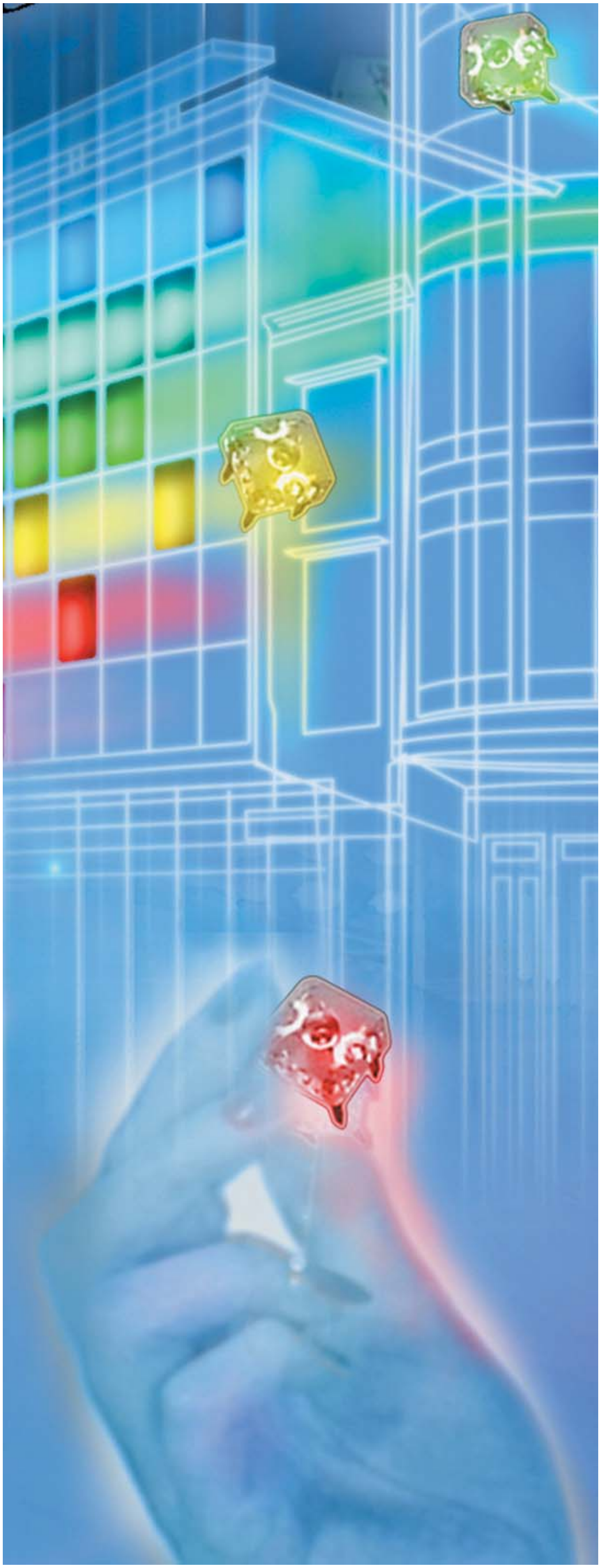

Multi-Year Program Plan

Solid-State Lighting Research and Development Portfolio

Section 4.0: Technology Research and Development Plan

FY'07-FY'12

Prepared for:

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

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January 2007

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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.

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 five to ten years. 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[28]

The following 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 inefficiencies 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

At their most basic level, LED luminaires are comprised of three components, the *driver*, the *LED device* and the *fixture and optics* of the luminaire. These are illustrated by example photos in Figure 4-1 below.

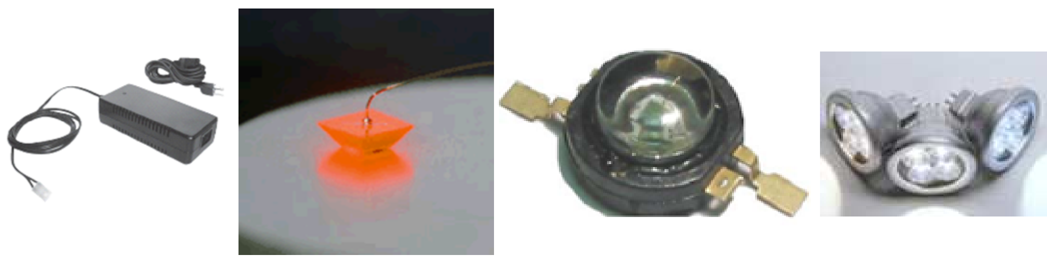
- The driver consists of the power supply and electronic controls that manage the LED device. It converts line power to appropriate voltage and current, and may also provide sensing of and corrections for shifts in color or intensity that occur due to age or temperature effects over the life of the product.

- The LED device includes the chip and its associated packaging. The device

[28] In the March 2006 edition of the SSL MYP, the term "system" was used to describe the combined source, driver, and fixture. However, 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

includes the semiconductor die itself, the mounting substrate, the encapsulant which in some cases forms a lens, and the phosphor (if applicable). The encapsulant surrounds the chip for protection, and affects light extraction from the chip (through index of refraction and loss).

- The fixture houses these components and provides optical management of the light emission. "Optical management" may include color mixing optics, reflectors, and diffusers, or any other light-modifying structure.



a) Driver **b) Chip** **c) Device** **d) Fixture and Optics**

Figure 4-1: Photos of LED Luminaire Components

Sources: Lumileds, Color Kinetics.

4.1.2. Components of OLED Luminaires

The OLED may be described in similar terms, although the "device" and "fixture" are difficult to distinguish in some panel configurations that are currently being explored. The OLED device consists of layers of materials, including an emissive layer that corresponds to the basic LED chip and other layers that provide encapsulation, electrical connection and packaging. The existence of the electrode and the substrate in the light path is an important distinction between an OLED and an LED. The OLED's substrate adds scattering losses, which is not a significant issue with glass, the typical material in today's OLEDs, but may become an issue with flexible polymers that may be used in the future. For large area OLEDs, electrode sheet resistance may also become significant; however, this can be minimized with certain electrical designs. As the complexity of the electrodes or the segmentation increases, a diffuser may become necessary to obscure blocked areas (visible in the panel shown in Figure 4-2). In some OLEDs, the emissive layers (there may be more than the one shown in the simplified diagram below) emit light in both directions, but the metal cathode reflects the light so that it, too, passes through the substrate. Therefore, the reflective properties of the cathode may also introduce losses into the luminaire. The simple planar structure shown in this diagram would trap much of the light within the OLED device due to internal reflections. Therefore, modification of the substrate surface could be employed to improve the efficiency. It is also possible to manufacture an OLED with a highly transparent cathode (typically with up to 80% transmission across the visible spectral region). This creates the potential for either entirely transparent devices or "top emitting" structures built on opaque or reflective substrate and anode combinations. By engineering the thickness and refractive index of the transparent cathode, an additional degree of control over optical out-coupling is accomplished which might lead to higher extraction efficiency. Furthermore, these architectures enable the use of opaque metal foil substrates and perhaps cheaper, large area materials yet to be invented. Components of an OLED luminaire are shown in Figure 4-2.

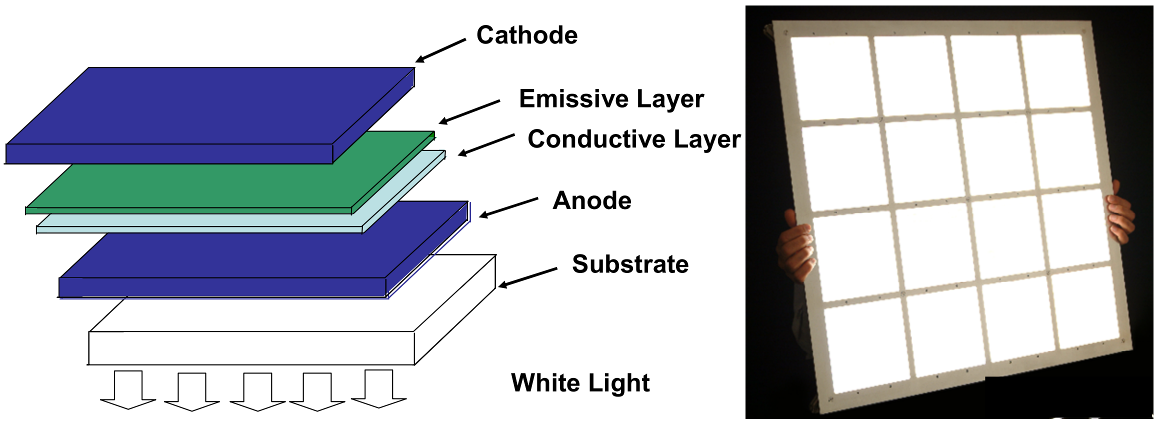


Figure 4-2: Diagram/Photo of OLED Panel

Photo source: General Electric.

