



# Solid-State Lighting R&D Plan

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**Solid-State Lighting Program**

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Illumination Engineering Society of North America (IES) recently articulated TM-30,<sup>q</sup> a new method for evaluating color rendering that includes both a “fidelity index” and a “gamut index.”

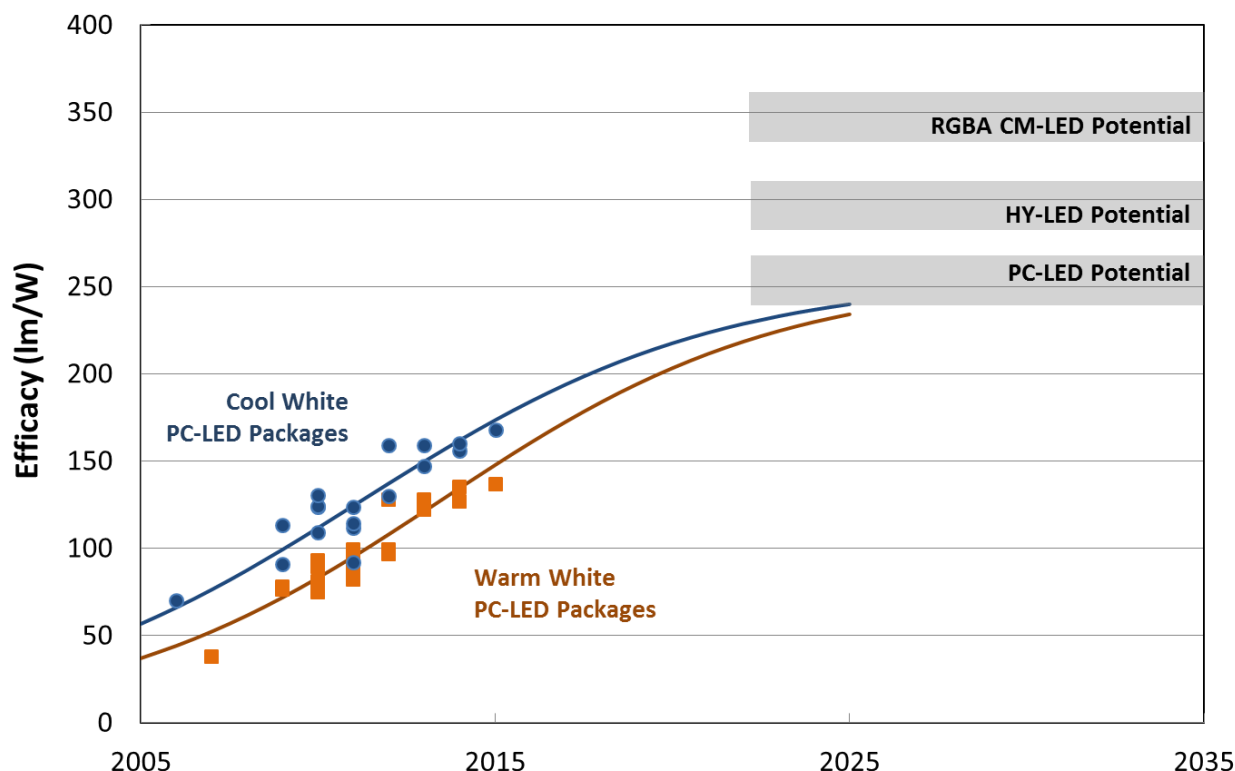
### 5.1.1 Pc-LED Architecture: Current Status

The pc-LED architecture was the first and is by far the dominant white light architecture. It has three major advantages over the other architectures: simplicity (only one LED to “drive”), temperature robustness (the indium gallium nitride, InGaN, blue LED and phosphor downconverters can operate at relatively high temperatures), and color stability (the fractions of red, green, and blue source colors is determined during manufacture by the phosphor optical density and is relatively stable over time).

Figure 5.4 shows a history of the luminous efficacy of pc-LEDs since the DOE SSL Program began and the progress that has been made. In just 10 years, luminous efficacies have increased by a factor of more than three, from less than 50 lm/W to approximately 150 lm/W. The principle reason has been improvement in blue LED efficiency; improvements also have been made in phosphors (efficiency and wavelength match to the human eye response) and package (optical scattering/absorption) efficiency.

