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LEDs: the new revolution in lighting / Les LED : la nouvelle révolution de l'éclairage

LED lighting efficacy: Status and directions

Efficacité de l'éclairage LED : état de l'art et directions

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ABSTRACT

A monumental shift from conventional lighting technologies (incandescent, fluorescent, high intensity discharge) to LED lighting is currently transpiring. The primary driver for this shift has been energy efficiency and associated cost savings. LED lighting is now more efficacious than any of the conventional lighting technologies with room to still improve. Near term, phosphor-converted LED packages have the potential for efficacy improvement between 160 lm/W (now) to 255 lm/W. Longer term, color-mixed LED packages have the potential for efficacy levels conceivably as high as 330 lm/W, though reaching these performance levels requires breakthroughs in green and amber LED efficiency. LED package efficacy sets the upper limit to luminaire efficacy, with the luminaire containing its own efficacy loss channels. In this paper, based on analyses performed through the U.S. Department of Energy Solid State Lighting Program, various LED and luminaire loss channels are elucidated, and critical areas for improvement identified. Beyond massive energy savings, LED technology enables a host of new applications and added value not possible or economical with previous lighting technologies. These include connected lighting, lighting tailored for human physiological responses, horticultural lighting, and ecologically conscious lighting. None of these new applications would be viable if not for the high efficacies that have been achieved, and are themselves just the beginning of what LED lighting can do.

RÉSUMÉ

Un passage radical des techniques d'éclairage conventionnelles (incandescent, fluorescent, décharge de haute intensité) aux technologies LED est en train de s'opérer. La première raison de cette mutation est à rechercher dans l'efficacité énergétique de ces dernières et dans les économies associées. L'éclairage LED est maintenant plus efficace qu'aucune des technologies d'éclairage conventionnelles, mais il reste de l'espace pour des améliorations. À court terme, les ensembles à LED converties au phosphore peuvent encore voir leur efficacité améliorée de 160 lm/W à 255 lm/W. À long terme, il est concevable que les ensembles à LED à mélange de LED de différentes couleurs puissent atteindre des niveaux

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d'efficacité de 330 lm/W, quoiqu'atteindre de telles performances demande des avancées majeures du côté des LED de couleurs verte et ambre. L'efficacité des ensembles à LED détermine la limite supérieure du luminaire, ce dernier contenant ses propres canaux de perte d'efficacité. Dans cet article, sur la base d'analyses réalisées au *Department of Energy* au sein du *Solid State Lighting Program* américain, différents canaux de perte des LED et des luminaires ont été élucidés, et des domaines critiques permettant leur amélioration ont été identifiés. Au-delà d'économies d'énergie massives, la technologie LED permet de nouvelles applications et une valeur ajoutée non possible ou non économiquement faisable avec les anciennes technologies d'éclairage. Celles-ci incluent l'éclairage connecté, l'éclairage adapté aux réponses physiologiques humaines, l'éclairage horticole et l'éclairage respectueux de l'écologie. Aucune de ces nouvelles applications ne serait viable sans les hautes efficacités qui ont été atteintes, et qui ne sont elles-mêmes que les prémices de ce que l'éclairage LED peut faire.

1. Introduction

Light-emitting-diode (LED) lighting, has advanced to the point where it is the best option for almost every lighting application. Over the last 15 years, the efficacies of cool white LED packages have improved from around 25 lm/W (lumens per watt) to over 160 lm/W, depending on color quality and drive conditions. Simultaneously, the costs of LED packages have decreased to the point where LED lighting products can be competitive with conventional lighting products on a first cost basis, while offering significantly lower cost of ownership (initial cost plus cost of electricity cost) during its life cycle. Increasing efficacy and decreasing cost have allowed luminaire manufacturers to provide improved color performance, optical distribution, form factor, and advanced control of the LED lighting products.

Even with these advancements, considerable room for further improvements remains, not only in efficacy and cost, but also in a broader range of functionalities. In this article, drawing heavily on 2017 stakeholder inputs to the U.S. DOE SSL R&D Program [1], we give a status report on LED lighting, and discuss the opportunities and challenges associated with those further improvements. Our emphasis is on efficacy and the resulting energy savings, but we mention at the end some of the new directions in lighting for which new functionality enables additional value beyond efficacy. These include human physiological responses to light and its impact on human health and productivity; connected lighting and its impact on the Internet of Things and on sensing/control of the built environment; horticultural lighting and its impact on indoor farming; and ecologically conscious lighting and its impact on the environment.

2. Lighting product efficacies and energy savings

A comparison between the luminous efficacies (output of optical lumens/input of electrical watts, lm/W) and lifetimes of top-performing LED and conventional lighting products is shown in Table 1. The efficacies of LED products compare well to conventional products in every product category, and are now more efficacious than even the best performing conventional lighting products. The lifetimes also compare well, although, we note that the listed lifetimes for the LED products account only for the 70% lumen depreciation point, not for other possible failure mechanisms such as catastrophic failure and parametric color shift.

Taken together, the higher efficacy and extended lifetime of LED products give them a lower life cost of ownership compared to conventional lighting products. This is spurring adoption, which in turn results in significant energy savings at national and global scales; and as both efficacy and adoption of LED lighting continue to increase, these energy savings are projected to become even more significant.