4.2. Current Technology Status and Areas of Improvement

To further define the relationship among these components 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 opportunities for LED and OLED luminaires are shown in several figures that follow (Figure 4-3, Figure 4-4, and Figure 4-5). 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 provides both device efficacy and luminaire efficacy values. 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 (heat generation) in the device; improving the efficiency of conversion of electrons into photons and the extraction of those photons from the material (quantum efficiency); and tailoring the spectrum of the radiated light to increase the eye response. Tailoring of the spectrum is constrained by the need to provide light of a particular color quality (correlated color temperature and color rendering index).

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. So, while 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* the program's intention, by stating these intermediate efficiencies, to impede novel developments using a different allocation of losses that may result in a better overall luminaire performance.

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 4-3 presents a diagram of a color-mixing LED luminaire. The percentage efficiencies in the diagram next to each component indicate the typical performance in 2006 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 2006 products typically have color temperatures in the range of 4100-6500°K, and usually a lower CRI. The 2006 typical numbers reflect these less than optimal parameters, and therefore may overstate our current capability.

Over the course of the program, performance improvements will make possible the manufacturing of lamps with lower color temperature and better CRIs without seriously degrading the efficiency. Achieving the program goals will require more efficient emitters (particularly in the green area of the spectrum), and improvements elsewhere in the luminaire greater than those indicated in Figure 4-3.

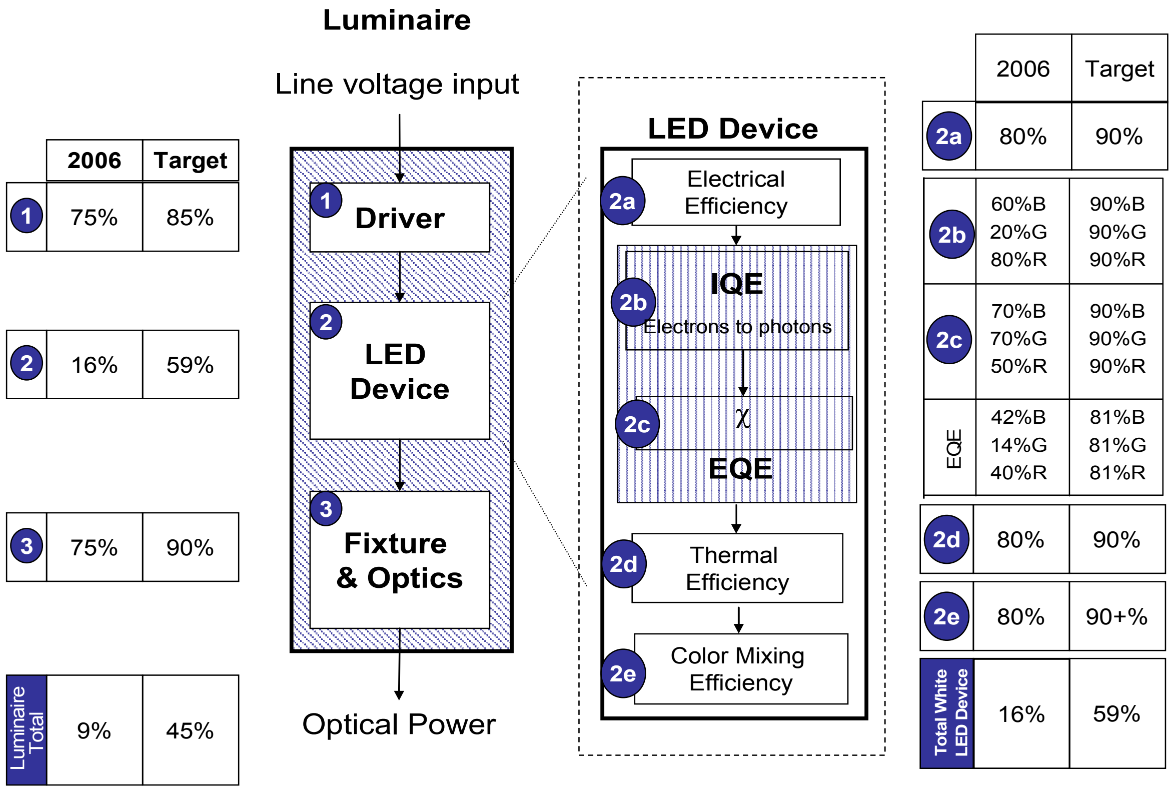


Figure 4-3: Current and Target Luminaire Efficiencies – Color-Mixing LED

(The target assumes a CCT of 4100K and CRI of 80; Current CCT: 4100-6500K, CRI: 75)
Source: NGLIA LED Technical Committee, Fall 2006

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. The losses in the driver are electrical.

Device efficiency, There are several components of the device electrical efficacy that are shown on the right in Figure 4-3 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. Losses in the device are both electrical and optical.

Fixture and optics efficiency, η_{fo}, is the ratio of the lumens emitted by the luminaire to the lumens emitted by the LED lamp, or 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 ("wall plug 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, wall plug efficiency excludes driver losses. The device electrical *efficacy* is the product of the wall plug efficiency and the spectral or optical efficacy due to the human eye response. Elements of the power efficiency are:

> Electrical efficiency, η_v, accounts for the conversion to photon energy from electrical energy (photon energy divided by the product of the applied voltage and electron charge). The forward voltage applied is determined by the diode characteristics, and should be as low as possible in order to get the maximum current (hence maximum number of electrons eligible to convert to photons) for a given input power. When resistive losses are low, it is essentially the breakdown voltage which is approximately the bandgap energy divided by the electronic charge. Resistive losses and electrode injection barriers add to the forward voltage.
>
> 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 LED.
>
> Extraction efficiency, χ, is the ratio of photons emitted from the encapsulated chip into air to the photons generated in the chip. 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.[29]
>
> Thermal Efficiency, is the ratio of a device lumens emitted by the device in thermal equilibrium under continuous operation to the lumens emitted by the device at 25°C. [30]

[29] 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, perhaps a role for NIST.

[30] 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, the device operates a temperature higher than 25°C at thermal equilibrium.

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 4-3 is assumed to occur in the lamp/device.

The device-related parameters of the luminaire have the greatest headroom for improvement in the short term. For example, the external quantum efficiencies (2c) of the chips range from 14% to 42%, depending on color. The ultimate goal is to raise the EQE of the chip blend to 81%. However, as the diodes 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 4-4) because the driver needs to produce different colors with different (and controllable) colors. The ultimate target for this component is to improve the efficiency to greater than 85%. Likewise, there is considerable room for improvement of the fixture and optics. Currently, the color-mixing LED luminaire is approximately 9% efficient at converting electrical energy into visible white-light. If all targets are achieved, the LED device (lamp) would have an efficiency of 59%, with an overall luminaire efficiency of 45%.

The losses estimated above are with respect to power and independent of spectrum. However, the electrical luminous efficacy (in lm/W_e)[31] of the color-mixing LED device can be calculated by multiplying the wall plug efficiency (W_o/W_e) by the *optical* or *spectral* luminous efficacy of radiation (LER). For blended LEDs, the LER is approximately 360[32] lm/W_o (exact value varies with the CRI and CCT for the particular design and the available wavelengths). Using this conversion, the target for a color mixing LED device would be close to 212 lm/W_e (59% efficiency, above, multiplied by 360 lm/W_o). This would result in an overall luminaire efficacy, absent significant breakthroughs, of approximately 160 lm/W_e. 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 retrofittable 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.

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[31] The subscript "e" denotes electrical Watts into the lamp and "o" denotes optical Watts within the lamp. Unless otherwise stated, "efficacy" means electrical luminous efficacy.

[32] NIST has simulated an LER of 361 lm/W_o at a CRI of 97 and CCT of 3300K. The committee chose 360 lm/ W_o as a realistic number for a CCT of 4100K and a CRI of 80, the parameters for these projections. (Ono, Y. "Color Rendering and Luminous Efficacy of White LED Spectra." Proc. SPIE 49th Annual Mtg., Conf. 5530 (2004).)

Phosphor Converting LED

Figure 4-4, below, presents a diagram of a phosphor converting LED luminaire. The definitions for the various efficiencies are the same as listed for Figure 3-7, with an additional definition for phosphor conversion efficiency:

> Phosphor efficiency, η_{phos} , accounts for the conversion efficiency, Stokes loss, of the phosphor. This is a fundamental property of phosphor-converting LEDs.
>
> Scattering efficiency is the ratio of the photons emitted from the LED lamp to the number of photons emitted from the semiconductor chip. This efficiency, relevant only to the phosphor converting LED in Figure 4-4, accounts for scattering losses in the encapsulant of the lamp.