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<sup>q</sup> For more information on TM-30, please see: <https://www.ies.org/store/product/ies-method-for-evaluating-light-source-color-rendition-3368.cfm>

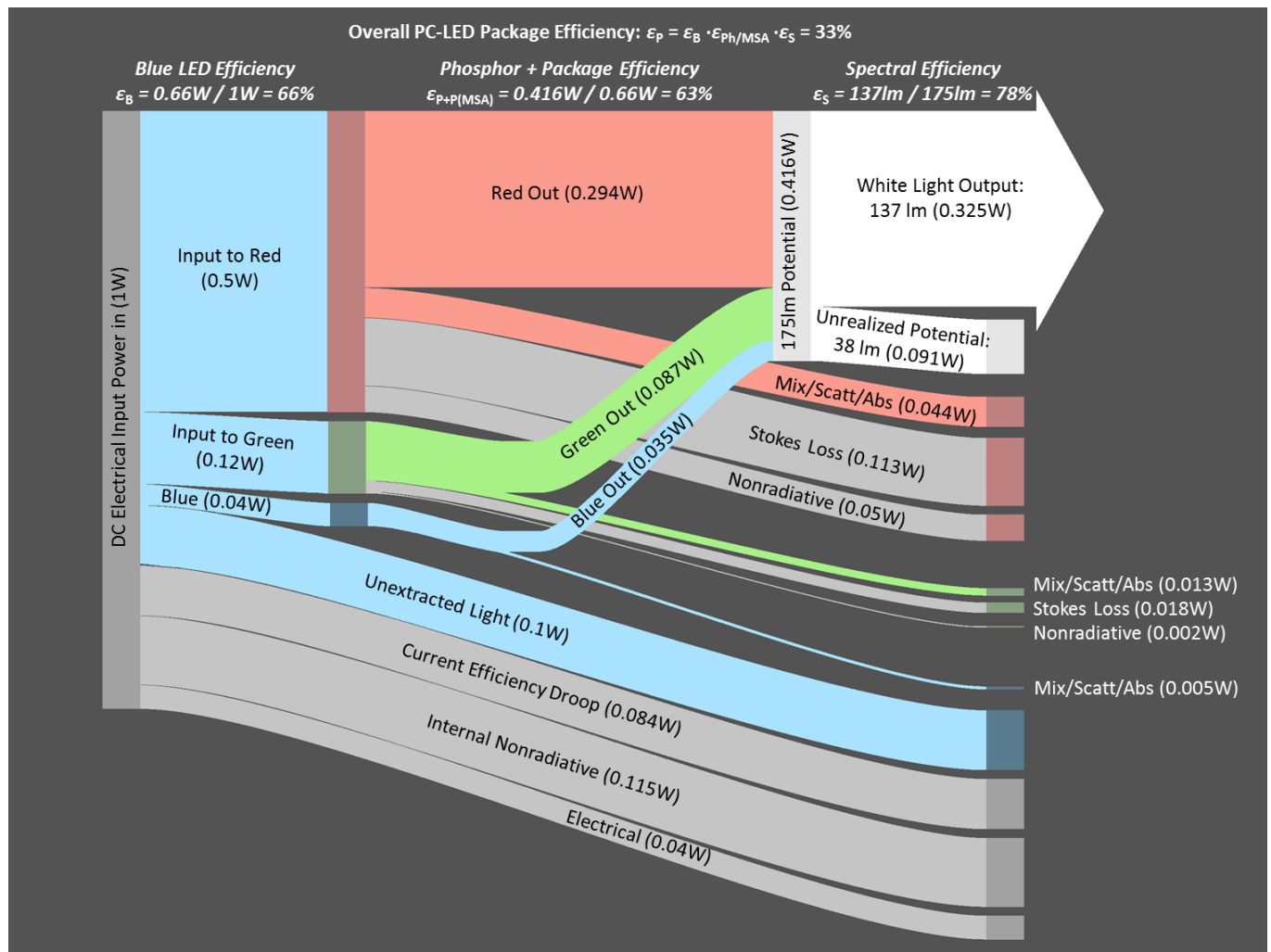


Note: Blue = cool white (5700K) data (circles) and logistic fit (line); orange = warm white (3000K) data (squares) and logistic fit (line). Late-2015 measured commercial products reach approximately 160 lm/W for cool white and approximately 140 lm/W for warm white. Approximate long-term-future potential efficacies of three white-light architectures (pc-LED, hy-LED, RGBA cm-LED) are shown as grey bars.