Current annual primary energy savings for the U.S. from LED lighting are estimated at 0.3 Quads (quadrillion British thermal units), equivalent to approximately 30 TWh/yr and \$3B/yr in energy and cost savings. Similar savings can be expected from the penetration of LEDs in Europe. As shown by the top line in Fig. 1 [2], total lighting energy consumption is expected to increase over the next two decades. However, as indicated by the light blue region of the figure, by 2035, if the U.S. Department of Energy (DOE) cost and performance targets are met, LED lighting could save 5.1 Quads of primary energy per year, equivalent to 500 TWh/yr and \$50B/yr, and accounting for possibly 5% of the total U.S. energy budget. Worldwide, the savings would be 3–5$\times$ higher.

3. LED package efficacies

The heart of LED lighting and LED lighting products is the LED package, which both produces the various colors of light as well as mixes them to create white light. Here, we consider two LED package architectures whose spectra are illustrated in Fig. 2 [3]: the phosphor-converted (pc) architecture, which is dominant in today's products; and the color-mixed (cm) architecture, which has the most headroom for improvement.

Table 1
Comparison between luminous efficacies of (top) best in class LED products and (bottom) conventional lighting products.

2016 Top performing LED products*	Luminous efficacy (lm/W)	Usable life (L70)† (h)
LED A19 lamp (dimmable, 2700 K)	100	25,000
LED PAR38 lamp (3000 K)	88	25,000
LED T8 tube (4000 K)	149	50,000
LED 6″ downlight (3000 K)	86	50,000
LED troffer 2′ × 4′ (3500 K)	129	50,000
LED high/low-bay fixture (4000 K)	136	60,000
LED street light (5000 K)	118	60,000

Conventional lighting products	Luminous efficacy (lm/W)	Usable life (h)
Incandescent A19	15	1,000
Halogen A19	20	8,400
CFL A19 replacement	70	12,000
CFL (dimmable) A19 replacement	70	12,000
Linear fluorescent system+	108	25,000
HID (high-watt) system+	115	15,000
HID (low-watt) system+	104	15,000

* The 90th percentile of either ENERGY STAR®-qualified products (for LED A19, PAR38, and 6″ downlight) or DesignLights Consortium-qualified products (for LED tube, troffer, high/low-bay, and streetlight) was used to characterize the efficacy of "top-performing" products, and then average prices were found for products at this efficacy point. ENERGY STAR® is an international standard for energy efficient consumer products that originated in the United States but has since been adopted by Australia, Canada, Japan, New Zealand, Taiwan, and the European Union; see, e.g., the Energy Star (https://www.energystar.gov/) and EU Energy Star (https://www.eu-energystar.org/) websites.

† For non-SSL technologies, the lifetime values mark the end of life due to product failure. Because LEDs undergo gradual lumen depreciation in addition to catastrophic failure, L70 values, the time at which products produce 70% of initial light level, are used as the useful lifetime of the LED products [3].

\+ Includes ballast losses.

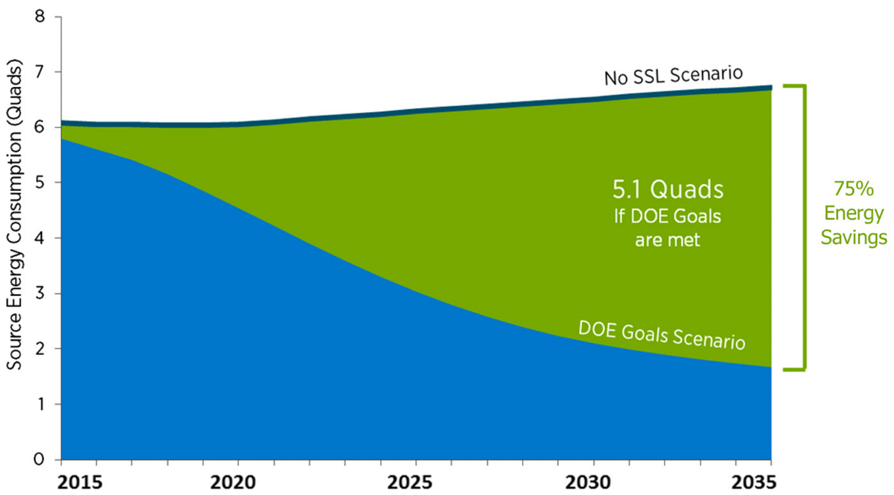

Fig. 1. Forecast of energy consumption due to lighting for the U.S. from 2015 to 2035. The two scenarios forecast are: "No SSL," in which conventional lighting technologies are assumed; and "DOE Goals Scenario," in which SSL meets relatively aggressive goals for efficacy and cost, and gradually displaces conventional lighting at a rate that depends on the degree of its improvement in efficacy and cost over conventional lighting [2]. Although lighting demand is expected to increase by 15%, which without SSL would require a 15% increase in primary energy consumption from 5.8 Quads/yr to 6.7 Quads/yr; instead, if aggressive DOE goals are met, a 72% decrease in primary energy is expected from 5.8 Quads/yr to 1.6 Quads/yr.

Throughout, we analyze the power conversion efficiencies (optical power out divided by electrical power in) and luminous efficacies (perceived lumens out divided by electrical power in) by separating their overall efficiencies into sub-efficiencies associated with the various source colors, and then re-assembling them into white light using an optical modeling worksheet [3]. We also assume four overall "operating" characteristics. First, we assume a drive current density of 35 A/cm^2: high enough to enable relatively low cost, but low enough to avoid the most severe effects of the efficiency droop discussed below. Second, we assume operating junctions at room temperature (25 °C). Third, we generally assume a warm-white correlated color temperature (~3000 K), which is more challenging for the current pc-LED architecture. Fourth, we assume color rendering indices (CRIs) of Ra ∼ 80 and R9 > 0, thought to be sufficient for most white light applications.