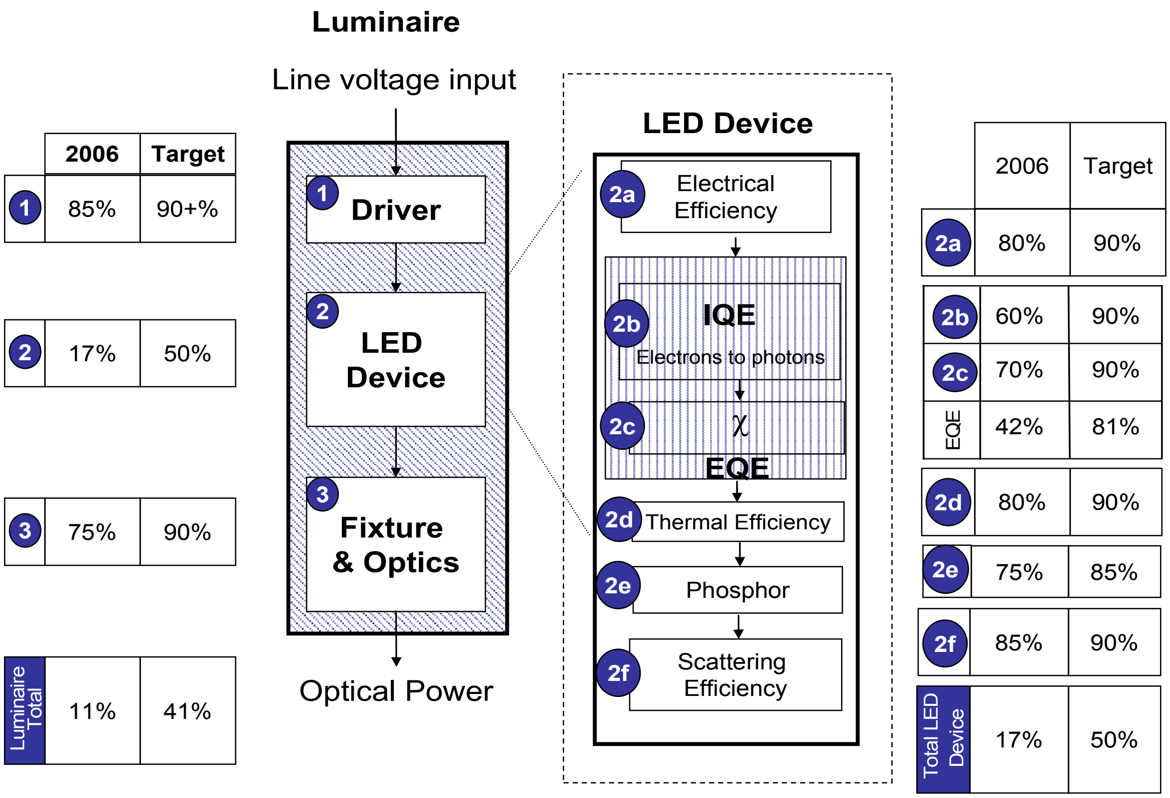

Figure 4-4: Current and Target Luminaire Efficiencies - Phosphor Converting LED

(The target assumes a CCT of 4100K and CRI of 80; Current CCT: 4100-6500K, CRI: 75)

Source: NGLIA LED Technical Committee, Fall 2006

In the above figure, Component 1, the driver, has an efficiency of 85% for 2006 products (with available switching techniques). The ultimate target for this component is to improve the efficiency to greater than 90%. In comparison, other components of the luminaire have more room for efficiency improvements. For example, the extraction efficiency of the LED chip is currently only 70%. 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 11% efficient at converting electrical energy into visible white-light. If all targets are reached, the LED device (lamp) would have an efficiency of 50%, with a luminaire efficiency of 41%. 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 wall plug 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 147 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 4-5 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.

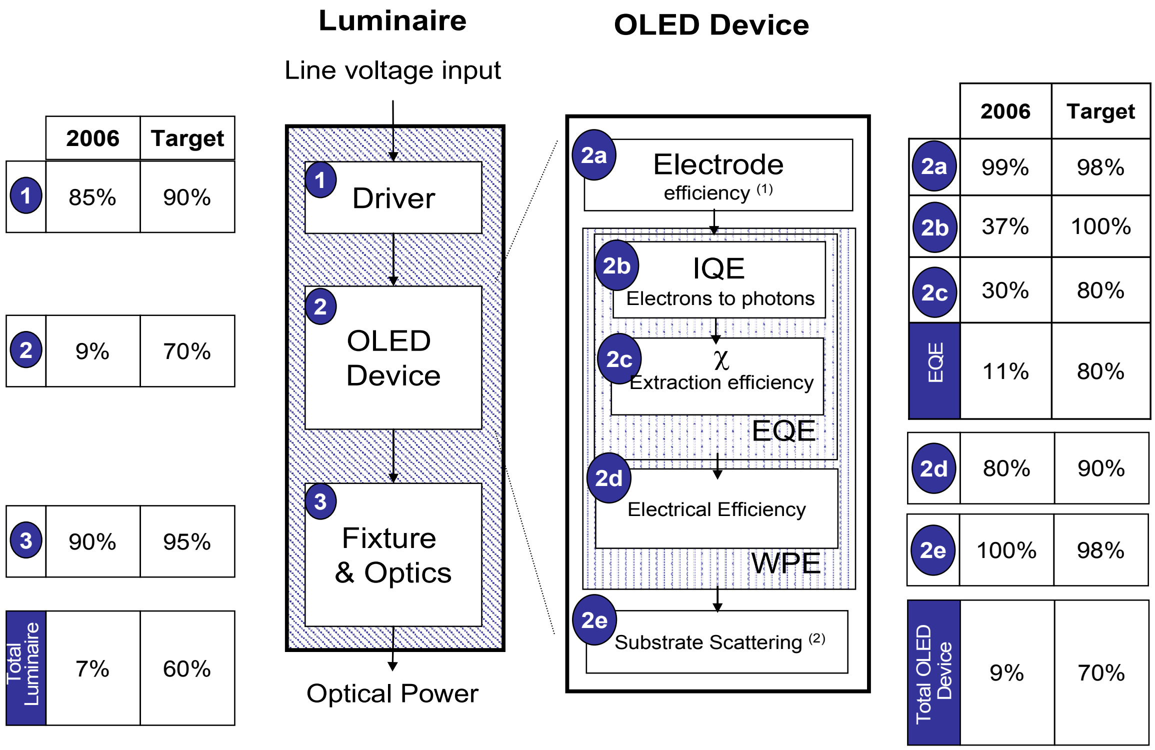

Figure 4-5: OLED Luminaire Efficiencies & Opportunities

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

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 2006

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 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 tricks 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. Only a short while ago it was thought that efficiencies of OLEDs would be limited to 25%, but the realization that triplet states could be harvested has raised the projections. 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 are area emitters, fixtures, to the extent that they are used to reduce glare, could almost be eliminated if the brightness of the OLED lamp itself could be kept below 800 cd/m^2, distributing the total lumen output over a large 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. It is also somewhat difficult to achieve low forward voltages primarily because of barriers at the electrodes, but also due to series resistance. 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 a “reasonable” level of funding by both government and private industry. A figure that has been quoted for the SSL program is $25M for 20 years. This is probably a good overall figure, albeit over-simplified. For instance, the profile of spending may be lower in the early years as fundamental issues are explored, but higher in the later years as practical problems of achieving high efficiency are encountered. 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, forecasts in this section only project performance to 2015.

Note that these performance goals are *exclusive* of the driver and fixture as discussed above. Thus, the goals do not entirely capture the objectives of the SSL program which relate to *luminaire* efficiency or cost. Reaching these ultimate objectives will take longer than may be inferred from these graphs of device performance as shown by the luminaire efficiency values in Table 4-2. It is not anticipated that it will be difficult to achieve good driver performance (although there are some challenges). On the other hand, innovative fixtures for LEDs can have a significant impact on overall efficiency, and the challenge in this area is to accommodate aesthetic and marketing considerations while preserving the energy-saving advantages.

4.3.1. Light Emitting Diodes

The price and performance of white LED devices are projected assuming that they are operating at a correlated color temperature (CCT) of approximately 4100-6500°K[33] and a color rendering index (CRI) of 70-80 or higher. The choice of the rather cool light provides a reference point based on commercial product today. The goal is to have future improvements that will allow warmer light at similar efficiencies, but such improvements may occur later in the SSL program, beyond the forecast period of this report. Two projection estimates are shown, one for laboratory prototype LEDs, and one for commercially available LEDs. In the March 2006 edition of the SSL MYP, the commercial efficacy projection assumed a three year lag between laboratory demonstrations and commercialization. However, new data, shown in Figure 4-6, suggests a one and a half year lag is more appropriate. Because new data also suggests that progress could be advancing more rapidly than previously projected, the slope of the laboratory and commercial projections was increased from the March 2006 projections.