**Figure 5.4: Efficacies of Commercial LED Packages Measured at 25°C and 35 A/cm<sup>2</sup> Input Current Density**

Despite these improvements, there is much further to go. As illustrated by the lower gray band in Figure 5.4, luminous efficacies of approximately 255 lm/W are practically possible for pc-LEDs, a factor 1.6 times beyond the current state-of-the-art. To help visualize where this factor might come from, Figure 5.5 shows an estimated electricity-to-visible-light power-flow diagram for a current LED warm white light state-of-the-art commercial pc-LED package, in which a hypothetical 1 W (0.35 A x 2.85 V) is injected into the blue LED package at the left of the diagram, and 137 lumens of white light emerges from the pc-LED package at the right.

The blue LED converts the 1 W of electrical power with an efficiency of 66% into 0.66 W of blue optical power. En route, the blue LED loses 34% or 0.34 W of that electrical power to a combination of electrical resistance losses, internal quantum efficiency losses due to non-radiative recombination of injected electrons and holes at low current density, efficiency droop due to operation at higher (35 A/cm<sup>2</sup>) current density, and losses due to incomplete extraction of blue light from the high-index InGaN semiconductor material.



*Note: The diagram gives estimates for how 1 W = 0.35 A x 2.85 V of DC power is distributed into various useful and non-useful (loss) streams en route to being converted into white light. The colors of the various streams indicate the type of power they contain: gray for electronic excitations, colored for light at various RGB wavelengths, and white for white light formed from a combination of colors. For each loss stream we indicate both its absolute power as well as the percentage it represents of its immediately preceding parent stream.*

**Figure 5.5: Electricity-to-Visible-Light Power-Flow Diagram for a Late-2015 State-of-the-Art Warm White Commercial pc-LED Package**

*Source: Tsao, Coltrin, Crawford, and Simmons, Solid-State Lighting: An Integrated Human Factors, Technology, and Economic Perspective, July 2010 [78]*

The green and red phosphors convert the 0.66 W of blue optical power with an efficiency of 63% into 0.416 W of blue (0.035 W), green (0.087 W), and red (0.294 W) optical power. En route, the phosphors lose 37% or 0.244 W of the initial blue optical power to a combination of internal quantum efficiency losses due to non-radiative recombination of electrons and holes excited in the phosphors, a fundamental Stokes deficit due to the lower energies of green and red versus blue photons, and a mixing/scattering/absorption loss as the green, blue, and red photons mix, scatter in, and occasionally get absorbed within the LED package.

Finally, the 0.416 W of white optical power, distributed spectrally in a 20 nanometer (nm) full width half maximum (FWHM) blue LED band, a 100 nm FWHM green phosphor band, and an 80 nm red phosphor band, yields a lumen output of 137 lm. The maximum luminous efficacy of radiation (LER) of white optical power at this CRI (80) and CCT (3,000K), when optimally distributed into three or four narrower (less than 20 nm) bands in the blue, green and red, is approximately 414 lm/W. Thus, 0.416 W of white optical power, if spectrally redistributed, could potentially give 175 lumens (0.416 W x 414 lm/W). The spectral efficiency of the LED package is thus 78% (137 out of a maximum of 175 lumens)

Taken together, the current overall LED warm white, state-of-the-art, commercial package efficiency is 33%, and is equal to the product of the blue LED efficiency (66%), phosphor and mixing/scattering/absorption efficiency (63%), and white light spectral efficiency (78%).

These estimates of sub-efficiency breakdowns and overall efficiency roll-ups are for warm white. Historical and current commercial pc-LED efficacies are somewhat higher for cool white because they require a lower optical power fraction of red light, and red light contributes more losses in the pc-LED architecture than either blue or green. The most important loss contribution is its Stokes efficiency loss (25% for the red, in contrast to 15% for the green and 0% for the blue). The second most important loss contribution is the 15% to the white light spectral efficiency loss, because the current 80 nm FWHM-wide red phosphor emission linewidth causes a significant spillover of light into the deeper red, where the human eye is less sensitive. This will be discussed in more detail in Section 5.1.2.