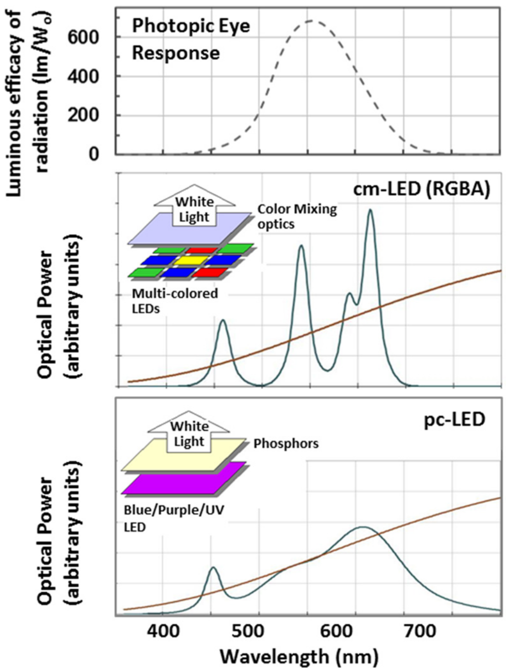

Fig. 2. Simulated optical power spectra for the two white-light LED package architectures considered: pc-LED (bottom panel) and cm-LED (middle panel). Also shown is the photopic eye response (top panel). For both optical power spectra simulations, the peak wavelengths and relative intensities are those which maximize luminous efficacy of radiation (LER) for a 3000 kelvin (K) (warm white) CCT, a "standard" color rendering index (CRI) Ra of 80, and a CRI associated with the ninth, deep-red Munsell color sample of R9 > 0. The spectral widths of the various source colors correspond to the current state-of-the-art. Overlaid on each spectrum is the spectrum from an incandescent blackbody source at 3000 K.

An overview of past and projected future efficacies of the two LED package architectures (pc-LED and cm-LED) with respect to illumination for humans is presented in Fig. 3. Although illumination for plants is still a nascent market, it is also included because it serves as a proxy for other applications for which "efficacy" takes on a different meaning than the usual luminous efficacy calibrated to the human eye response.

3.1. Luminous efficacy

Past and projected-future luminous (human eye response) efficacies for are given in Fig. 3(a). Here we use the standard term – luminous efficacy (lm/W): the ratio between the lumens (lm) associated with a given optical power (the integral of the optical power spectrum $p_{\mathrm{o}}(\lambda)$, weighted by the human eye response $V(\lambda)$, over wavelength) and the electrical source power (p_{e}) used to create the optical power:

$$\text{Luminous efficacy} = \frac{\int p_{\mathrm{o}}(\lambda)V(\lambda)\mathrm{d}\lambda}{p_{\mathrm{e}}} \tag{1}$$

The maximum white light luminous efficacy for a lossless white light source (no loss on conversion from electrical to optical power) with reasonable color rendering quality is 414 lm/W, and there is no fundamental physical reason why this cannot someday be approached [3,4].

For the pc-LED architecture, luminous efficacies have increased in a decade by more than a factor of three, from ~40 lm/W to ~137 lm/W (at 35 A/cm^2) for warm white. Assuming a maximum luminous efficacy of 414 lm/W, this is an increase from 12% to 33% in power conversion efficiency. The principle reason has been improvement in the blue LED efficiency, although improvements have also been made in phosphor (efficiency and wavelength match to the human eye response) and package (optical scattering/absorption) efficiency as well. Despite these improvements, though, because of the fundamental Stokes losses as blue photons are down converted to green and red photons, practical luminous efficacies are not anticipated to increase beyond 255 lm/W (power conversion efficiency of 62%) at 35 A/cm^2.

For the cm-LED architecture, there are various possibilities to consider: 3-color RGB, 4-color RYGB (or RGBA), and perhaps even 5-color RYGCB. Here, we consider only 4-color RYGB as the best balance between high ultimate luminous efficacy and high color rendering. As indicated by the dashed gray line in Fig. 3(a), its ultimate "upper potential" might be on the order of 330 lm/W, limited only by the anticipated 80 to 90% internal quantum efficiencies of the LEDs themselves and by small losses associated with mixing of their pure source colors to create for white light. The current luminous efficacy of the cm-LED architecture, however, is quite low: about 90 lm/W, or 22%. Consequently, it is rarely used except in applications requiring chromaticity tuning.