Figure 4-6 shows *device* efficacy improving linearly through 2015 (driver/fixture efficacies are excluded). The dotted lines indicate a continuation of this linear projection though it is unclear whether devices will eventually reach those efficacies. The efficacy for high power laboratory prototypes reaches 162 lm/W in 2013. Commercial products should reach a level of about 145 lm/W by that time. These projections assume the CRI and CCT mentioned above and a prototype with a "reasonable" lamp life. A number of actual reported results for both high power and low power diodes are plotted on the curve as well, 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, the two reported results are not directly comparable. However, there is a possibility one could achieve a high efficiency light source using these low-power devices. While higher efiicacy claims have been made, they cannot be compared unless all these parameters are known. By stating the assumptions, it should be easier in the future to track progress against the Department's goals.

Although the program is planned to continue past 2015, it is difficult to make meaningful

[33] The cooler color temperature has been chosen to reflect the current and near-term state of the art. Warmer color temperatures will result in lower efficacies, primarily because of the eye response. Notwithstanding, the expectation is that devices near these operating goals will be achieved in the future with lower color temperatures and higher efficacies so as to make them useful for a wider space of applications.

projections further into the future. Additional improvements are anticipated for future years, for example, warmer light at similar energy performance. For comparison to the projected performance, a rough estimate of progress towards a higher future CRI of 85, lower CCT of approximately 2800-3500°K lamps (still excluding other luminaire components) is also indicated in the figure. Plans and goals will be revisited as the program progresses.

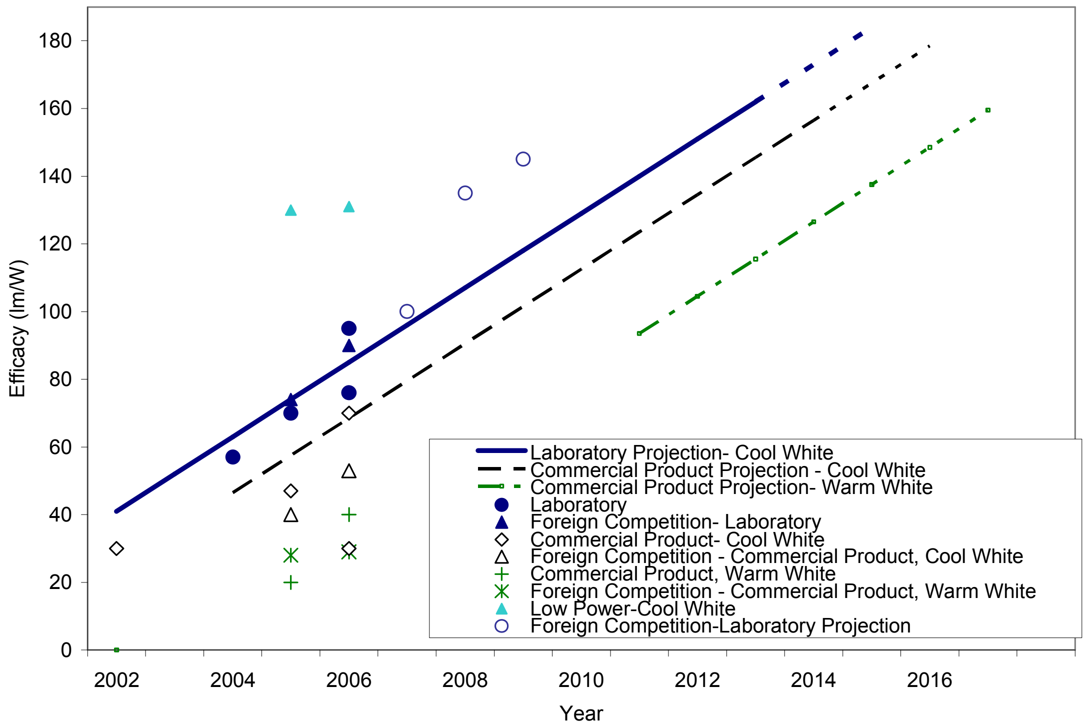

Figure 4-6: White Light LED Device Efficacy Targets, Laboratory and Commercial

Note:
1. Cool white efficacy projections assume CRI=70 → 80, Color temperature = 4100-6500°K,
2. Warm white efficacy projections assume CRI>85, Color temperature=2800-3500°K
3. All projections are for high-power diodes with a 350 ma drive current at 25°C, lamp-level specification only (driver/luminaire not included), and reasonable lamp life.
4. Low power diodes shown have a 20 mA drive current.
5. The dotted line indicates a continuation of the projection though it is uncertain whether devices will eventually reach those efficacies.

Source: Projections: NGLIA LED Technical Committee and the Department of Energy, Fall 2006, Points: Press Releases

The cost estimates were also developed in consultation with the NGLIA Technical Committee, and represent the average performance of 1-3 watt white-light LED devices driven at 350 mA (excluding driver or fixture costs). 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 4-7. 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.[34]

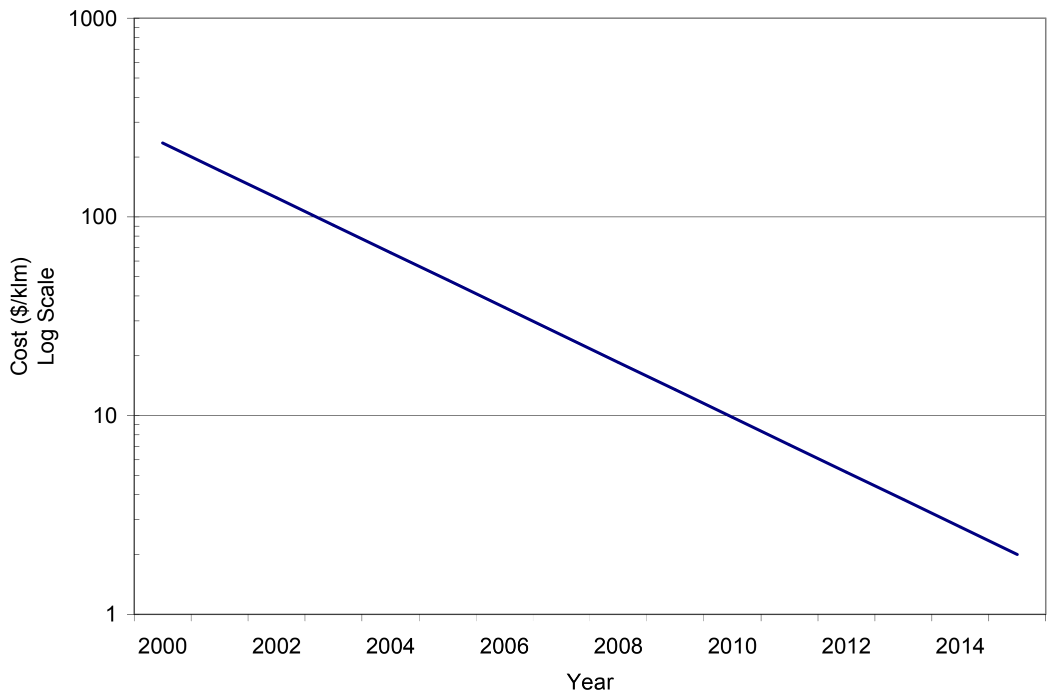

Figure 4-7: White Light LED Device Price Targets, Commercial

(On a logarithmic scale)

Note: Price targets assume "reasonable volumes" (several 1000s), CRI=70 → 80,
Color temperature = 4100-6500K, and lamp-level specification only (driver/fixture not included)
Source: NGLIA LED Technical Committee, Fall 2006

[34] The first cost of light sources listed in section 2.3.2 is 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. By 2015, LEDs will be able to compete with both High-Intensity Discharge lamps and Compact Fluorescents based solely on first cost. It is important to keep in mind that energy savings, replacement cost, and labor costs also factor into a lamps overall price. Because of these factors, LEDs are already competing with niche incandescent products.

Figure 4-8 presents the projection for LED device lifetime. The device life, measured to 70% lumen maintenance, is projected to increase linearly until it reaches 50,000 hours in 2008. An average lamp life of 50,000 hours would allow 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. It is important to note that projections below represent the lifetime of the device, not the luminaire. Because drivers may limit the lifetime of the LED luminaire, improving the lifetime of the driver to equal or exceed that of the LED device is a goal of the SSL program.