### **5.1.2 Pc-LED Architecture: Opportunities and Challenges**

As discussed above, the current state-of-the art commercial pc-LED, with a luminous efficacy of approximately 137 lm/W, is about 33% efficient. Because of the fundamental Stokes efficiency loss associated with this architecture, 100% efficiency is not possible. As indicated in Table 5.1 and Table 5.2, even if all other losses were eliminated, the current pc-LED with its current spectral distribution of optical power can at most have a luminous efficacy of approximately 220 lm/W (LER x Stokes losses). This can be improved through improved spectral distribution of optical power, as discussed in more detail below, but it is not likely that all other losses will be eliminated. Thus we consider a luminous efficacy of 255 lm/W, or an efficiency of 61%, to be the “upper pc-LED potential,” and is indicated as such in Figure 5.4 by both the gray bar and the value that the logistic fit to the historical data has been set to approach.

Note that this upper pc-LED potential can be considered to be approximately equal for warm and cool white. This is because warm white requires a higher optical power fraction of red than blue light, which this leads to two offsetting effects. On the one hand, the human eye is more sensitive to red than to blue light, so warm white light will have an intrinsically higher spectral efficiency than cool white light. On the other hand, in the pc-LED architecture, red light has a higher Stokes deficit than blue light, so warm white light will have an intrinsically lower phosphor plus mixing/scattering/absorption efficiency than cool white light. These effects offset each other, with the net result being approximately similar potential efficacies.

For both warm and cool white, there is significant opportunity: 255 lm/W is considerably higher than the current state-of-the-art for both warm white (137 lm/W) and cool white (168 lm/W). To achieve such a

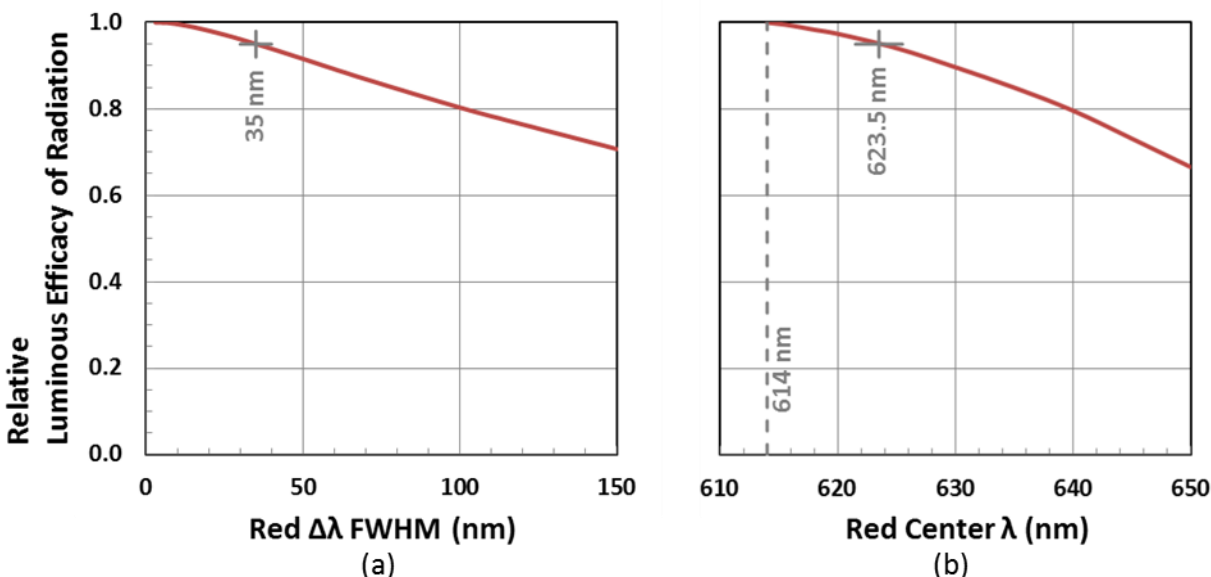
high luminous efficacy, a number of improvements will be required, ranging from continuing to improve the internal quantum efficiencies of the green and red phosphors, modestly narrowing the linewidth of the green phosphor emission to 50 nm FWHM or so, and improving the electrical efficiency of the blue LED. Three particularly important opportunities (and challenges) can be identified, as shown in Figure 5.5, Table 5.1, and Table 5.2.