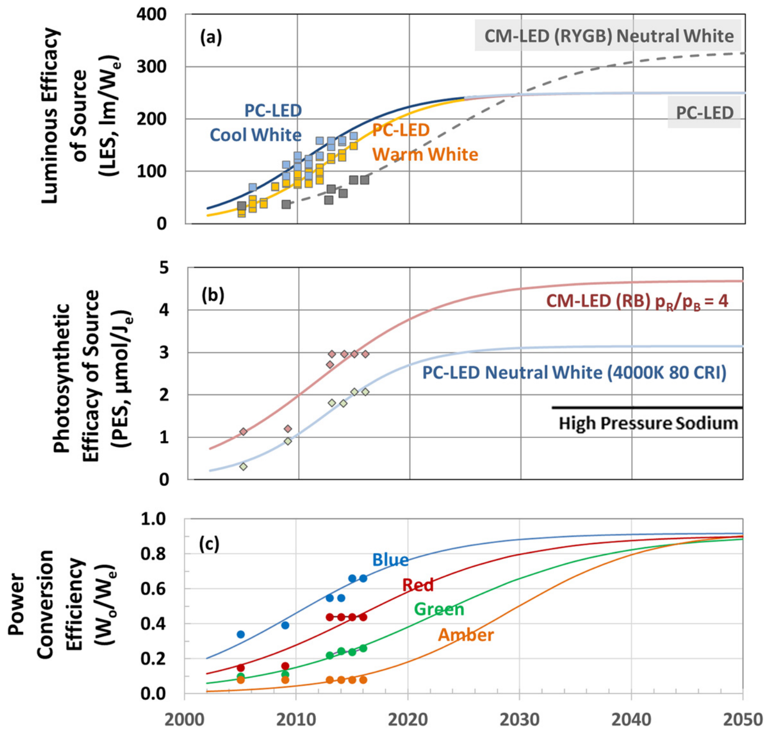

Fig. 3. Efficacies of Commercial LED Packages Measured at 25 °C and 35 A/cm^2 input current density. (a) Luminous efficacies of source (LES). Blue = cool white (5700 K) data (squares) and logistic fit (line); orange = warm white (3000 K) data (squares) and logistic fit (line). Year 2016 commercial products reach ∼160 lm/W for cool white and ∼137 lm/W for warm white. Approximate long-term-future potential efficacies of the pc-LED white light architecture are their values after saturation, depicted as beginning in the years 2020–2025. The long-term-future potential efficacy of the RYGB cm-LED architecture is shown as the dashed gray curve. The cm-LED architecture currently has lower performance than the current dominant pc-LED architecture, but it has the potential in future years to leapfrog beyond. (b) Photosynthetic efficacies of source (PES). Blue = neutral white pc-LED architecture. Orange = cm-LED (RB) architecture with red:blue optical power ratio 4:1. For both architectures, the points and lines represent the photosynthetic efficacies of source assuming the same historical (points) and projected (lines) efficiencies of the underlying LED technologies as in (a) and (c). (c) Power conversion efficiencies of LEDs at the various red, amber, green, blue colors necessary for high-color-rendering-quality cm-LED (RGBA) white light. Data (colored circles) are historical efficiencies; lines (colored lines) are logistic fits out to assumed long-term target efficiencies of ∼86%.

3.2. Photosynthetic efficacy of LEDs in horticultural application

Past and projected-future efficacies for plant illumination are given in Fig. 3(b). Here we use a measure that we call photosynthetic efficacy (μmol/J): the ratio between the photosynthetic photon flux (*PPF*, μ-moles/second) and the electrical source power (p_e) used to create that photosynthetic photon flux:

$$\text{Photosynthetic efficacy} = \frac{PPF}{p_\mathrm{e}} \tag{2}$$

The photosynthetic flux is the molar flux of photons within the plant absorption spectrum (typically taken to be wavelengths between 400 and 700 nm):

$$PPF = \frac{1}{N_A}\int_{400}^{700} \frac{p_\mathrm{o}(\lambda)}{hc/\lambda}\mathrm{d}\lambda \tag{3}$$

where N_A is Avogadro's number, c is the speed of light, h is Planck's constant, and hc/λ is the energy of a photon at wavelength λ. Note that there is no wavelength-dependent weighting of photon efficacy, though one could imagine someday including such a weighting as our understanding of plant responses to light becomes more sophisticated [5].

Two photosynthetic efficacy curves are shown in Fig. 3(b), along with a marker for the ∼1.7 μmol/J photosynthetic efficacy associated with conventional high-pressure sodium lamps [6].

The curve in blue is associated with conventional pc-LED white light. We have chosen a neutral-white 4000 K color temperature, though the dependence on color temperature is minimal. Since LED packages that have been optimized for humans are being used in some horticulture applications, we have also assumed here an LED package with a color rendering index of 80 – even though plants of course are not sensitive to color rendering as defined by humans. For this pc-LED architecture, one sees that the trend for plants is like that for humans: a steady increase this past decade by also more