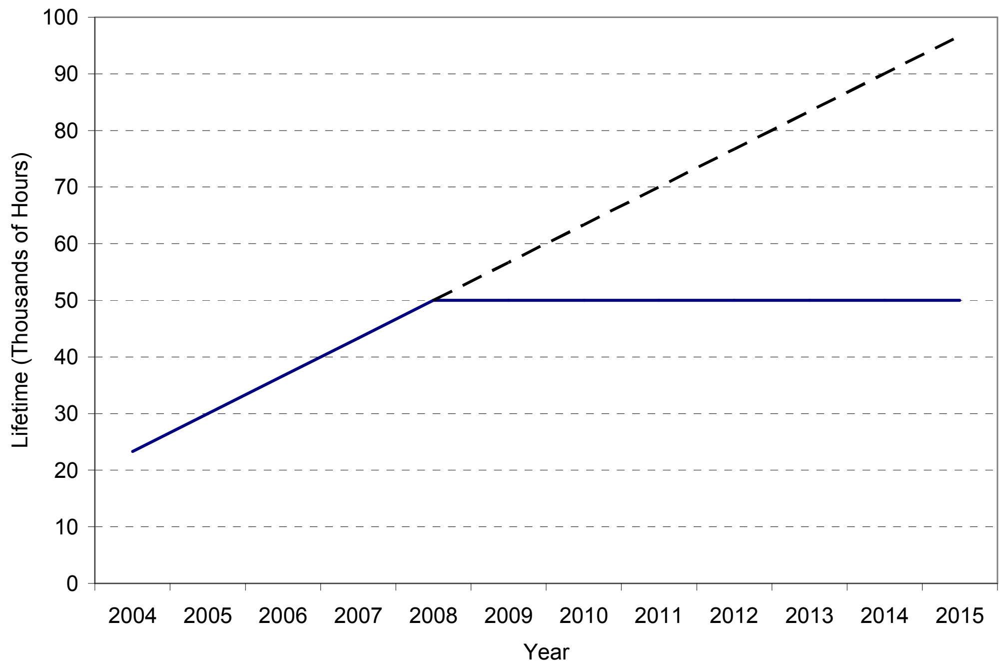

Figure 4-8: White Light LED Device Lifetime Targets, Commercial

Note: Lamp life projections assume 70% lumen maintenance, “1 Watt device,” 350mA drive current.
Source: NGLIA LED Technical Committee, Fall 2006

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 flattens out at approximately 50,000 hours. Yet, LED products for niche/specialty applications could be developed with longer lamp life, upwards of 100,000 hours, by trading off with other performance parameters. A lifetime projection for these specialty products is shown as a dashed line in Figure 4-8.

A lifetime of 50,000 hours is not easy to measure or substantiate. There are some who argue that lifetime is already not an issue for LEDs, but it is not proven. 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 4.4. Table 4-1 presents a summary of the LED performance projections in tabular form.

Table 4-1: Summary of LED Device Performance Projections

Metric	2006	2010	2012	2015
Efficacy- Lab (lm/W)	85	129	151	184
Efficacy- Commercial Cool White (lm/W)	68	113	135	168
Efficacy- Commercial Warm White (lm/W)	38	83	105	138
OEM Lamp Price- Product ($/klm)	35	10	5	2
Lamp Life- (1000 hours)	37	50	50	50

Note:
1. Efficacy projections for cool white lamps assume CRI=70 → 80 and a Color temperature = 4100-6500°K, while efficacy projections for warm white lamps assume CRI= >85 and a Color temperature of 2800-3500°K. All efficacy projections assume that devices are measured at 25°C.
2. All lamps are assumed to have a 350 mA drive current, lamp-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 lamp-level specification only (driver/luminaire not included)
4. Lamp life projections assume 70% lumen maintenance, "1 Watt device," 350 mA drive current.
Source: NGLIA LED Technical Committee, Fall 2006

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 4-2 are luminaire performance projections to complement the device performance projections given in Table 4-1.

Values in Table 4-2 assume a linear progression over time from the current 2006 fixture and driver efficiency values to eventual fixture and driver efficiency 2015 program targets as given in section 4.1.1. After taking into account all of the factors that affect the performance of an LED luminaire and multiplying them by the original device efficacy projections, it was found that the cool white luminaire efficacy 2006 status is 35 lm/W while the 2015 cool white luminaire efficacy projection is 123 lm/W.

Table 4-2: Summary of LED Luminaire Performance Projections (at operating temperature)

Metric	2006	2010	2012	2015
Device Efficacy-Commercial Cool White (lm/W, 25 degrees C)	68	113	135	168
Device Efficacy Commercial Warm White (lm/W, 25 degrees C))	38	83	105	138
Thermal Efficiency	80%	84%	87%	90%
Efficiency of Driver	85%	87%	88%	90%
Efficiency of Fixture	75%	82%	85%	90%
Resultant luminaire efficiency	51%	60%	65%	73%
Luminaire Efficacy-Commercial Cool White (lm/W)	35	59	88	123
Luminaire Efficacy-Commercial Warm White (lm/W)	20	44	68	101

Notes:
1. Efficacy projections for cool white luminaires assume CRI=70 → 80 and a Color temperature = 4100-6500°K, while efficacy projections for warm white luminaires assume CRI= >85 and a Color temperature of 2800-3500°K. All projections assume a 350ma drive current, reasonable lamp life and operating temperature.
2. Efficacies are obtained by multiplying the efficiency degradation by the device efficacy values shown in Table 4-1.
Source: NGLIA LED Technical Committee, Fall 2006

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 were prepared, 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) shows the efficacy for laboratory prototypes growing exponentially to exceed 150 lm/W by 2014. Unlike the LED device projection which is based off a product that has had time to mature, the efficacy projection for commercial products does not begin until 2008 (the target date for the first niche OLED products) and lags approximately three years behind the laboratory products. Efficacy for commercial products reaches approximately 100 lm/W by 2015.

These projections assume the CRI and CCT mentioned above and a luminance of 1,000 cd/m^2. These projections apply to a white-light OLED device "near" the blackbody curve (Δc_{xy}<.01), 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.

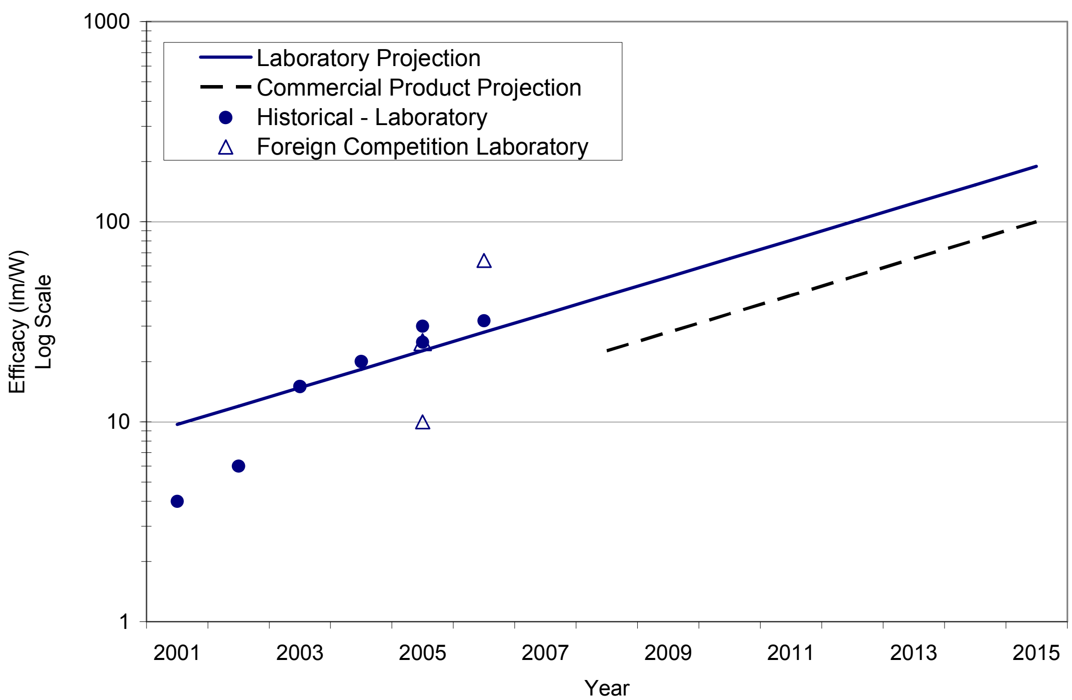

Figure 4-9: White Light OLED Device Efficacy Targets, Laboratory and Commercial

(On a logarithmic scale)

Note: Efficacy projections assume CRI = 80, Color temperature = 2700-4100°K ("near" blackbody curve (Δc<.01xy), luminance of 1,000 cd/m^2, and lamp level specification only (driver/luminaire not included). Source: Projections: NGLIA OLED Technical Committee, Fall 2006, Laboratory Points: Press Releases

Today, the efficacy of OLED devices lags behind LED devices, both in the laboratory and in the market. However, when the projections of commercial LEDs and OLEDs are compared (see Figure 4-10), the efficacy of OLED products should approach that of the LED products in the latter part of the current forecast. This figure reflects the anticipated exponential efficacy improvements of OLED devices as compared to the projected linear improvement in the commercial efficacy of LED devices.

