45 lm/W
Milestone 3	FY12	< \$30/klm
Milestone 4	FY15	> 100 lm/W

Assumptions: CRI > 80, CCT < 2700-4100K and luminance = 1,000 cd/m², and total output ≥ 500 lumens for an OLED panel. All milestones assume continuing progress in the other overarching parameters - lifetime and cost.

Figure 4.14: White OLED Program Gantt Chart *[to be added following the 2009 DOE SSL R&D workshop]*

4.7. Unaddressed Opportunities *[may be revised following the 2009 DOE SSL R&D workshop]*

Funding for the research tasks for LEDs and OLEDs is allocated, to the extent possible, according to the priorities agreed upon by the LED and OLED Technical Committees, 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 be 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 this area is 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 occurs in Asia.
- 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 a barrier to this technology.

While some manufacturing subtasks can be prioritized for core R&D, there is not



sufficient funding at this time to support advanced manufacturing development to the extent contemplated above.