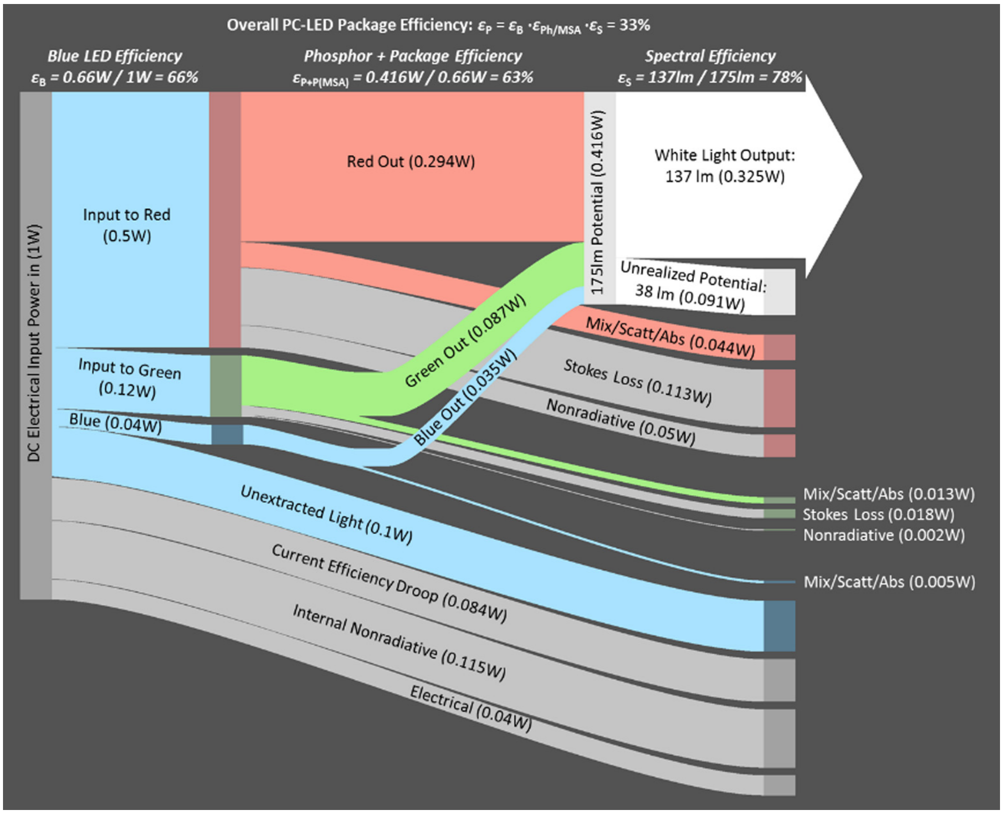

Fig. 4. Electricity-to-visible-light power-flow diagram for a 2016 State-of-the-Art Warm White Commercial pc-LED Package [4]. The diagram gives estimates for how 1 W = 0.35 A × 2.85 V of DC power is distributed into various useful and non-useful (loss) streams en route to being converted into white light. 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, values indicate both its absolute power as well as the percentage it represents of its immediately preceding parent stream.

than a factor of three, from ∼0.6 to ∼2.0 μmol/J, driven similarly by the increasing efficiencies of the blue LED, phosphor, and package. One also sees a projected future saturation at ∼3.1 μmol/J, similarly limited by phosphor conversion efficiency losses, not including Stokes losses.

The curve in red is associated with a cm-LED architecture. Just as for humans, for this architecture there are various possibilities to consider depending on how many colors one includes. Here, we consider 2-color RB in a ∼4:1 power ratio, as this is a common configuration. The photosynthetic "workhorse" is the optical power in the red, as it has the highest molar flux per optical Watt (lowest hc/λ in Equation (3)); while plant growth morphology is improved by the presence of some optical power in the blue. These two colors are also fortuitously those most efficiently created by LEDs: blue from InGaN LEDs and red from AlInGaP LEDs. Thus, the photosynthetic efficacy of source for plants, opposite to the luminous efficacy of source for humans, is already much higher for the cm-LED than for the pc-LED architecture. That difference persists out to the future, where long-term target efficiencies for red and blue LEDs would give photosynthetic efficacies of sources of 3.1 and 4.7 μmol/J for the pc-LED and cm-LED architectures, respectively. Caution is advised about the choice of wavelengths for the cm-LED architecture, however. Much is not known about the influence of spectra on plant growth, particularly the role of green light [7].

4. LED package loss channels and opportunities for improvement

To understand where the opportunities for efficacy improvement are for LED packages, Fig. 4 shows an electricity-to-visible-light power-flow diagram for a current LED warm white light state-of-the-art commercial pc-LED package, along with the various channels via which electrons or photons are lost en route [8].

A hypothetical 1 W (0.35 A × 2.85 V) is injected into a blue LED at the left of the diagram, of which 66% is converted into 0.66 W of blue optical power. 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^2) current density, and losses due to incomplete extraction of blue light from the high-index InGaN semiconductor material.

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. 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 (3,000 K), 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 $\times$ 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%). Conversely, one might say that the state-of-the-art commercial package inefficiency is $67\% = 100 - 33\%$, and that this inefficiency is due to a combination of a blue LED inefficiency ($33\% = 100 - 66\%$), a phosphor and mixing/scattering/absorption inefficiency ($37\% = 100 - 63\%$), and a white light spectral inefficiency ($22\% = 100 - 78\%$).

In the following, we describe briefly the opportunities for decreasing these losses.

4.1. Light extraction and mixing

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 indices 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 travel paths 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 opportunity is to develop ways in which light can be made to escape from both the blue LED and white light package much faster, preferably during the first pass. Examples of possible solutions include engineered high refractive index materials, novel micro- and nano-optical shapes or geometries, or coherent or partially coherent directed beams. Another opportunity is to develop architectures and materials which minimize parasitic absorbers, or at least the degree to which light interacts with parasitic absorbers.

4.2. Red down-converter spectrum

In current warm white pc-LEDs, there is a spectral inefficiency of 22%, due in large part to the current 100 nm FWHM wide red phosphor emission linewidth which causes a significant spillover of light into the deeper red, where the human eye is less sensitive. 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 opportunity is thus to develop new red down-converters – phosphors [9,10], quantum dots [11], etc. – with narrower emission linewidths, while maintaining high (greater than 90%) internal radiative quantum efficiency. For on-chip phosphor applications (rather than remote), robustness at high (85 °C) operating temperatures and high optical flux (1 watts per square millimeter, W/mm^2) saturation is also critical. Finally, as narrower linewidth red wavelength downconverters are explored, their center emission wavelength is also important. 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.

4.3. Blue LED efficiency droop

The efficiency of the blue LED has improved immensely, with the current "best" research showing external quantum efficiencies (EQE) exceeding 80% efficiency, but only at relatively low current densities. At the higher current density desirable for low cost of light to drive higher market penetration, LED efficiencies decrease. This so-called "efficiency droop" from about 10 A/cm^2 to 35 A/cm^2 results in $\sim$10% EQE penalty, and from 35 A/cm^2 to 100 A/cm^2 is about another 15%.