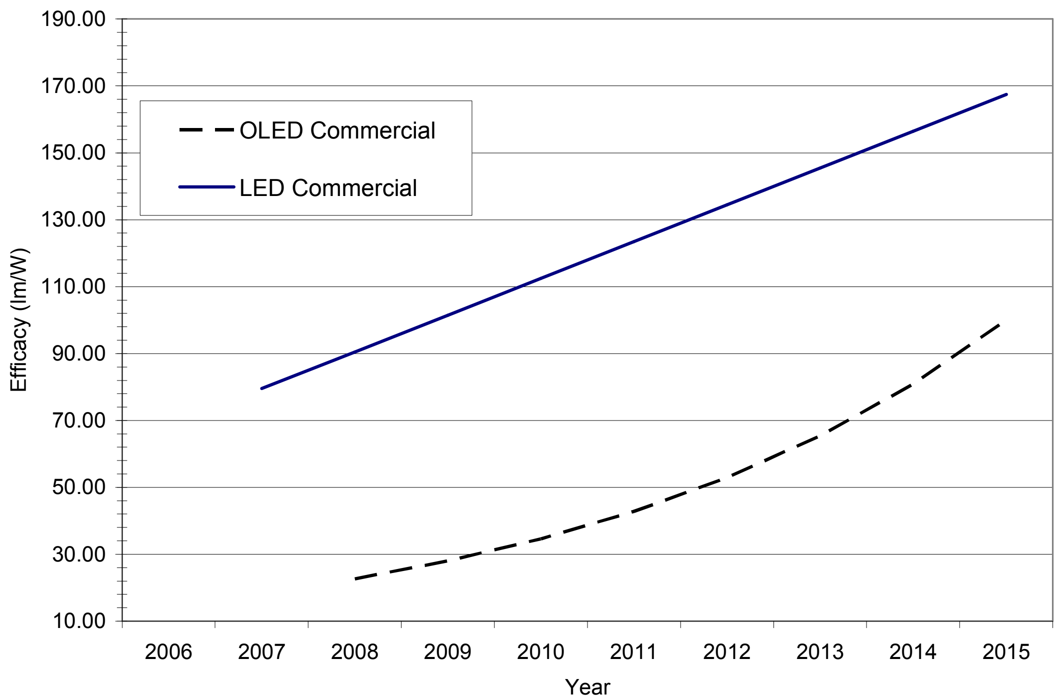

Figure 4-10: LED and OLED Device Efficacy Projections, Commercial

Source: NGLIA OLED Technical Committee and the Department of Energy, Fall 2006

Figure 4-11 presents the projected OEM price of commercially available white-light OLED devices (driver and fixture not included) for a luminance of 1,000 cd/m^2. The OEM lamp price decreases exponentially from an estimated $100/klm in 2008 to $10/klm by 2015, assuming reasonable volumes of tens of thousands. The OEM lamp 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 "lamp/device" may still be cost competitive with a conventional luminaire.

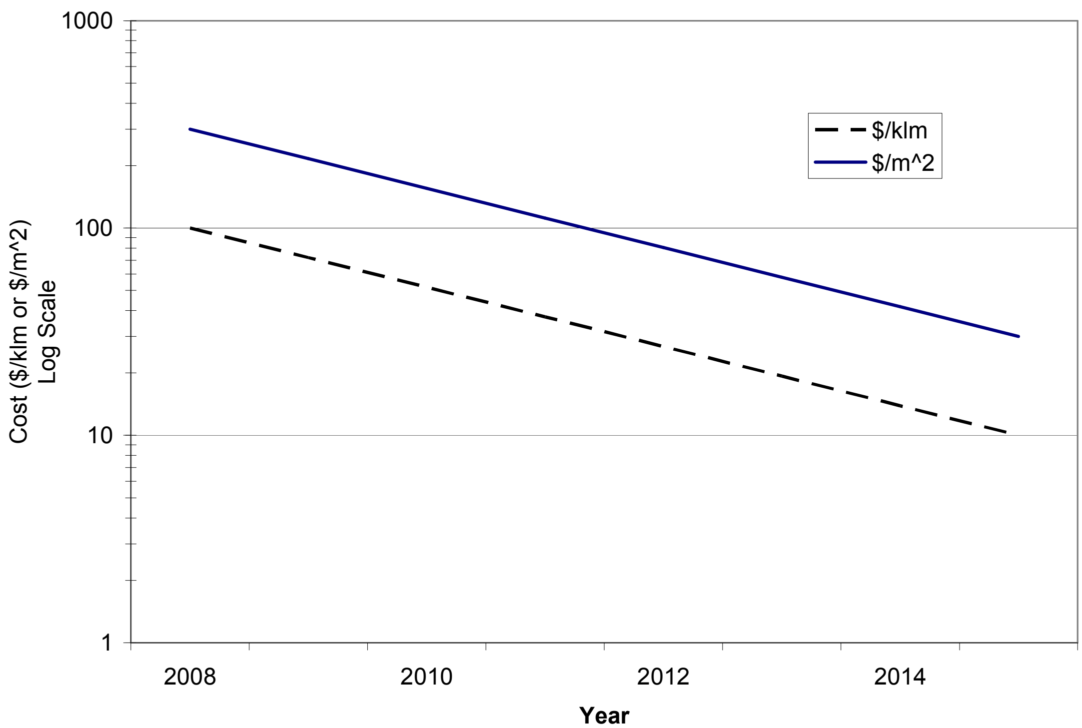

Figure 4-11: White Light OLED Device Price Targets, $/klm and $/$m^2$

(On a logarithmic scale)

Source: NGLIA OLED Technical Committee, Fall 2006

The lamp life for commercial products, measured to 70% lumen maintenance or its "half-life," increases linearly to a value of approximately 40,000 hours in 2015. In the March 2006 version of the SSL MYP, projections were made using 50% lumen maintenance which is industry practice for evaluation of displays. However, in this version we use 70% lumen maintenance in order to compare lifetimes with other lighting products.

Table 4-3 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.

Table 4-3: Summary of OLED Device Performance Projections

Metric	2006	2007	2010	2012	2015
Efficacy- Lab (lm/W)	28	35	65	100	189
Efficacy- Commercial (lm/W)	N/A	18	35	53	100
OEM Lamp Price- ($/klm)	N/A	139	52	27	10
OEM Lamp Price- ($/m2)	N/A	417	155	80	30
Lamp Life- Commercial Product (1000 hours)	N/A	2	16	25	40

Notes:
1. Efficacy projections assume CRI = 80, Color temperature = 2700-4100°K ("near" blackbody curve ($\Delta c < .01xy$), luminance of 1,000 cd/m^2, and lamp level specification only (driver/luminaire not included)
2. OEM Price projections assume CRI = 80, luminance of 1,000 cd/m^2 and lamp level specification only (driver/luminaire not included)
3. Lamp life projections assume CRI = 80, 70% lumen maintenance, luminance of 1,000 cd/m2
Source: NGLIA OLED Technical Committee, Fall 2006

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 4-2. Again, a linear improvement over time is assumed from current 2006 driver and fixture efficiency values to 2015 efficiency program targets as given in Figure 4-5. 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 2007 OLED commercial luminaire efficacy status becomes 14 lm/W while the 2015 OLED commercial luminaire efficacy projection becomes 86 lm/W.

Table 4-4: Summary of OLED Luminaire Performance Projections

Metric	2006	2007	2010	2012	2015
Commercial Device Efficacy (lm/W) (Table 4-3)	N/A	18	35	53	100
Efficiency of Fixture	90%	91%	92%	93%	95%
Efficiency of Driver	85%	86%	87%	88%	90%
Total Efficiency from Device to Luminaire	77%	77%	80%	82%	86%
Resulting Luminaire Efficacy-Commercial Product (lm/W)	N/A	14	28	44	86

Notes:
1. Efficacy projections assume CRI = 80, Color temperature = 2700-4100°K ("near" blackbody curve (Δc<.01xy), luminance of 1,000 cd/m^2, and lamp level specification only
Source: NGLIA OLED Technical Committee, Fall 2006

4.4. Critical R&D Priorities

In order to achieve these projections, progress must be achieved in several research areas. For planning purposes, DOE and the NGLIA Technical Committee have identified the critical research tasks, identified metrics to measure progress in these tasks, and identified ultimate goals for these research tasks.

DOE held a SSL workshop on February 3-4, 2005 to provide a forum for participants to refine and re-prioritize DOE's SSL R&D activities. Table 4-5, Table 4-6, Table 4-7, Table 4-8 list subtasks for LED and OLED Core Technology Research and Product Development, as defined in that forum, that are likely to be necessary to complete the goals as reviewed in this report. At that session, the top priority tasks for 2005-2006 were identified. These tables also identify some metrics for the priority subtasks (titled in bold) that DOE will use to measure progress, together with the targets for these metrics. When considering milestones for overall project progress (see below), it became apparent that additional tasks, not among the top priorities, would also need attention. Therefore, the continuation tables below include some additional "later-priority" tasks; these numbers are not bolded. The committee did not address metrics or intermediate targets for the later-priority tasks listed in these tables.