***Opportunity/Challenge 1: Light extraction and mixing/scattering/absorption efficiency improvement.***

As can be seen from Figure 5.5, and from Table 5.1 and Table 5.2, a significant fraction (approximately 13%) of blue LED light is not extracted from the blue LED, and an equally significant fraction (approximately 13%) of white (blue, green, and red) light is not extracted from the white light package due to mixing/scattering/absorption losses. Taken together, minimizing these two loss channels represents a major opportunity for efficiency improvement. For both loss channels, the fundamental challenge is the high refractive indexes of the InGaN semiconductor that emits blue light and of the phosphors and encapsulants that absorb the blue light and mix/scatter the subsequent white light. The combination of high refractive indexes and scattering cause light to be trapped inside the white light package, and the long residence time of the light ultimately leads to optical absorption. Some of that absorption (e.g., blue light by the blue LED, or blue/green/red light by the green/red phosphors) might be recycled by photon re-emission, but most is lost to parasitic absorbers (e.g., metal contacts, interface states, heavily doped radiatively dark semiconductor layers). One challenge is to develop ways in which light can be made to escape from both the blue LED and white light package much faster (and the trapping time made much shorter). Examples of possible solutions include lower refractive index materials, novel micro- and nano-optical shapes or geometries, or coherent or partially coherent directed beams. Another challenge is to develop architectures and materials which minimize parasitic absorbers, or at least the degree to which light interacts with parasitic absorbers.

***Opportunity/Challenge 2: Red downconverter linewidth reduction.***

As mentioned earlier, the current 100 nm FWHM wide red phosphor emission linewidth causes a significant spillover of light into the deeper red, where the human eye is less sensitive, and is a significant contributor to the spectral inefficiency of current pc-LED white light. As can be seen in Figure 5.6(a), relative LER is higher with narrower red linewidth, increasing by 15%, from 80% to 95%, as the linewidth decreases from the current 100 nm FWHM to 35 nm FWHM. It is important to note that the improvement continues as linewidth continues to narrow to even less than 35 nm, with no penalty in color rendering quality. The challenge is thus to develop new red downconverters – phosphors, quantum dots, etc. – with narrower emission linewidths, while maintaining high (greater than 90%) internal radiative quantum efficiency. For on-chip (rather than remote) phosphor applications, robustness at high (85°C) operating temperatures and high impinging optical flux (1 watts per square millimeter, W/mm<sup>2</sup>) saturation are also critical. Finally, as narrower linewidth red wavelength downconverters are explored, their center emission wavelength is also important. As can be seen in Figure 5.6(b), relative LER is higher the closer the center emission wavelength is to 614 nm. A center wavelength of 623.5 nm would incur a 5% efficiency penalty, and a center wavelength of 630 nm would incur a 10% efficiency penalty.



Note: Relative white light LER (a) as the FWHM linewidth of the red phosphor increases, for a given red center wavelength of  $\lambda = 614$  nm, and (b) as the red center wavelength increases, for a given FWHM linewidth of  $\Delta\lambda = 7$  nm. In both cases, the blue and green linewidths were fixed at 20 nm and 50 nm FWHM, but their center wavelengths were allowed to vary so as to optimize LER while maintaining  $R_a = 80$  and  $R_g > 0$ . The 95% efficiency points are indicated: FWHM of 35 nm and center wavelength of 623.5 nm.

**Figure 5.6: Relative White-Light Luminous Efficacy of Radiation**

### ***Opportunity/Challenge 3: Blue LED efficiency droop.***

As can be seen from Figure 5.2, Figure 5.5, Table 5.1, and Table 5.2, the efficiency of the blue LED has improved enormously, but it is still highest at low current densities. The current “best” research has seen LED packages exceed 80% efficiency, but only at relatively low current densities. At the higher current densities desirable for low cost of light, higher market penetration, and ultimately the highest national energy savings, efficiencies decrease. This so-called “efficiency droop” from about 10 A/cm<sup>2</sup> to 35 A/cm<sup>2</sup> is about 10%, and to 100 A/cm<sup>2</sup> is about 15%. The challenge will be to circumvent the key physical mechanism responsible for efficiency droop, Auger recombination. Auger recombination is a non-radiative carrier recombination process which increases nonlinearly with carrier density and hence current density. Possible approaches to circumvent Auger recombination losses include: increasing the rate of competing radiative recombination (either through composition/geometry engineering or through use of alternative recombination mechanisms such as stimulated emission in laser diodes) or decreasing carrier densities (either through band-structure/transport engineering or through alternative geometries such as stacked active regions connected via tunnel junctions). The key to any of these approaches is to understand and control the complex epitaxial materials synthesis process so as to maintain the material quality that has been painstakingly engineered into current LED structures [79].