The opportunity is to circumvent the key physical mechanism responsible for efficiency droop, Auger recombination – a non-radiative carrier recombination process which increases nonlinearly with carrier density and hence current density.

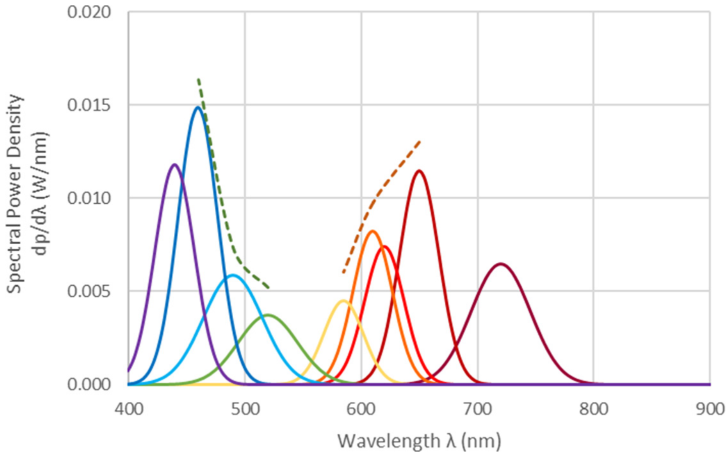

Fig. 5. Spectral power densities vs wavelength of state-of-the-art commercial LEDs. Dashed lines are guides to the eye, illustrating the "green gap": the decrease in efficiency from the blue to the green–yellow (left to right) and from the red to the green–yellow (right to left). Spectral power densities were calculated from the efficiencies, center wavelengths and spectral widths given in Lumileds Rebel Color Line Product Datasheet DS68, updated January 22, 2017.

Possible approaches 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 to maintain the material quality that has been painstakingly engineered into current LED structures [12].

4.4. Green/amber/red LED efficiencies [1]

Note that not all of the inefficiencies mentioned above are reducible. The Stokes loss due to phosphor downconversion is not reducible within the pc-LED architecture. Combined with other likely limits, such as a blue LED efficiency limited to 90%, and optical mixing efficiencies limited to 95%, a luminous efficacy of 255 lm/W, or an efficiency of 61%, might be considered the "upper pc-LED potential," and indicated by the saturation values in Fig. 3. Thus, the opportunity is to eliminate the phosphors and move to a cm-LED architecture. However, the efficiencies for green, amber and red direct emission light sources limit their performance.

Green and amber LEDs, with ideal wavelengths at approximately 540 nm and 575 nm respectively, are right in the middle of the so-called "green gap" (Fig. 5). Efficiency reduces as the green emission wavelengths are approached, both from the short wavelength and long wavelength sides. While performance of InGaN-based blue and violet LEDs has advanced rapidly over the past couple of decades with internal quantum efficiencies at low current densities now approaching 95%, increasing the indium composition to provide emission in the green spectral region results in a rapid reduction in efficiency. There is mounting evidence that performance of green LEDs is limited by efficiency droop, just like in blue LEDs but more pronounced, caused by Auger recombination. Therefore, fundamental research in droop mitigation strategies should benefit both blue and green LEDs. Another issue to be resolved is the strain-associated lattice mismatches between InGaN (with a high enough indium fraction to emit in the green and amber).

Red LEDs are currently based on aluminum indium gallium phosphide (AlInGaP) materials, and face two challenges. First, AlInGaP-based red LED efficiencies decrease the shorter their red wavelengths; by 614 nm, the ideal red wavelength for lighting, their external quantum efficiencies are only about 25%. Second, the thermal efficiency droop associated with these AlInGaP-based red LEDs is much greater than that associated with InGaN-based blue LEDs, requiring a control system to maintain a consistent color point. Both of these challenges are associated with AlInGaP materials themselves: an unfavorable band structure in the shallow red both for carrier transport/confinement and radiative carrier recombination (due to a direct to indirect bandgap crossover). A novel variant of AlInGaP, or a different material system entirely (e.g., InGaN), may provide a solution.

5. Luminaire efficacies and opportunities for improvement

There is an almost infinite range of lighting applications, and the luminaire is the final element that tailors how the light fits into the application. The brightness, size, direction, and diffusion of the final beam; the aesthetics, shape, size, and cost of the fixture and overall luminaire; and the environment with which the luminaire must be compatible and integrate are considerations that lead to such a wide proliferation of luminaire types. While the LED package is at the heart of the overall

Table 2
Breakdown of warm-white (CCT = 3000 K, CRI = 80) LED luminaire efficacy projections. Package luminous efficacies are based on the efficiencies in Fig. 2.

Efficacy or efficiency channel	2016	2018	2020	2025	Goal
Package efficacy projection* (lm/W)	137	175	208	237	255
Thermal efficiency droop (increased T_{op})	88%	91%	93%	95%	95%
Driver efficiency	88%	91%	93%	95%	95%
Fixture/optical efficiency	90%	92%	94%	95%	95%
Overall luminaire efficiency	70%	76%	81%	86%	86%
Luminaire efficacy† (lm/W)	95	133	169	203	218

* Package efficacy projections are for the warm-white pc-LED at 25 °C, per Fig. 2.

† Luminaire efficacy is obtained by multiplying the package efficacy by the overall luminaire efficiency.

system that produces and delivers white light to the environment, it is surrounded on either side (input and output) by components which collectively make up the luminaire.