> ***The NGLIA advisory committee made minor revisions to the priority tasks in the fall of 2006 that reflect both progress to date as well as current research needs. More revisions will be made to the table after the DOE SSL workshop on January 31- February 2, 2007.***

Table 4-5: LED Core Technology Research Tasks and Descriptors (2006-Priority Tasks)

Subtask		Short Descriptor	Metric	2006	Program Target (2015)
1.1.2	High-efficiency semiconductor materials	Research includes: creating a more efficient green LED for a better color-mixing device, and examining the impact of doping on performance.	IQE[35]	20% green, 80% red, 40% blue	90%
1.1.3	Reliability and defect physics for improved emitter lifetime and efficiency	Research areas include: dopant and defect physics, device characterization and modeling, and investigation of droop (reduced efficiency at high temperature and current density) to increase lifetime while maintaining wavelength stability.	-Lifetime and efficiency at high current density $-\Delta\lambda$/ºC		50k hours and 150lm/W at $150A/cm^2$
1.2.1	Device approaches, structures and systems	Work in this area is actually to increase extraction efficiency, but will be measured by progress in EQE.	EQE	50%	80 %
1.2.2	Strategies for improved light extraction and manipulation	Research into integrating optics into the chip, transport structures, device configuration, and reflector design.	Package efficiency	70%	90%
1.3.1	Phosphors and conversion materials	Research into high-efficiency phosphors suitable for LEDs, lumen maintenance issues, nanophosphor research.	Lumens/optical Watt (phosphor)	200 lm/optical Watt (@6000K and 75 CRI)	250 lm/optical Watt (@4100K and 80 CRI)

[35] IQE and EQE status and projections assume pulsed measurements.

Table 4-5: LED Core Technology Research Tasks and Descriptors (later priorities)

Subtask		Short Descriptor
Core Technology		
1.1.1.	Large-area substrates, buffer layers, and wafer research	Create efficient broadband semi-conducting materials. Develop lower defect density materials (GaN, ZnO substrates).
1.3.2	Encapsulants and packaging materials	Create high temperature (~185C), long-life, UV-tolerant encapsulants and packaging materials. Also includes work to develop thermal management strategies and modeling of encapsulants.
1.3.4	Measurement metrics and color perception.	Research in this area includes standardizing metrics to measure electrical and photometric characteristics of LED devices.
1.4.x[36]	Inorganic growth and fabrication processes and manufacturing research.	Research in this task includes: physical, chemical and optical modeling for substrate and epitaxial process, design and development of in-situ diagnostics tools for the substrate and epitaxial process, research into low cost, high-efficiency reactor designs, and investigating of die separation, chip shaping, and wafer bonding techniques.

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

Table 4-6: LED Product Development Tasks and Descriptors (2006-Priority Tasks)

Subtask		Short Descriptor	Metric	2006	Program Target (2015)
2.1.2	High-efficiency semiconductor materials	Develop efficient broadband light emitting materials (including yellow-green, orange, and UV (360nm to 410nm)) and develop alternate low-cost materials (e.g., nitride materials)	IQE	20% green, 80% red, 40% blue	90%
2.2.1	Manufactured materials	Include phosphors and luminescent materials and high temperature encapsulants and mounting materials.[37]	% of original transmission per mm	85-90% (@150C and 10-15 kHrs)	95% (@150C Junction Temp. and 50 kHrs)[38]
2.2.3	Electronics development	Research in this area includes developing lower cost electronics of smaller size with better color control and longer lifetime.	• %Energy Conversion • $/Watt • X-step MacAdam Ellipse • Lifetime	• 85% • 0.50 $/Watt • 7-step MacAdam Ellipse • 20-50kHrs[39]	• 90+% • 0.10 $/ Watt • 4-step MacAdam Ellipse. • 50kHrs
2.3.1	Optical coupling and modeling	Solving problem of extracting LED photons and getting them to desktop. This includes issues such as coupling to multiple sources and the multi-shadowing problem.	Optical/ Fixture Efficiency	70%	90%
2.3.4	Thermal design	Solving problem of removing heat away from the emitter chip and reducing thermal resistance to keep LED device at a low operating temperature while integrating the packaged LED device into a luminaire.	Thermal resistance (Junction to case)	8-9 ºC per Watt	5ºC per Watt
2.3.6	Evaluate luminaires lifetime and performance characteristics	Develop reliable information on lamp performance characteristics (e.g., lamp life, UV emission)	MTTF, (Mean time to failure)		

[37] NGLIA Technical Committee suggested breaking out this subtask as it represents several different types of materials efforts.
[38] This target may change to 185C as efficiency goals are met and cost becomes a higher priority
[39] Some 50kHr devices exist today, but these are presently military specification and are too costly for general illumination applications.

Table 4-6: LED Product Development Tasks and Descriptors (later priorities)

Subtask		Short Descriptor
Product Development		
2.1.3	Implementing strategies for improved light extraction and manipulation	Develop high refractive index encapsulants for improved light extraction and large-area light extraction and current injection
2.2.2	LED packages and packaging materials	Solving problem of removing heat from the chip, delivering high-lumen output chips with ultra-low resistance contacts.
2.4.x	Inorganic growth and fabrication processes and manufacturing issues.	Solving problem of incorporating proven in-situ diagnostics into existing equipment, developing low-cost, high efficiency reactor designs, and developing techniques of die separation, chip shaping, and wafer bonding techniques.

[40] There are several subtasks to 2.4, designated “x”; all need attention.

Table 4-7: OLED Core Technology Research Tasks and Descriptors (2006-Priority Tasks)

Subtask		Short Descriptor	Metric	2006	Program Target (2015)
3.1.2, 3.2.2 [41]	High-efficiency, low-voltage, stable materials and approaches to OLED structures between the electrodes for improved-performance low-cost white-light devices	This task involves material research encompassing stable hole and electron blocking layers and single and multi-layered devices to increase IQE. It also involves engineering between the electrodes (as opposed to chemistry), including layering the device for optimal efficiency.	-IQE -Voltage T70[42] at 1000 cd/m^2	*Singlet:* B>20% W >20%, G >20% *Triplet:* G 100% R 60% 4-5V	*Singlet*: 25% *Triplet*: 100% 2.8V T70 = 40,000 hrs
3.2.1	Strategies for improved light extraction and manipulation	This subtask involves research into optical and device design for improving light extraction.	-Extraction Efficiency	20%-30%	80%
3.2.3	Research on low-cost transparent electrodes	This subtask involves research into better transparent electrode technology that offers an improvement over ITO cost and deposition rate and allows for roll-to-roll manufacturing.	-Ohms/□ -transparency -\$/m^2	Flexible: 40 Ohms/□ 75-80%	Flexible: <10 Ohms/□ 92% < \$1/m^2
3.4.2	Investigation of low-cost fabrication and patterning techniques and tools	This subtask includes modeling to understand the fabrication process and fundamentally improved fabrication processes.	-Deposition Speed -Material utilization		

[41] Because it is difficult to compare the performance of a new material without the use of that material in a device, Tasks 3.2.2 and 3.1.2 from March 2006 MYP were combined. Standardizing a method to compare materials will be discussed at the January 2007 workshop.
[42] Time it takes to reach 70% Lumen Maintenance.

Table 4-7: OLED Core Technology Research Tasks and Descriptors (later priorities)

Subtask		Short Descriptor
Core Technology		
3.1.3	Improved contact materials and surface modification techniques to improve charge injection	This subtask includes research into n- and p- doped polymers and molecular dopants with emphasis on new systems and approaches to get charge into the device at the lowest possible voltage.
3.1.4	Fundamental Physics	This subtask involves research at the fundamental science level, including understanding and controlling singlet to triplet ratios to achieve 100% IQE and understanding degradation mechanisms to maximize lifetime.
3.3.2	Low-cost encapsulation and packaging technology	This subtask involves working on low-cost ways to seal the device to protect the luminaire from its environment to ensure a long device lifetime.

Table 4-8: OLED Product Development Research Tasks (2006-Priority Tasks)

Subtask		Short Descriptor	Metric	2006	Program Target (2015)
Product Development					
4.1.1	Low-cost substrates	This subtask includes developing low cost, readily available substrates with a low water permeability and high thermal conductivity.	-cost -thermal conductivity -%dark spot area		$< \$3/m^2$ 10x <10% dark spots at T70[43]
4.1.2, 4.2.2 [44]	Between electrodes high-efficiency, low-voltage materials and architectures that improve device robustness, increase lifetime and increase efficiency.	This subtask involves developing architectures and materials that improve robustness, lifetime and efficiency and the optimization of materials that show mass production potential.	-Efficacy (lm/W)[45] -CRI -EQE -Voltage -T70 at 1000 cd/m^2	32 lm/W	>100 lm/W 90 2.8V T70 = 40,000 hrs
4.2.1	Implementing strategies for improved light extraction and manipulation	This subtask involves improving on known approaches for extracting light.	Extraction Efficiency	25-30%	90%
4.3.1	OLED encapsulation packaging for lighting applications	This subtask includes research in heat management, dissipation techniques, encapsulants, and down-conversion materials for maximizing high-quality lumen output and reduced water permeability.	-$\$/m^2$ -%dark spot area - Loss penalty (compared to glass)	$\$4/m^2$	$< \$3/m^2$ <10% dark spots at T70[46] 0%
4.4.1	Module and process optimization and manufacturing	This subtask involves inventing and adapting OLED manufacturing technologies to the needs of lighting. It also covers developing flexible substrates for roll-to-roll manufacturing.	-Luminaire cost/m^2		$<\$30/m^2$ [47]

[43] Task 4.3.1 "dark spots" at T50 assumes small uniformly distributed spots and no localized failure. Dark spots also include pixel shrinkage.
[44] Tasks 4.1.2 and 4.2.2 were combined from the March 2006 MYP.
[45] This efficacy refers to an OLED device absent of any effort to improve light extraction efficiency.
[46] Task 4.3.1 "dark spots" at T50 assumes small uniformly distributed spots and no localized failure.
[47] In order to be competitive with a fluorescent luminaire, OLEDs must cost less than or equal to this amount.