The white light production efficiency of an LED luminaire can only reduce the efficiency of the integrated LED package(s). The other subsystems of the luminaire – the power supply on the front end, the mechanical and thermal-management structure, and the optical diffusing and/or directing on the back end – can be improved to minimize their contribution to system losses. Progress and future targets for the various efficiencies associated with these subsystems of the luminaire are indicated in Table 2. Please note: Table 2 estimates best case efficiencies, not average efficiencies, so they may not be achievable in all lighting applications. In addition, many luminaires use LED packages operated at current densities below 35 A/cm^2, so the efficacy of the package can be higher than the levels described in Table 2 and Fig. 3.

5.1. Power supply

On the front end is the power supply that converts alternating current (AC) line power to a voltage and current compatible with the LED packages, and may incorporate control functions such as dimmability. A variety of driver configurations accommodate different numbers of LED packages, varied circuit architectures, and various voltage levels of either AC or DC input. The various driver topologies and LED drive schemes, functionality, size, and cost will dictate the exact performance of the driver. Table 2 provides a representative driver efficiency, though some topologies today show higher performance and some show worse.

Perhaps the biggest challenge for drivers is not efficiency, but reliability. Driver reliability is the weakest link among all components in the luminaire [13] and a significant challenge lies ahead to improve it, including fundamental reliability limitations of many of the driver subcomponents. Solid-state component integration into the driver should be explored as a more robust alternative since solid-state drivers can simplify the part count and reduce failures. It would also improve the surge rating and reduce the driver size. Moving to GaN- or SiC-based power electronics has the potential to improve the efficiency and reliability, though today these solid-state components are still very costly and further research is required in the electronics industry to improve the defect count to reduce cost. Establishing the reliability for GaN and SiC components and the impact on driver reliability is an important opportunity that has common research elements with LED material and device advancements.

There are numerous additional development opportunities for LED power supplies. Efficiency and flicker performance at dimmed settings can be improved. Controls and communications functionality can be embedded in the power supply to enhance energy savings and functionality of the luminaire. Additional levels of functionality and control could be achieved by addressing and controlling individual strings of LEDs. And, finally, the size of the power supply can be reduced and/or the form factor optimized for the specific lighting application.

5.2. Thermal/mechanical

On the back end of the light generation process is the mechanical, thermal management, and optical structures that are used to integrate LED packages into the larger luminaire. Unlike traditional incandescent lamps, LED sources do not radiate heat, so any heat generated by inefficiencies must be dissipated through the luminaire itself. The operating current of the LED package, the ambient temperature, and the thermal design of the luminaire then determine the operating temperature of the LED package and its efficiency after accounting for thermal droop (the loss in efficiency of the LED as it is operated at an elevated temperature). Improved thermal handling and/or reduced operating current will result in a lower operating temperature of the LED and, in turn, higher LED efficiency.

Luminaire developers have found that removing thermal interfaces within the luminaire thermal path can improve the thermal handling of the luminaire and improve LED efficiency. Using mechanical structures in the luminaire to help dissipate heat, e.g., the front trim of a downlight or the sheet metal backing of a troffer, can help the thermal design while keeping the size and cost of the thermal system down. The thermal design of the luminaire also affects reliability. LED output depreciation is a function of operating temperature and failure rates of the components in the power supply are influenced by temperature.

5.3. Optics

The optical system in the luminaire controls and manipulates the intensity and spatial distribution of light to the application. Various permutations of lenses, reflectors, optical mixing chambers, remote white converters, and diffusers can be used depending on the lighting application, the desired optical distribution, and the form factor of the lighting product. LED lighting systems, with their improved optical control, have demonstrated they can often use less total light to achieve prescribed illuminance levels. For outdoor applications, this is achieved by reducing overlighting and non-useful, off-target lighting which is manifested as light trespass or uplight that is emitted into the atmosphere and results in sky-glow [14].

Well-designed luminaires in certain applications can experience less than 10% optical losses, and new approaches may reduce this further. In general, the fewer and smaller the LED packages with smaller etendue, the more efficient the optical system can be. In the limit of laser diodes, optical systems that are extremely efficient, as well as novel (e.g., ultra-thin edge-lit waveguide geometries), can be envisioned.

Taking advantage of the inherent properties of LED lighting not only can lead to new form factors that can transform how light is integrated into buildings, but it can also lead to designs that improve the efficiency of delivering light in the application. By designing the luminaire to put a greater percentage of light to the target area, the overall light required to reach the required illuminance levels can be reduced resulting in improved light utilization. Maximizing light utilization for SSL sources will require a move beyond legacy form factors such as the light bulb and the recessed luminaire, toward form factors that maximize application efficiency as well as optical, electrical, and thermal efficiency. Dynamic control of the optical distribution through the use of MEMS mirrors, liquid crystal lenses, electrowetting, or other novel approaches could further improve the efficiency of light delivery and functionality of the luminaire.

5.4. Form factor

Most LED lighting technologies have been engineered to address nearer-term market opportunities in the form of replacement lamps and retrofit luminaires. However, typical lamp form factors are not ideal for integration of LED packages into a lighting product. With bulb form factors, there is no natural thermal path to conduct heat away from the LED packages; the LED package light distribution is not ideal for most bulb types; and integrating power supplies into individual lamps can be costly and inefficient. LED product integrators have done a remarkable job developing products that surmount these challenges, but legacy form factors fail to exploit the unique features and design flexibility associated with LED technology and will always require LED technology to be forced into a vestigial, sub-optimal form factor.

The unique properties of LEDs allow for new lighting form factors that can change the way lighting is integrated into buildings. SSL is not limited to conventional bulbs or fixture size; LED products will require less depth and volume in recessed lighting applications allowing for more compact building architectures that require less in the way of building materials. LED lighting also provides new integration opportunities such as working with DC microgrids to minimize AC/DC conversion losses at each fixture or when using renewable energy sources and their battery systems without requiring DC to AC conversion to power the lights.

6. Opportunities beyond simple efficacy

The energy savings delivered by LED lighting technology are already measurable and profound, and further opportunities exist for practical improvements to the source efficacy of LEDs and the efficiency of the ultimate lighting products. Improvements for phosphor converted LEDs are still possible resulting in a practical maximum efficacy of 255 lm/W. The color mixed approach, using all direct emitting LEDs, will require greater breakthroughs, but no fundamental barriers are currently understood to prevent this approach from reaching efficacy levels of around 330 lm/W.

Although the focus of this article was efficacy, we close by emphasizing that the benefits of LED technology go well beyond lighting efficacy. LED lighting technology will enable new applications and human productivity previously thought impractical or not even thought of [15].

Human health and well-being is one broad class of such application. Humans are continuously exposed natural and electric lighting, all of which has some effect on our physiology. Light not only enables vision, but is a critical signal to our biological systems, affecting circadian rhythms, pupillary response, alertness, and more [16]. Light is an effective treatment for a variety of conditions, such as seasonal affective disorder (typically the depression suffered by people when outside light decreases, particularly in northern countries in winter) and dementia [17]. LED lighting opens up the possibility to tailor lighting everywhere to positively affect human health and well-being.

Connected lighting is another broad class of application. The convergence of SSL, low-cost sensors, smartphones and apps, and the Internet of Things (IoT) is expected to enable new lighting system functionality and an unprecedented exchange of data among lighting and other building systems, the Internet, and other devices. The ubiquity of lighting in the built environment provides a unique and valuable opportunity to create a dense grid of networked data collection nodes in and near buildings. Such connected lighting systems, i.e., networked devices with sensors, can become key data-collection platforms in buildings and in cities, thereby providing a backbone for the fast-emerging IoT, and enabling a unique array of services, benefits, and revenue streams that would take lighting well beyond its traditional definition and greatly enhance its value.

Horticulture lighting is yet another broad class of application. Light-regulated plant attributes, including flowering, branching, plant height, biomass accumulation, plant immunity and defense, stress tolerance, and phytoceutical production, are influenced by changes in the spectrum of light [18]. This can then influence various aspects of plant growth, such as the size of the plant, germination process, flowering, vegetation, and even nutritional value. LED lighting, via spectral tailoring and tuning, intensity control, and light distribution control, can enable an unprecedented level of control over the growth and economics of controlled environment agricultural (e.g., green house or indoor), particularly when other aspects of the growth environment (temperature, irrigation, humidity, CO_2 levels, etc.) are also enabled for control by the use of electric lighting. These new levels of control and the inherent separation from the outside environment also enable reduction in the use of water by more than 90% [18] and reductions in use of chemicals in the plant growth process such as insecticides and plant growth regulators [19].

Ecologically conscious lighting is another broad class of application. Outdoor lighting and indoor lighting that escapes from buildings both contribute to light pollution via sky glow, as well as detrimentally impact a variety of wildlife, including, but not limited to, migratory birds, seabirds, bats, amphibians, sea turtles, and insects. LED lighting offers a tremendous opportunity for conservation of wildlife and landscape ecology. The optical distribution and spectral control offered by LED technology combined with the use of controls can enable night lighting that is optimized for reduced sky glow and human activity simultaneously [20]. The ability to economically implement adaptive lighting and remote monitoring and control technologies will help biologists react and modify the night lighting spectra based on wildlife behavior documented in the field.

Another element of ecological benefit from LED lighting are the lifecycle benefits described by the lifecycle analysis process. A DOE-sponsored life-cycle assessment (LCA) [21] from 2013 showed that LED products reduce the total life-cycle energy consumption, including energy consumed during manufacturing, transportation, and use of the products. Since the initial study, LEDs have improved in efficacy resulting in a reduction of about half of the life-cycle energy consumption from LED products 5 years ago. The LCA study also showed that SSL can reduce energy use from lighting and maintain performance levels without using large amounts of toxic or scarce materials. LED lighting products do not require mercury or lead, and they make much more effective usage of rare-earth materials than fluorescent lighting. The LCA study concluded that LED-based SSL already represents an advancement in sustainability for lighting, and the advantages will continue to grow as further improvements in efficiency are realized.

All of these broad new classes of applications for electric lighting will necessitate new metrics for an emerging concept that might be called “application efficiency.” The full application efficiency of a luminaire depends not only on (a) how efficiently light is created (creation efficiency), but on (b) how efficiently light is utilized in space and time (utilization efficiency), and (c) how well the spectral content of the light matches the application need (spectral efficiency). Each lighting application is unique and has unique requirements; how effectively and efficiently the lighting system achieves those requirements defines the lighting system’s application efficiency.

We can envision three exciting opportunities within this topic. First, a deeper understanding of the requirements of the application, including the physiological responses of the recipient of the light. Second, precisely tailoring the light (spectral, intensity, spatial) to the application – so as to create in real time only the type of light required by the application and to direct it only to where it is needed. Third, developing new ways of measuring how well the light has in fact been tailored to the application – again perhaps in real time.

LED lighting technology offers the possibility to totally rethink how lighting is deployed in our world. The future of lighting is just beginning!

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