Table 4-8: OLED Product Development Research Tasks (later priorities)

Subtask		Short Descriptor
Product Development		
4.1.3	Improved contact materials and surface modification techniques to improve charge injection	Activities under this subtask include the refinement of currently available technologies and investigation of problems with the supply chain (i.e., improving the quality of material inputs for manufacturing).
4.2.3	Demonstrate device architectures: e.g., white-light engines (multi-color versus single emission)	Research in this area includes demonstrating a device that scalable.

The task lists above do not include all that were considered at the planning meeting, only those that appear to be important to meet the milestones for this multi-year plan. For a complete list of task voting results and a summary of the discussion in each Session, see the 2005 *Solid-State Lighting Program Planning Workshop Report*, available at: http://www.netl.doe.gov/ssl/PDFs/DOE_SSL_Workshop_Report_Feb2005.pdf.

4.5. 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 a milestone description, it is assumed that progress on the others is proceeding, but the task priorities are chosen to emphasize the identified milestone.

4.5.1. Light Emitting Diodes

The interim (FY08) LED milestone reflects a goal of producing an LED product with an efficacy of 80 lm/W, an OEM price of $25/klm (lamp only), and a life of 50,000 hrs with a CRI greater than 80 and a CCT less than 5000°K. With this performance it would be a "good" general illumination product that could achieve significant market penetration. Current laboratory devices have reached an efficacy of approximately 95 lm/W; so it is expected that this target will be reached in commercial products in 2008 (a one and a half year lag). The 2008 price and life targets represent a 70% improvement over current products, and therefore pose a significantly larger challenge. By FY10, it is expected that the interim goal of 100 lm/W will be exceeded. Other parameters will also progress, but the task priorities are set by the goal of reaching this particular mark. Finally, by FY15, the end of the current forecast period, costs should be below $2/klm for LED devices while also meeting other performance goals, as outlined above.

Table 4-9: LED Product Milestones

Milestone	Year	Milestone Target
Milestone 1	FY08	80 lm/W, < $25/klm, 50,000 hrs
Milestone 2	FY10	> 100 lm/W
Milestone 3	FY15	< $2/klm

Assumption: CRI > 80, CCT < 5000°K

Using the subtask descriptions in the tables in the previous section, it is possible to associate those that must show significant early progress with the individual milestones. This linkage is graphically shown in the Gantt charts that follow. On these charts, the "2006-priority" subtasks, as defined in the Fall of 2006 by NGLIA are bold. The additional "later-priority" subtasks are not bolded.

The key to these charts is described below:

Key:

- Milestone (Occur at end of fiscal year, so blocks are placed in following year)
- Priority Tasks for M1 (FY08)
- Priority Tasks for M2 (FY10)
- Priority Tasks for M3 (FY15)

For example, to reach Milestone 1, a commercial LED product for general illumination in FY08, progress is necessary in several subtasks in core technology and product development. The duration of these activities are shown in yellow with crosshatching. To reach Milestone 2, an efficacy target of >100 lm/W, additional research is necessary on the subtasks shown in green with diagonal lines. To reach Milestone 3, a price target of <$2/klm, additional research is necessary on the subtasks shown in blue with vertical lines.

There is not enough detail in the subtasks as defined at the 2005 workshop to identify strict linkages and required "predecessor" tasks that would define a critical path to the various milestones. Nonetheless, the chart identifies, at least to some extent, those tasks that must see significant progress in order to meet the objectives and thus provides a basis for deciding work priorities. But additional work on the early tasks will also be needed *after* meeting the early milestones in order to continue progress towards the overall program goals. Thus, on the Gantt charts, an individual task may show two or even all three colors or patterns over the time period from now to 2015.

Table 4-10: Planned Research Tasks – LEDs

Task	Description[48]	FY'06	'07	'08	'09	'10	'11	'12	'13	'14	'15	'16
1.1.2	High efficiency semic. materials											
1.2.1	Device approaches, structures, systems											
1.2.2	Strategies for improved light extraction.											
2.2.2	LED packages & packaging materials											
2.3.4	Thermal design											
2.2.1	Manufactured materials											
2.3.6	Eval luminaires lifetime & performance											
M1	***Niche lighting product by FY08***											
1.3.1	High efficiency phosphors…											
1.3.4	Measurement metrics…											
1.3.2	Encapsulants & packaging mtls.											
2.1.3	Implementing strategies for light extrac.											
2.4.x	…manufacturing issues											
M2	***>100 lumens/watt by FY10***											
1.1.1	Large area substrates, …											
1.1.3	Reliability & defect physics…											
1.4.x	…manufacturing research											
2.3.1	Optical coupling & modeling											
2.2.3	Electronics development											
2.1.2	High efficiency semic. materials											
M3	***<$2/klm by FY15***											

Source: NGLIA LED Technical Committee Date: November 2006.

[48] For a short description of these subtasks, see Table 4-5 and Table 4-6.

4.5.2. Organic Light Emitting Diodes

The interim (FY08) OLED milestone is to produce an OLED niche product with an efficacy of 25 lm/W, an OEM price of $100/klm (lamp only), and a life of 5,000 hrs. CRI should be greater than 80 and the CCT should be between 3,000-4,000°K. Importantly, the NGLIA team also thought that a luminance of 1000 cd/m^2 could be used to compare the accomplishments of different researchers. That is *not* to say that lighting products may not be designed at higher luminance levels.

Current laboratory devices have reached an efficacy of approximately 31 lm/W (at reasonable life, luminance, and CCT). Because it normally takes three years to develop a laboratory device into an equally efficient commercial product, the SSL OLED program will be able to meet the FY08 (Milestone 1) efficacy target. The FY08 price and life targets, however, represent a 70% improvement over current laboratory devices, which still pose a large challenge. As there are currently no general illumination products for OLEDs, this milestone is an ambitious goal, but one the group thought was necessary to maintain a healthy program.

Milestone 2 targets a price of less than $52/klm by FY10. Inasmuch as there are no "prices" today, this is a difficult target to set at this point. Nonetheless, reaching a marketable price for an OLED lighting product, with their large areas is seen as one of the critical steps to getting this technology into general use.

Despite the considerable challenges the first two milestones offer, industry representatives agreed that reaching the 100 lm/W target by FY15 in Milestone 3 is one of the largest challenges because there are so many different performance parameters that will need to be improved.

Table 4-11: OLED Product Milestones

Milestone	Year	Milestone Target
Milestone 1	FY08	25 lm/W, < $100/klm, 5,000 hrs
Milestone 2	FY10	<$52/klm
Milestone 3	FY15	40,000 hrs., > 100 lm/W

Assumptions: CRI > 80, CCT < 2700-4100°K, luminance = 1,000 cd/m^2

The key for the OLED Gantt chart is the same as for the LED chart.

Table 4-12: Planned Research Tasks - OLEDs

Task	Description[49]	FY'06	'07	'08	'09	'10	'11	'12	'13	'14	'15	'16
3.3.2	Low cost encapsulation…technology											
3.1.2, 3.2.2	High-efficiency..materials..structures…											
3.2.1	Strategies for improved light extraction…											
4.1.2, 4.2.2	Between electrodes..materials..architectures											
4.3.1	OLED encapsulation…											
4.2.1	Implementing..improved light extraction											
4.1.1	Substrates…											
M1	***Niche product by FY08***											
3.2.3	...low-cost transparent electrodes											
3.4.3	…low-cost fabrication ..and tools											
3.1.3	Improved contact materials…											
4.4.1	Module and process optimization..											
4.1.3	Improved contact materials…											
M2	***<$52/klm by FY10***											
3.1.4	Fundamental science [of OLEDs]											
4.2.3	Demonstrate device architectures…											
M3	***40 khours, 100 lm/w life by FY15***											

Source: NGLIA OLED Technical Committee Date: November 2006.

[49] For a short description of these subtasks, see Table 4-77 and Table 4-8 .